

Muriel Gargaud
William M. Irvine
Editors-in-Chief

Ricardo Amils
Philippe Claeys
Henderson James Cleaves
Maryvonne Gerin

Daniel Rouan
Tilman Spohn
Stéphane Tirard
Michel Viso
Editors

Encyclopedia of Astrobiology

Third Edition

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With 802 Figures and 94 Tables

 Springer

Editors-in-Chief

Muriel Gargaud Laboratoire d'Astrophysique de Bordeaux University of Bordeaux Pessac, France	William M. Irvine Department of Astronomy University of Massachusetts Amherst, MA, USA
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Editors

Ricardo Amils Centro Biología Molecular Severo Ochoa Universidad Autónoma de Madrid Cantoblanco Madrid, Spain	Philippe Claeys Analytical, Environmental, Geo- Chemistry Vrije Universiteit Brussel (VUB) Brussels, Belgium
---	--

Henderson James Cleaves Earth-Life Science Institute Tokyo Institute of Technology Tokyo, Japan	Maryvonne Gerin Radio Astronomy Paris Observatory Paris, France
--	--

Daniel Rouan LESIA, Observatoire de Paris-Site de Meudon Meudon, France	Tilman Spohn International Space Science Institute Bern, Switzerland
--	--

Stéphane Tirard Faculté des Sciences et des Techniques de Nantes Centre François Viète d'Histoire des Sciences et de Techniques EA 1161 Nantes, France	Michel Viso Innovaxiom Paris CX, France
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Foreword to the Third Edition

Are we alone? Already at the time of the Greek thinkers, more than two millennia ago, the question of the plurality of Worlds, even of the plurality of inhabited Worlds, was the subject of philosophical debates.

In the context of current research in astrobiology, it is impressive to reread this sentence of the philosopher Epicurus in the fourth century BC (341–270 BC): “Worlds are in an infinite number, some of them similar to our own one, some others being different . . . Living species, plants and all the other visible things could exist in some worlds and could not in others.” Exceptional vision: If the first part of this quotation has been fully proven by the discoveries of more than 5000 exoplanets, the second part is at the heart of the multi-disciplinary research conducted by many researchers of our time and the subject of this encyclopedia.

The interest for this question was not limited to antiquity, I like this quote from the philosopher and theologian Albertus Magnus (about 1200–1280):

Do there exist many worlds, or is there but a single world? This one of the most noble and exalted questions in the study of Nature.

During the last decades, the search for exoplanets has been rich in discoveries:

The frequency of planetary systems in our Galaxy, the diversity of these systems both by their architecture and by the physical nature of the exoplanets, the importance of orbital migration during the formation and evolution of these systems, and still the first steps for the determination of the compositions of planetary atmospheres . . . first step perhaps for the search of signatures of life.

Systematic searches for planetary systems, both on the ground using Doppler spectroscopy and in space with the detection of planetary transits, have shown that the vast majority (close to 100%!) of stars are hosts of such systems.

The detection bias of both techniques limits an accurate assessment of the number of rocky planets in the habitable zone of stars with masses not too different from that of the Earth's. Current estimates tell us that billions or even tens of billions of rocky planets, with a temperature adequate for the development of complex life chemistry, exist in our galaxy. Many observatories or space missions are focusing on the search for such planets among the stars closest to the Sun.

Planets in the habitable zones of very close stars have been detected. Let us mention for example the star systems Proxima Centauri and TRAPPIST-1. These stars of very small masses, of extremely low luminosity, have a habitable zone extremely close to the star, with orbital periods of a few days! Are these “Worlds” adequate for the development of life (synchronous rotation, intense flux of energetic particles?). Despite these uncertainties, these systems will probably be at the focus of coming research.

The search for true “earth twins,” these rocky planets in the habitable zone of stars with masses close to that of the Earth, is much more difficult, especially if we hope to discover one that presents transits. The amplitude of the variation of the stellar velocity wobble decreases strongly with the period. Worse the very small variations of the stellar velocity induced by the influence of the planet are dominated by the fluctuations produced by the magnetic activity of the star. Considerable efforts are made to improve the algorithms and to decrease the influence of the intrinsic stellar variability . . . hope is allowed.

Transmission spectroscopy during planetary transits has already allowed remarkable successes for our knowledge of the atmospheres of gas giant planets. The advent of very large telescopes both in space (JWST) and on the ground (e.g., the E-ELT in Chile and its 39 m diameter) should allow the first transmission spectroscopy of rocky planets.

For rocky planets on short period orbits other instrumental possibilities exist. By combining high spectral resolution and high spatial resolution (adaptive optics), it will be possible to study the light reflected by the planetary atmosphere.

If the past years were the golden age of the discovery of the diversity of planetary systems, the next decade will be the one of the atmospheres of exoplanets.

These few lines mention the contribution of astronomers (or even a small fraction of their efforts!). The research outlined here only concerns the search for planets likely to shelter life. But astrobiology is much broader: habitability, climatology, evolution of atmospheres, planetary interiors and their relation to atmospheres, chemistry, biology, and much more.

Unraveling the mystery of the composition of temperate rocky worlds is the first step toward maybe one day the detection of a signature of life. But what exactly are we looking for? This requires all the disciplines represented in this book.

A sufficiently rich subject . . . to justify an encyclopedia.

Preface

Where do we come from? Are we alone in the Universe? Where are we going? These are the questions addressed by astrobiology – the study of the origin, evolution, distribution, and the future of life in the Universe. The *Encyclopedia of Astrobiology* serves as the key to a common understanding of the astrobiology field among astronomers and astrophysicists, biologists and biochemists, chemists, geologists and geochemists, space scientists, historians of science, and others working in this interdisciplinary and rapidly expanding field.

Encyclopedias are unusual works. A quote from the prologue of one of the more famous early encyclopedias is instructive:

... the purpose of an encyclopedia is to collect knowledge disseminated around the globe; to set forth its general system to the men with whom we live, and transmit it to those who will come after us, so that the work of preceding centuries will not become useless to the centuries to come; and so that our offspring, becoming better instructed, will at the same time become more virtuous and happy, and that we should not die without having rendered a service to the human race in the future years to come. (Diderot and d'Alembert, *Encyclopédie* 1751)¹

Diderot and d'Alembert's eighteenth-century *Encyclopédie* was indeed ground-breaking, but perhaps more remarkable is the degree to which their description resembles the modern concept of genetic inheritance and natural selection: a civilization's accumulated knowledge being analogous to the traits encoded in an organism's time-tested DNA genome. In many ways, the *Encyclopédie* addressed the goals of astrobiology; between the lines, we find aspects of what makes biology biology.

Encyclopedias have now existed for approximately 2,000 years, the first being Pliny the Elder's *Naturalis Historia*, which was a compendium of the knowledge available to the citizen of the Roman Empire as documented by the first century AD.² It contained ~20,000 facts from 2,000 sources written by 200 authors. The present volume contains an unknown number of "facts" (indeed, some of the content will likely be proven false, as science is a living,

¹ A complete English and French version of the *Encyclopédie* can be found at <http://quod.lib.umich.edu/d/did/>

² For a complete English translation of Pliny the Elder's *The Natural History* by John Bostock see <http://www.perseus.tufts.edu/hopper/text?doc=Plin.+Nat.+toc&redirect=true>. A complete Latin version can be found at <http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.02.0138:toc&redirect=true>

breathing accumulation of presently accepted knowledge, all subject to future revision), but it does include some 2,200 contributions, references, uncounted thousands of prior publications, and is written by 613 authors.

Modern encyclopedias are derived from the dictionaries of the eighteenth century. The two are similar in that both are arranged alphabetically and generally are the work of a team of expert contributors. They differ in that encyclopedias contain a deeper level of analysis of the included terms and attempt to cross-reference and place the assembled contents in a useful context. The first encyclopedias attempted to cover all human knowledge. This is now impossible for a printed work because the body of human knowledge is presently growing exponentially, with no end in sight. Encyclopedias now exist for almost every definable field of study. A field requires a certain degree of maturity to have an encyclopedia, and conversely, the publication of an encyclopedia commonly records the birth of a definable field of study. Astrobiology is an interdisciplinary field, spanning geology, chemistry, physics, astronomy, biology, engineering, computer science, and the history of science to name only the core fields of study.

While some of these fields of research are fairly well-mapped, many others are in rapid flux, and still others remain perennially enigmatic, awaiting future breakthroughs by the scientists of tomorrow. To this end, the *Encyclopedia of Astrobiology* is primarily aimed at younger scientists or scientists new to the field who wish to understand how their expertise coincides with current knowledge in other areas of study. It is hoped that the encyclopedia will serve to orient researchers to the current state of the art. A more in-depth discussion of many of the topic areas can be obtained by referring to college or graduate level texts or to the articles cited at the end of many of the entries.

Encyclopedias are snapshots of the state of knowledge at a particular time. In 1844, the book *Vestiges of the Natural History of Creation* was published anonymously (it was later found to have been written by Scottish publisher William Chambers) and created a public sensation.³ It offered a sweeping and very secular view of the development of the Solar System, stretching from the nebular hypothesis to the development of man. While primitive by modern standards (it was, after all, based on state-of-the-art early nineteenth-century science), it was in many ways remarkably similar to modern cosmology. In broad brushstrokes, it is the precursor to the worldview developed in Carl Sagan's *Cosmos*⁴ and the grand view of myriads of habitable planets implicit in the Drake equation. The implication of *Vestiges* was simply this: the Universe operates everywhere and at all times according to physical principles, and the evolution of matter is largely predictable and often progressive, proceeding from the simple to the complex.

Science has advanced dramatically since Chambers' book was published. It is truly a long way from Sir William Herschel's 40-ft telescope to the James

³Chambers R (1994) *Vestiges of the natural history of creation and other evolutionary writings*. University of Chicago Press

⁴*Cosmos* was a remarkable 13-part popular science series narrated by Carl Sagan which aired in 1980. Most if not all of the episodes can be viewed on line, and a book was spun off: Sagan C (1985) *Cosmos*. Ballantine Books

Webb Space Telescope,⁵ and from a Universe with seven known planets orbiting the Sun to one with more than 5,000 planets orbiting other stars. It is also a long way from the work of Black, Priestly, and Lavoisier⁶ to SELEX technology and high-throughput automated chemical screening and analysis, and from Lyell's *Principles of Geology*⁷ to plate tectonics and isotope geochemistry. Nonetheless, certain questions permeate the sciences across time and discipline. Woese's three domains of life⁸ are direct descendants of Linnaeus' early classification scheme, and both are attempts to unify and classify terrestrial organisms. Darwinism has offered an underlying mechanism for doing so that has allowed for unification of the assorted observations of the living world. However, the question of whether terrestrial life is unique in the universe has fascinated mankind for millennia.

It was not until 1959, when NASA began funding the search for life in the Universe in its Exobiology program, that we at last achieved the technological prowess to try to answer this question.⁹ The paleontologist George Gaylord Simpson famously noted shortly thereafter that Exobiology was a science "that has yet to demonstrate that its subject matter exists."

NASA's first exobiology grant was awarded to Wolf Vishniac for the construction of the Wolf Trap, a device for detecting bacteria on Mars. Due to size limitations, the device never flew, but various descendants have made the trip to Mars and returned various negative or tantalizingly ambiguous results. These results are, amusingly, either disappointingly or encouragingly ambiguous, depending on one's point of view. Despite remarkable progress in the sciences, humanity still has no answer to the question, "Are we alone?," though the question is in principle answerable. The search continues enthusiastically.

Why should we think there might be life elsewhere in the Universe? In 1960, the radio-astronomer Frank Drake developed his now-famous equation for estimating the number of communicating civilizations in the Galaxy:

$$N = R^* \times f_p \times n_e \times f_l \times f_i \times f_c \times L;$$

where N is the number of civilizations in our galaxy for which communication might be possible, R^* is the average rate of star formation per year, f_p is the

⁵For a survey of the early developments in astronomy, see Lankford J (ed) (1996) History of astronomy: an encyclopedia, 1st edn. Routledge

⁶For an excellent discussion of the early history of chemistry (including the work of Black, Priestly and Lavoisier) see Partington JR (1989) A short history of chemistry, 3rd revised edn. Dover Publications

⁷Lyell C (2010) Principles of geology: being an inquiry how far the former changes of the earth's surface are referable to causes now in operation. Nabu Press (March 1, 2010). Originally published in three volumes between 1830–1833

⁸Woese C, Kandler O, Wheelis M (1990) Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. Proc Nat Acad Sci USA 87(12): 4576–4579

⁹For an insightful recounting of the early history of NASA's early efforts in exo- and astrobiology (including discussion of the roles of Wolf Vishniac and Frank Drake) see Dick SJ, Strick JE (2005) The living universe: NASA and the development of astrobiology. Rutgers University Press

fraction of stars that have planets, n_c is the average number of planets that can support life per star with planets, f_l is the fraction of the planets that can support life on which life actually develops, f_i is the fraction of those on which intelligent life develops, f_c is the fraction of those on which civilizations communicate using detectable signals, and L is the length of time these civilizations communicate.

When Drake unveiled his equation in 1960 and estimated that there were maybe ten communicating civilizations in the Galaxy, few of the parameters were known with any certainty; the rate of star formation was perhaps the only solid measurable value. Fifty years later, the flourishing search for exoplanets has placed the focus on the second value. Notably, it now appears to be close to what Drake estimated. Thousands of exoplanets have been found around other stars, and current technology allows the observation of even small planets. Theory suggests that the fraction of stars with Earthlike planets may be close to Drake's initial estimate (see this Encyclopedia's entry for Eta-Earth). The least well-known value is the question of how difficult is it for life to begin (one of the "perennially enigmatic" facts mentioned above). Based on present knowledge, the fraction of planets on which life actually emerges (f_l) could be anywhere from very, very close to 0 or far closer to 1. We simply do not know. On the ends of the spectrum, the scientific community is divided into two equally "hunch"-based camps: first, life is inevitable and is a cosmic imperative (where conditions are appropriate) and, second, the origin of life requires such a concatenation of improbable events that it is the scientific equivalent of a miracle.

On the one planet we know of with life, our own, putative evidence in the form of isotopically light carbon appears in the earliest known sedimentary rocks, suggesting life emerged relatively early in the history of the planet, although we do not know whether this took place 100 years or 700 million years after the planet formed. This implies that either something extraordinary happened on Earth, or that the origin of life is a mundane phenomenon on young planets, given appropriate chemistry, environmental conditions, and enough time. Radioastronomy has provided a glimpse of the chemical inventory of the cosmos which does appear to be universal. Spectral signatures of a veritable zoo of organic compounds suggest that the Universe is strewn with the potential precursors of life. Organic carbon (in the form of carbon monoxide) has now been observed more than 13 billion years ago, only some 700 million years after the birth of the Universe in the Big Bang. The picture emerging, reminiscent of Chambers' universe, is that physics and chemistry are the same everywhere in the Universe, and that the Earth, although remarkable in many respects, may not be unique.

As in any factorial equation, the most important values are the ones with the largest uncertainty. Two approaches could shed light on the " f_l problem": the duplication of the process in the laboratory or the discovery of life on another planet. It is difficult to say whether the first approach will ever succeed to anyone's complete satisfaction, given that the origin of life on Earth was a historical event that happened when no one was around to witness it. The second approach, while fraught with technological difficulties, is perhaps more promising. To that end, numerous instruments and space missions have been designed and launched to explore the Solar System and beyond. The spectral

signatures of planets around nearby stars are being monitored for the characteristic signs of life such as the signature of disequilibrium chemistry in the form of the presence in their atmospheres of both oxidized and reduced gases.

While the answers to the vast questions that define astrobiology as a field of study are unclear, it is evident that answering them will require an interdisciplinary effort, stretching across international borders. One is hesitant to speculate what the answer to the question “Are we alone?” will ultimately be. As good scientists, we should probably withhold judgment until the data are in. As better scientists, we must join hands and find the data. The editors of the *Encyclopedia of Astrobiology* hope that this volume will contribute to this effort.

Since the field of astrobiology continues to expand at a rapid rate, the editors of the *Encyclopedia of Astrobiology* have decided that a new, Third Edition, is needed to update the Second Edition, which was published in 2015. The present edition includes more than 100 new entries, as well as updates for almost half of the already existing entries. The exciting new scientific results include the discovery of thousands of new exoplanets; data from a number of new spacecraft exploring the Solar System’s planets, satellites, and small bodies such as asteroids and comets; new isotopic data that radically change our understanding of the formation of the Solar System in general and the early earth in particular; the identification of increasingly complex organic molecules in space and in protoplanetary disks; new techniques and discoveries in prebiotic chemistry; novel efficient methodologies to generate genomic information in phylogeny and evolution; the characterization of new extreme environments and the isolation of previously unknown microorganisms; and the development of a next generation of facilities for sample analysis, sample curation, planetary simulation environments, and remote observations from the ground. Moreover, this new edition includes new entries in the history, philosophy, and sociology of astrobiology. We believe that both new and experienced researchers as well as graduate students – either in the adjacent fields of astrobiology or those new to the subject – will appreciate this reference work during their quest to understand the whole picture. To aid this process, this edition includes a Topical Map, broken down by research area, which nicely illustrates the breadth and the depth of the field of astrobiology. Although members of the different disciplines commonly employ their own terminology and technical language, here we have made a special effort to eliminate specialized jargon and overtechnical terms from the Encyclopedia. Synonyms and keywords from the previous editions have been carefully revisited.

Both the carefully selected group of active researchers contributing to this work as well as the expert field editors hope that this new edition will be valuable to the scientific community and accelerate the interdisciplinary advance of astrobiology.

The Editors

Acknowledgments

A brief note is warranted about how we constructed the Encyclopedia. A glossary of terms was first compiled by a team of experts in each field. It was then cross-referenced between fields to check for conceptual overlap and was then both expanded and pared down to produce a consensus entry list.

Authors with peer-recognized contributions to their fields of study were then invited to contribute entries appropriate to their expertise. After a final draft was submitted, entries were proofread and vetted for scientific accuracy and readability by a team of field editors and then edited and modified to be accessible by a reader with general knowledge of college-level science. Finally, the entries were cross-referenced and edited for stylistic consistency and ease of reading.

The editors would like to sincerely thank all the authors of the content of the Encyclopedia for their efforts and understanding throughout the long and at times difficult triple review process. We are particularly grateful to those who also accepted to act as non-specialist reviewers for fields other than their own.

We would also like to thank several people who, although not all were authors, served as external reviewers for a significant number of entries: Maxence Claeys (CEA, France), Carlos Garcia-Ferris (Universitat de València, Spain), David Hochberg (CAB, Madrid, Spain), Pierre Léna (Académie des Sciences, Paris, France), Susan Leschine (University of Massachusetts, Amherst, USA), and Jean Vandenhaute (University of Namur, Belgium).

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About the Editors-in-Chief



Muriel Gargaud is a Senior Scientist at CNRS (Centre National de la Recherche Scientifique) – Université de Bordeaux, France. She is an enthusiastic and experienced editor who has proven in various Astrobiology projects that she can manage a large number of editors and authors and deliver an excellent publication. She is presently the Vice-President of the European Astrobiology Institute.



William Irvine was President of the Commission on Bioastronomy of the International Astronomical Union. His research activity is concentrated in two areas: the chemistry of dense interstellar clouds and the physics and chemistry of comets. He collaborated with various NASA astrobiology working groups and is the author of more than 200 scientific articles.

Field Editors

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Ricardo Amils Centro Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid Cantoblanco, Madrid, Spain

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Henderson James Cleaves II Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan

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Maryvonne Gerin Radio Astronomy, Paris Observatory, Paris, France

Institutions and Organizations

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Francois Dulieu LERMA, CY Cergy Paris Université and Paris Observatory, Cergy Pontoise, France

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Data Tables

Muriel Gargaud Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

Life Sciences: General Biology

Felipe Gómez Centro de Astrobiología (CSIC-INTA), Instituto de Técnica Aeroespacial, Madrid, Spain

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Felipe Gómez Centro de Astrobiología (CSIC-INTA), Instituto de Técnica Aeroespacial, Madrid, Spain

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Jörn Helbert DLR, Institut für Planetenforschung, Berlin, Germany

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Raffaele Saladino Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

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Raffaele Saladino Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

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J. Andy Spry SETI Institute, Mountain View, CA, USA

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Stephane Tirard Faculté des Sciences et des Techniques de Nantes, Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Nantes, France

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Valentine Wakelam Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Bordeaux, France

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Olivier Witasse European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Contributors

José Pascual Abad Facultad de Ciencias, Departamento de Biología Molecular, Universidad Autónoma de Madrid, Cantoblanco, Madrid, Spain

Farah Abdul-Rahman University of Massachusetts Amherst, Amherst, MA, USA

Delphine Acolat Centre François Viète, Université de Bretagne Occidentale, Brest, France

Solmaz Adeli Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

Angeles Aguilera Laboratorio de Extremófilos, Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Marcelino Agúndez Instituto de Física Fundamental, CSIC, Madrid, Spain

Alessandro Airo Fachbereich Geowissenschaften, Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Berlin, Germany

Francis Albarède Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Giulia Alemanno Institute of Planetary Research, German Aerospace Center, Berlin, Germany

Daniel S. Alessi University of Alberta, Edmonton, AB, Canada

A. Alhammadi Advance Technology Office, Dubai, United Arab Emirates

Yann Alibert Space Research and Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland

Romain Allart Department of Physics, and Institute for Research on Exoplanets, University of Montréal, Montréal, Quebec, Canada

Abigail Allwood Jet Propulsion Laboratory, Pasadena, CA, USA

Concepción Alonso Universidad Autonoma de Madrid, Madrid, Spain

Wladyslaw Altermann Department of Geology, University of Johannesburg, Johannesburg, South Africa

Linda Amaral-Zettler Marine Biological Laboratory, Josephine Bay Paul Center for Comparative Molecular Biology and Evolution, Woods Hole, MA, USA

Erin Amato Veterinary and Animal Sciences, University of Massachusetts Amherst, Amherst, MA, USA

Ricardo Amils Departamento de Biología Molecular, Universidad Autónoma de Madrid, Madrid, Spain

Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Luc André Department of Earth Sciences, Royal Museum of Central Africa, Tervuren, Belgium

Philippe André Laboratoire d'Astrophysique (AIM), CEA Paris-Saclay, Gif-sur-Yvette, France

Guillem Anglada Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain

Guillem Anglada-Escudé Institut de Ciències de l'Espai – CSIC, Barcelona, Spain

Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain

Ralf H. Anken Gravitational Biology, German Aerospace Center, Institute of Aerospace Medicine, Cologne, Germany

Josefa Anton Department of Physiology, Genetics and Microbiology, University of Alicante, Alicante, Spain

Nicholas Arndt Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Christopher R. Arumainayagam Wellesley College, Wellesley, MA, USA

Andrew Aubrey NASA Jet Propulsion Laboratory, Pasadena, CA, USA

Jeffrey Bada Scripps Institution of Oceanography, La Jolla, CA, USA

Victor R. Baker University of Arizona, Tucson, AZ, USA

Juan P. G. Ballesta Genome Dynamics and Function, Centro de Biología Molecular Severo Ochoa, Madrid, Spain

Nadia Balucani Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia, Perugia, Italy

Mickaël Baqué Institute of Planetary Research, Planetary Laboratories Department, German Aerospace Center (DLR), Berlin, Germany

Rory Barnes Astronomy Department, University of Washington, Seattle, WA, USA

Maria Antonietta Barucci LESIA, Observatoire de Paris, Université PSL, CNRS, Université Paris Cité, Sorbonne Université, Meudon, France

Gibor Basri Astronomy Department, University of California, Berkeley, CA, USA

Ugo Bastolla Unidad de Bioinformática, Centro de Biología Molecular “Severo Ochoa,” CSIC-UAM, Madrid, Spain

Fabia Ursula Battistuzzi Oakland University, Rochester, MI, USA

Kohen W. Bauer Departments of Microbiology and Immunology, and Earth, Ocean, and Atmospheric Sciences, The University of British Columbia, Vancouver, BC, Canada

Philipp Baumeister Institute of Planetary Research, German Aerospace Center Berlin, Berlin, Germany

Christa Baumstark-Khan German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Hagan Bayley Department of Chemistry, University of Oxford, Oxford, UK

Andrey Bekker Department of Earth and Planetary Sciences, University of California, Riverside, CA, USA

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Maria Teresa Beltrán INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy

G. Fritz Benedict McDonald Observatory, The University of Texas, Austin, TX, USA

Stefan Bengtson Department of Palaeozoology, The Swedish Museum of Natural History, Stockholm, Sweden

Johannes Benkhoff ESA-ESTEC, Noordwijk, Zuid Holland, The Netherlands

Karim Benzerara Institut de Minéralogie et de Physique des Milieux Condensés, UMR 7590, CNRS, Sorbonne Université & Muséum National d’Histoire Naturelle, Paris, France

Jose Berenguer Centro de Biología Molecular Severo Ochoa, UAM-CSIC, Madrid, Spain

Astrid Bergeat Univ. Bordeaux, CNRS, Bordeaux INP, ISM, Talence, France

Sylvain Bernard Laboratoire de Minéralogie et de Cosmochimie du Muséum (LMCM), Paris, France

Hugues Bersini IRIDIA, Université Libre de Bruxelles, Brussels, Belgium

Tanguy Bertrand Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Denis Diderot, Sorbonne Paris Cite, Meudon Principal Cedex, France

Bruno Bézard LESIA, Observatoire de Paris, Meudon, France

Jean-Pierre Bibring Institut d'Astrophysique Spatiale, Université Paris Sud, Orsay, France

Ludovic Biennier Institut de Physique de Rennes, UMR CNRS 6251, Université de Rennes 1, Rennes Cedex, France

Saskia Bindschedler Laboratory of Microbiology, University of Neuchâtel, Neuchâtel, Switzerland

Bruno Mattia Bizzarri Organic, Bioorganic and Natural Substances Chemistry, Biological and Ecological Sciences Department (DEB), University of Tuscia, Viterbo, Italy

Donna Blackmond The Scripps Research Institute, La Jolla, CA, USA

Jeffrey Blanchard Biology Department, University of Massachusetts Amherst, Amherst, MA, USA

Laurent Boiteau Institut des Biomolécules Max Mousseron, UMR5247 CNRS, University Montpellier-2, Montpellier, Cedex, France

Emeline Bolmont Department of Astronomy, Université de Genève, Versoix, Switzerland

Observatoire de Genève, Université de Genève, Sauverny, Switzerland

Tyler Bourke Square Kilometre Array Observatory, Macclesfield, UK

Jessica C. Bowman School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, USA

Samuel A. Bowring Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

Maud Boyet Université Blaise Pascal, Clermont-Ferrand, France

Caroline Brachmann Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

André Brack Centre de Biophysique Moléculaire CNRS, Orléans Cedex 2, France

Robert Braun Square Kilometre Array Observatory, Macclesfield, UK

Amanda Brecht NASA Ames Research Center, Moffett Field, CA, USA

Doris Breuer German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Carlos Briones Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

John R. Brucato Astrophysical Observatory of Arcetri, Florence, Italy

Gilles Bruylants Engineering of Molecular NanoSystems, Université Libre de Bruxelles, Brussels, Belgium

Casey Bryce Geomicrobiology, Center for Applied Geoscience, University of Tübingen, Tübingen, Germany

Sergey Bulat NRC ‘Kurchatov Institute’-Petersburg Nuclear Physics Institute, Gatchina, Russia

Rogers C. C. Buntin Old Dominion University, Norfolk, VA, USA

Adam J. Burgasser Center for Astrophysics and Space Sciences, Department of Physics, UC San Diego, La Jolla, CA, USA

Andrew M. Burkhardt Center for Astrophysics, Harvard & Smithsonian, Cambridge, MA, USA

Vincent Busigny Institut de Physique du Globe de Paris, Paris, France

Gary R. Byerly Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA, USA

Michel Cabane LATMOS/IPSL B102/T45-46, Université Pierre et Marie Curie UPMC-Paris 6, Paris, France

Jean Cadet Département de Médecine Nucléaire et Radiobiologie, Faculté de Médecine et des Sciences de la Santé, Université de Sherbrooke, Sherbrooke, QC, Canada

Michael P. Callahan Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Jan Cami Department of Physics and Astronomy & Institute for Earth and Space Exploration, The University of Western Ontario, London, ON, Canada
SETI Institute, Mountain View, CA, USA

Tiago L. Campante Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, Porto, Portugal

Departamento de Física e Astronomia, Faculdade de Ciências da Universidade do Porto, Porto, Portugal

Ian Campbell Research School of Earth Sciences, The Australian National University, Canberra, ACT, Australia

Tammy Campbell The Scripps Research Institute, La Jolla, CA, USA

Donald E. Canfield Institute of Biology, University of Southern Denmark, Odense, Denmark

Klara Anna Capova Department of Anthropology, Durham University, Durham, UK

María Luz Cárdenas Unité de Bioénergétique et Ingénierie des Protéines, Centre National de la Recherche Scientifique, Aix-Marseille Université, Marseille, France

Damien Cardinal LOCEAN-IPSL, Sorbonne Université, Paris, France

Leticia Carigi Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Nathalie Carrasco LATMOS, Paris-Saclay University, Guyancourt, France

P. Brandon Carroll Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

California Institute of Technology, Pasadena, CA, USA

Piergiorgio Casavecchia Dipartimento di Chimica, Università degli Studi di Perugia, Perugia, Italy

Claude Catala LESIA, Observatoire de Paris – PSL, Meudon, France

Franco Cataldo Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania, Catania, Italy

Actinium Chemical Research, Rome, Italy

David C. Catling Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA

Cecilia Ceccarelli Institut de Planétologie et d’Astrophysique de Grenoble (IPAG), Université Grenoble Alpes, CNRS, Grenoble, France

Gilles Chabrier Centre de Recherche Astrophysique de Lyon, Ecole Normale Supérieure de Lyon, Lyon, France

John H. Chalmers Scripps Institute of Oceanography Geosciences Research Division, University of California, San Diego, La Jolla, CA, USA

Gregory Chambon Faculty of Arts and Humanities, Ecole des Hautes Etudes en Sciences Sociales, Paris, France

Benjamin Charnay LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, Meudon, France

Steven B. Charnley Solar System Exploration Division, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Marc Chaussidon Institut de Physique du Globe de Paris (IPGP), Paris, France

Guillaume Chaverot Observatory of Geneva, University of Geneva, CH-1290 Versoix, Switzerland

Ernest Chi Fru Centre for Geobiology and Geochemistry, School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK

Octavio A. Chon-Torres Programa de Estudios Generales, Universidad de Lima, Lima, Perú

Andrea Ciardi LERMA, Sorbonne University and Observatoire de Paris, Paris, France

Glenn E. Ciolek New York Center for Astrobiology, Rensselaer Polytechnic Institute, Troy, NY, USA

Philippe Claeys Earth System Science, Vrije Universiteit Brussel, Brussels, Belgium

Analytical-Environmental and Geo-Chemistry, Vrije Universiteit Brussel, Brussels, Belgium

Henderson James Cleaves Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Alain Coc IJCLab (Laboratoire Irène Joliot-Curie), Université Paris-Saclay, Orsay, France

Charles S. Cockell UK Centre for Astrobiology, Scottish Universities Physics Alliance (SUPA), School of Physics and Astronomy, The University of Edinburgh, Edinburgh, UK

Geomicrobiology Research Group, PSSRI, Open University, Milton Keynes, UK

Marion Cointepas Observatoire de Genève, Université de Genève, Sauverny, Switzerland

Catharine A. Conley NASA Headquarters, NASA Ames Research Center, Washington, DC, USA

Joanna F. Corby University of Virginia, Charlottesville, VA, USA

Stuartt A. Corder Joint ALMA Observatory, National Radio Astronomy Observatory, Santiago, Chile

Martin A. Cordiner NASA Goddard Space Flight Center, Astrochemistry Laboratory, Greenbelt, MD, USA

Athel Cornish-Bowden Unité de Bioénergétique et Ingénierie des Protéines, Centre National de la Recherche Scientifique, Aix-Marseille Université, Marseille, France

Giovanna Costanzo Institute of Molecular Biology and Pathology (IBPM)-National Research Council (CNR), Rome, Italy

Hervé Cottin Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, Créteil, France

Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université Paris Est-Créteil, Créteil, France

Athena Coustenis Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, Meudon Cedex, France

Audrey Coutens Laboratoire d'Astrophysique de Bordeaux, Pessac, France
Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Toulouse, France

Vanessa Cox Georgia Institute of Technology, Atlanta, GA, USA

Jacques Crovisier LESIA, Observatoire de Paris, Meudon, France

Sean A. Crowe Departments of Microbiology and Immunology, and Earth, Ocean, and Atmospheric Sciences, The University of British Columbia, Vancouver, BC, Canada

J. Cynan Ellis-Evans UK Arctic Office, Strategic Coordination Group, British Antarctic Survey, Cambridge, UK

Louis d'Hendecourt Institut d'Astrophysique Spatiale, Université Paris-Sud 11, Orsay Cedex, France

Marco d'Ischia Department of Chemical Sciences, University of Napoli Federico II, Naples, Italy

Claude D'Uston Géophysique Planétaire & Plasmas Spatiaux, Institut de Recherche Astrophysique et Planétologique, Toulouse, France

Billi Daniela University of Rome Tor Vergata, Rome, Italy

Emmanuel Dartois Institut des Sciences Moléculaires d'Orsay, CNRS, Université Paris-Saclay, Orsay Cedex, Orsay, France

Ashley B. Davidson Departments of Microbiology and Immunology, and Earth, Ocean, and Atmospheric Sciences, The University of British Columbia, Vancouver, BC, Canada

Alfonso F. Davila SETI Institute – NASA Ames Research Center MS 245-3, Moffett Field, CA, USA

Bradley De Gregorio Materials Science and Technology Division, U.S. Naval Research Laboratory, Washington, DC, USA

Andrés de la Escosura Nanoscience and Molecular Materials Research Group, Universidad Autónoma de Madrid, Madrid, Spain

Rafael R. de la Haba Department of Microbiology and Parasitology, Faculty of Pharmacy, University of Sevilla, Sevilla, Spain

Barbara De Toffoli German Aerospace Center, DLR, Berlin, Germany

Jean-Pierre de Vera German Aerospace Center (DLR), Institute of Space Operations and Astronaut Training, Microgravity User Support Center (MUSC), Cologne, Germany

David Deamer Department of Biomolecular Engineering, UC Santa Cruz, Santa Cruz, CA, USA

Department of Chemistry, University of California, Santa Cruz, CA, USA

Luis Delaye Departamento de Ingeniería Genética, CINVESTAV-Irapuato, Irapuato, Gto, Mexico

René Demets ESTEC (HSF-USL), Noordwijk, The Netherlands

Brice-Olivier Demory Centre for Space and Habitability, University of Bern, Bern, Switzerland

Karine Demyk Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, Toulouse Cedex 4, France

Didier Despois Laboratoire d'Astrophysique de Bordeaux, CNRS-Université de Bordeaux, Bordeaux, France

Pietro Speroni di Fenizio CISUC, Department of Informatics Engineering, University of Coimbra, Coimbra, Portugal

Phil Diamond Square Kilometre Array Observatory, Macclesfield, UK

Mark A. Ditzler Ames Research Center, Moffett Field, CA, USA

Mark Dörr University of Southern Denmark, Odense, Denmark

Thierry Douki Univ. Grenoble Alpes, CEA, CNRS, Grenoble, France

Nadja Drabon Stanford University, Stanford, CA, USA

Line Drube DLR Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

David Dunér Lund University, Lund, Sweden

Jean Duprat Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, CNRS-Muséum national d'histoire naturelle-Sorbonne Université, Paris Cedex 05, France

Jason P. Dworkin Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Patrick Eggenberger Geneva Observatory, University of Geneva, Geneva, Switzerland

Pascale Ehrenfreund Space Policy Institute, George Washington University, Washington, DC, USA

Sylvia Ekström Observatoire Astronomique de l'Université de Genève, Faculté des Sciences, Université de Genève, CH, Versoix, Switzerland

J. Cynan Ellis-Evans UK Arctic Office, Strategic Coordination Group, British Antarctic Survey, Cambridge, UK

Josef Elster Faculty of Science, Centre for Polar Ecology, University of South Bohemia, Ceske Budejovice, Czech Republic
Institute of Botany, Academy of Sciences of the Czech Republic, Trebon, Czech Republic

Therese Encrenaz LESIA, Observatoire de Paris, PSL, CNRS, Sorbonne University, University Paris-Diderot, Meudon, France

Cecile Engrand IJCLab, CNRS/IN2P3, Université Paris-Saclay, Orsay Cedex, France

Sümeyya Eroglu Westfälische Wilhelms-Universität Münster, Institut für Geologie und Paläontologie, Münster, Germany

Gözen Ertem National Institutes of Health, Bethesda, MD, USA

C. Escudero Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Alberto G. Fairén NASA Ames Research Center, Moffett Field, CA, USA

James Farquhar Department of Geology, University of Maryland, College Park, MD, USA

Victor M. Fernández Institute of Catalysis, CSIC, Madrid, Spain

Emma Fernández-Alvar Observatoire de la Côte d'Azur, Laboratoire Lagrange, Nice, France

David C. Fernandez-Remolar State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Taipa, China
CNSA Macau Center for Space Exploration and Science, Macau, People's Republic of China

Franco Ferrari CASA, Faculty of Mathematics and Physics, University of Szczecin, Szczecin, Poland

Martin Ferus J. Heyrovsky Institute of Physical Chemistry, Czech Academy of Sciences, Prague, Czech Republic

Fernando B. Figueiredo CITEUC, University of Coimbra, Coimbra, Portugal

Zoe V. Finkel Department of Oceanography, Dalhousie University, Halifax, NS, Canada

Woodward W. Fischer Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Ricardo Flores Instituto de Biología Molecular y Celular de Plantas (UPV-CSIC), Universidad Politécnica de Valencia – Consejo Superior de Investigaciones Científicas, Valencia, Spain

François Forget Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, UMR 8539, Université Paris 6, Paris, France

Sonia Fornasier LESIA, Observatoire de Paris, Université PSL, CNRS, Université Paris Cité, Sorbonne Université, Meudon, France
Institut Universitaire de France (IUF), Paris Cedex 05, France

Nathaniel W. Fortney University of Wisconsin-Madison, Madison, WI, USA

Yves Fouquet Institut Français de Recherche pour l'Exploitation de la mer (IFREMER), Issy-les-Moulineaux, France

Dionysis Foustoukos Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Stephen Freeland Astrobiology Institute, University of Hawaii NASA, Honolulu, HI, USA

Malcolm Fridlund Max-Planck-Institut für Astronomie, Heidelberg, Germany

Douglas Galante Brazilian Center for Research in Energy and Materials, Campinas, Sao Paulo, Brazil

University of Sao Paulo, Sao Paulo, Brazil

Daniele Galli INAF Osservatorio Astrofisico di Arcetri, Florence, Italy

Juan Manuel García-Ruiz Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, Armilla, Granada, Spain

Muriel Gargaud Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

William Garnier Square Kilometre Array Observatory, Macclesfield, UK

Stéphane Le Gars Centre François Viète, Université de Nantes, Nantes, BP, France

José Carlos Gaspar Institute of Geosciences, University of Brasília, Brasília, DF, Brazil

María Gasset Consejo Superior de Investigaciones Científicas, Instituto Química-Física Rocasolano, Madrid, Spain

Eric Gaucher School of Biology, Georgia Institute of Technology, Atlanta, GA, USA

B. Scott Gaudi Department of Astronomy, Ohio State University, Columbus, OH, USA

Wolf D. Geppert Department of Physics, Stockholm University, Stockholm, Sweden

Carlos Gershenson Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas & Centro de Ciencias de la Complejidad, Universidad Nacional Autónoma de México, México, CDMX, México

Richard Ghail Department of Earth Sciences, Royal Holloway, University of London, London, UK

Rosario Gil Institute for Integrative Systems Biology, Universitat de València – CSIC, Paterna (València), Spain

Michaël Gillon Astrobiology Research Unit, University of Liège, Liège, Belgium

Jennifer Glass Georgia Institute of Technology, Atlanta, GA, USA

Jules M. Goldspiel Planetary Science Institute, Tucson, AZ, USA

George Mason University, Fairfax, VA, USA

Maya Gomes Johns Hopkins University, Baltimore, MD, USA

Felipe Gomez Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Aldo González Centro de Biología Molecular, CBMSO Consejo Superior de Investigaciones Científicas Universidad Autónoma de Madrid, Madrid, Spain

Elena González-Toril Laboratorio de Extremófilos, Centro de Astrobiología (INTA-CSIC), Madrid, Spain

Matthieu Gounelle Laboratoire de Minéralogie et Cosmochimie du Muséum (LMCM) MNHN USM 0205 – CNRS UMR 7202, Muséum National d'Histoire Naturelle, Paris, France

Pierre-Henri Gouyon Département Systématique et Evolution, UMR 7138 CNRS-MNHN-UPMC-IRD, Muséum National d'Histoire Naturelle, Paris, France

Felix M. Gradstein University of Oslo, Oslo, Norway

Olivier Grasset University of Nantes, Nantes, Cedex 1, France

Jimi Green CSIRO Astronomy and Space Sciences, Parkes Observatory, Parkes, NSW, Australia

John Lee Grenfell Institut für Planetenforschung, Extrasolare Planeten und Atmosphären, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany

Elizabeth C. Griffith University of Colorado, Boulder, CO, USA

Roderich Groß Department of Automatic Control & Systems Engineering, The University of Sheffield, Sheffield, UK

Manuel Güdel Department of Astrophysics, University of Vienna, Vienna, Austria

Sabrina Guilbon LATMOS, IPSL, Paris, France

Stephane Guillot LGCA, Université de Grenoble, St Martin d'Hères, France

Tristan Guillot Observatoire de la Côte d'Azur, Université de Nice-Sophia Antipolis, Nice, France

Weifu Guo Carnegie Institution of Washington, Washington, DC, USA

Lina Z. Hadid Laboratory of Plasma Physics (LPP), CNRS, Paris-Saclay University, École Polytechnique, Palaiseau, France

Nader Haghighipour Institute for Astronomy, University of Hawaii–Manoa, Honolulu, HI, USA

Gerhard Hahn Asteroids and Comets, DLR, Institute of Planetary Research, Berlin, Germany

Salman Hameed Hampshire College, Amherst, MA, USA

Maximilian Hamm Planetology and Remote Sensing, Freie University Berlin, Berlin, Germany

Institute for Planetary Research, German Aerospace Centre, Berlin, Germany

Colleen M. Hansel Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Alan W. Harris German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Emma Hart School of Computing, Edinburgh Napier University, Edinburgh, UK

Lee Hartmann University of Michigan, Ann Arbor, MI, USA

Ko Hashizume Faculty of Science, Ibaraki University, Bunkyo Mito, Japan

Ernst Hauber Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Rutherfordstrasse 2, Berlin, Germany

Rasmus Haugaard Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

Robert Hazen Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Jörn Helbert DLR, Institut für Planetenforschung, Berlin, Germany

Ravit Helled Geophysical, Atmospheric and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

Coel Hellier Keele University, Keele, UK

Ruth Hemmersbach Gravitational Biology, German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Patrick Hennebelle Service d'Astrophysique, Gif-sur Yvette, France

Eric Herbst University of Virginia, Charlottesville, VA, USA

Otto Hermelin Department of Geological Sciences, Stockholm University, Stockholm, Sweden

Judith Herzfeld Brandeis University, Waltham, MA, USA

Christoph Heubeck Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

Keyron Hickman-Lewis Natural History Museum, London, UK

Ake Hjalmarson Chalmers University of Technology, Gothenburg, Sweden

Tori M. Hoehler Exobiology Branch, NASA Ames Research Center, Moffett Field, Mountain View, CA, USA

Paul Felix Hoffman Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA, USA

School of Earth & Ocean Sciences, University of Victoria, Victoria, BC, Canada

Harald Hoffmann DLR, Institute of Planetary Research, Berlin, Germany

Axel Hofmann Department of Geology, University of Johannesburg, Johannesburg, South Africa

Michiel R. Hogerheijde Leiden Observatory, Leiden University, Leiden, The Netherlands

Pentti Hölttä Geological Survey of Finland, Espoo, Finland

Martin Homann Institut für Geologische Wissenschaften, Freie Universität Berlin, Berlin, Germany

Gerda Horneck DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

David P. Horning Department of Molecular Biology, The Scripps Research Institute, La Jolla, CA, USA

Nicholas V. Hud School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, USA

Elizabeth Humphreys ESO European Southern Observatory, Garching, Germany

Richard Hutchins Classics, University of Miami, Miami, FL, USA

Susana Iglesias-Groth Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain

Heshan Grasshopper Illangkoon Department of Chemistry, University of Florida, Gainesville, FL, USA

Eiichi Imai Nagaoka University of Technology, Nagaoka, Japan

William M. Irvine Department of Astronomy, University of Massachusetts Amherst, Amherst, MA, USA

Andrew J. Irwin Department of Mathematics and Statistics, Dalhousie University, Halifax, NS, Canada

Jordi Isern Institute for Space Sciences (ICE, CSIC), Barcelona, Spain
Institute for Space Studies of Catalonia (IEEC), Ed. Nexus, Barcelona, Spain
Section of Mathematics and Astronomy, Fabra Observatory, Royal Academy of Sciences and Arts of Barcelona (RACAB), Barcelona, Spain

Akizumi Ishida Graduate School of Science, Tohoku University, Sendai, Japan

Mathieu Isidro Square Kilometre Array Observatory, Macclesfield, UK

Terry T. Isson Department of Geology and Geophysics, Yale University, New Haven, CT, USA

University of Waikato, Tauranga, New Zealand

Magnus Ivarsson Department of Paleobiology, Swedish Museum of Natural History, Stockholm, Sweden

Emmanuel Jacquet Institut de Minéralogie, Physique des Matériaux et Cosmochimie (IMPMC), Sorbonne Université et Muséum National d'Histoire Naturelle, UMR 7590 CNRS, Paris, France

Ralf Jaumann German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Institute of Geological Sciences, Planetary Sciences and Remote Sensing, Freie Universität Berlin, Berlin, Germany

Emmanuelle J. Javaux Palaeobiogeology-Palaeobotany-Palaeopalynology, Geology Department, Université de Liège, Liège, Belgium

Early Life Traces & Evolution-Astrobiology, UR Astrobiology, Université de Liège, Liège, Belgium

Michel Jébrak Département des Sciences de la Terre et de l'Atmosphère, Université du Québec à Montréal, Montreal, QC, Canada

Izaskun Jimenez-Serra Centro de Astrobiología (CSIC/INTA), Torrejon de Ardoz, Spain

Anders Johansen Lund University, Lund, Sweden

Natasha M. Johnson NASA Goddard Space Flight Center, Greenbelt, MD, USA

Geraint H. Jones Mullard Space Science Laboratory, University College London, Surrey, UK

Prachi Joshi Geomicrobiology, Centre for Applied Geosciences, University of Tuebingen, Tuebingen, Germany

Takeshi Kakegawa Graduate School of Science, Tohoku University, Sendai, Japan

Paul Kalas Astronomy Department, University of California, Berkeley, CA, USA

Institute of Astrophysics, FORTH and the University of Crete, Heraklion, Crete, Greece

Lisa Kaltenegger Cornell University, Ithaca, NY, USA

Balz Samuel Kamber School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, QLD, Australia

Andreas Kappler Geomicrobiology, Center for Applied Geoscience, University of Tübingen, Tübingen, Germany

Juha A. Karhu Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

Michael J. Kaufman Department of Physics and Astronomy, San José State University, San Jose, CA, USA

Kunio Kawamura Department of Human Environmental Studies, Hiroshima Shudo University, Hiroshima, Japan

Yoko Kebukawa Faculty of Engineering, Yokohama National University, Yokohama, Japan

Laura Kelly Ecogenomics of Interactions Lab, Nancy, France

Pierre Kervella LESIA, Observatoire de Paris-PSL, Meudon, France

Martin F. Kessler European Space Astronomy Centre (ESAC), Madrid, Spain

Walter Kiefer Lunar and Planetary Institute/USRA, Houston, TX, USA

Daisuke Kiga Tokyo Institute of Technology, Tokyo, Japan

Eun-Kyong Kim Chemistry, The Scripps Research Institute, La Jolla, CA, USA

Adrienne Kish Institut de Génétique et Microbiologie, Université Paris-Sud 11, Orsay Cedex, France

Daniel Kitzmann University of Bern, Bern, Switzerland

David M. Klaus Aerospace Engineering Sciences, University of Colorado, Boulder, CO, USA

Thorsten Kleine Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Münster, Germany

Kateryna Klochko Carnegie Institution of Washington, Washington, DC, USA

Kensei Kobayashi Department of Chemistry, Yokohama National University, Yokohama, Japan

Christian Koeberl Department of Lithospheric Research, University of Vienna, Vienna, Austria

Daniel D. B. Koll Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

Kurt O. Konhauser Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

Akira Kouchi Institute of Low Temperature Science, Hokkaido University, Kita-ku, Sapporo, Hokkaido, Japan

Ramanarayanan Krishnamurthy Chemistry, The Scripps Research Institute, La Jolla, CA, USA

Mark Krumholz Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT, Australia

E. C. Krupp Griffith Observatory, Los Angeles, CA, USA

Marc Kuchner NASA Goddard Space Flight Center, Exoplanets and Stellar Astrophysics Laboratory, Greenbelt, MD, USA

Ekkehard Kührt Institute of Optical Sensor Systems, German Aerospace Center, Berlin, Germany

Michael Küppers European Space Agency (ESA), European Space Astronomy Centre (ESAC), Madrid, Spain

Stan Kurtz Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia, Michoacán, México

Jana Kviderová Institute of Botany, Academy of Sciences of the Czech Republic, Trebon, Czech Republic

Sun Kwok Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada

Sun Kwok Faculty of Science, The University of Hong Kong, Hong Kong, China

Olivier La Marle Centre National d'Etudes Spatiales DSP/EU, Paris, Cedex 01, France

Jean-François Lambert Laboratoire de Réactivité de Surface, Université Pierre et Marie Curie, Paris, France

Doron Lancet Weizmann Institute of Science, Rehovot, Israel

David W. Latham Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

Amparo Latorre Institute Cavanilles for Biodiversity and Evolutionary Biology, Universitat de Valencia, Valencia, Spain

D. S. Lauretta Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA

Ester Lázaro Molecular Evolution Laboratory, Centro de Astrobiología (CSIC-INTA), Madrid, Spain

Antonio Lazcano Facultad de Ciencias, UNAM, Cd. Universitaria, Mexico, DF, Mexico

Romane Le Gal Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

William Leavitt Dartmouth College, Hanover, NH, USA

Michael Lebert Biology Department, Cell Biology, Friedrich-Alexander-University Erlangen/Nuremberg, Erlangen, Germany

Sébastien Lebonnois Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, CNRS, Paris, France

Laura M. Lechuga Nanobiosensors and Bioanalytical Applications Group, Institut Català de Nanociència i Nanotecnologia (ICN2) CSIC and CIBER-BBN, Barcelona, Spain

Guillaume Lecointre Département Systématique et Evolution, UMR 7138 CNRS-MNHN-UPMC-IRD, Muséum National d'Histoire Naturelle, Paris, France

Emmanuel Lellouch Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Denis Diderot, Sorbonne Paris Cite, Meudon Principal Cedex, France

Tom Lenaerts Département d'Informatique, Université Libre de Bruxelles, Brussels, Belgium

Rodrigo Leonardi SPO/ Policial Sul, Agência Espacial Brasileira, Brasília, Brazil

Kevin Lepot Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, UMR 8187 - LOG Laboratoire d'Océanologie et de Géosciences, F-59000, Lille, France
Institut Universitaire de France (IUF), Paris, France

Hugues Leroux Unité Matériaux et Transformations (UMET), University Lille 1, Lille, France

Susan Leschine Veterinary and Animal Sciences, University of Massachusetts Amherst, Amherst, MA, USA

Anny-Chantal Levasseur-Regourd Sorbonne Université/LATMOS, Campus Pierre et Marie Curie, Paris, France

Richard Léveillé Natural Resource Sciences, McGill University, St. Anne de Bellevue, QC, Canada

Matthew Levy Michael F. Price Center, Albert Einstein College of Medicine, Bronx, NY, USA

Usha F. Lingappa Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Montoliu Lluís National Centre for Biotechnology (CNB-CSIC), Madrid, Spain

Purificación López-García Unité d'Ecologie, Systématique et Evolution, CNRS UMR8079 Université Paris-Sud 11, Paris, Orsay Cedex, France

Christophe Lovis University of Geneva, Geneva, Switzerland

Theresa Lueftinger Science Division, Directorate of Science, European Space Research and Technology Centre (ESA/ESTEC), Noordwijk, The Netherlands

Christophe Malaterre Institut d'Histoire et Philosophie des Sciences et Techniques (IHPST), Université Paris 1-Panthéon Sorbonne, Paris, France

Physicalism Malaterre Institut d'Histoire et Philosophie des Sciences et Techniques (IHPST), Université Paris 1-Panthéon Sorbonne, Paris, France

John F. Malloy School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA

Irena Mamajanov School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, USA

Rocco Mancinelli Bay Area Environmental Research Institute, NASA Ames Research Center, Moffett Field, CA, USA

Kaarel Mänd University of Alberta, Edmonton, AB, Canada

Avi M. Mandell NASA Goddard Space Flight Center, Greenbelt, MD, USA

Paola Manini Department of Chemical Sciences, University of Napoli Federico II, Naples, Italy

Susanna Manrubia Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Irma Marín Departamento de Biología Molecular, Universidad Autónoma de Madrid, Ciudad Universitaria de Cantoblanco, Madrid, Spain

Agúndez Marcelino Instituto de Física Fundamental, CSIC, Madrid, Spain

Emmanuel Marcq LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France

Lori Marino Emory Centre for Ethics, Emory University, Atlanta, GA, USA

Mark S. Marley NASA Ames Research Center, Moffett Field, CA, USA

Jean-Emmanuel Martelat LST UMR5570, Université Claude Bernard Lyon 1, Grenoble, France

Hervé Martin Laboratoire Magmas et Volcans, Université Clermont Auvergne, OPGC, CNRS, IRD, Campus des Cézeaux, Aubière Cedex, France

José Manuel Martínez Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Jesús Martínez-Frías Instituto de Geociencias, IGEO (CSIC-Universidad Complutense de Madrid), Madrid, Spain

Bernard Marty Institut Universitaire de France, Ecole Nationale Supérieure de Géologie, Centre de Recherches Pétrographiques et Géochimiques (CRPG), CNRS, Vandoeuvre les Nancy Cedex, France

Koichiro Matsuno Nagaoka University of Technology, Nagaoka, Japan

Mark J. McCarthy Wright State University, Dayton, OH, USA

Mark J. McCaughrean Senior Advisor for Science & Exploration (SCI-A), European Space Agency, Noordwijk, The Netherlands

Thomas McCollom Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

Francis McCubbin Institute of Meteoritics, University of New Mexico, Albuquerque, NM, USA

Brett A. McGuire Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA, USA

National Radio Astronomy Observatory, Charlottesville, VA, USA

Christopher P. McKay NASA Ames Research Center, Moffett Field, CA, USA

Nicola McLoughlin Department for Geology, Rhodes University, Makhanda (Grahamstown), South Africa

Uwe J. Meierhenrich Institut de Chimie de Nice (ICN), Université Côte d'Azur, Nice, France

H. Jay Melosh Departments of Earth, Atmospheric and Planetary Sciences, Physics and Aerospace Engineering, Purdue University, West Lafayette, IN, USA

Francesca Merlin CNRS UMR 8690 IHPST & Université Paris 1, Paris, France

Allyssa Metzger Harvard University, Cambridge, MA, USA

Mar Mezcua Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Magrans, Barcelona, Spain

Institut d'Estudis Espacials de Catalunya (IEEC), Carrer Gran Capità, Barcelona, Spain

François Mignard Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France

CNRS, Observatoire de la Côte d'Azur, University of Nice Sophia-Antipolis, Nice, France

Stefanie N. Milam Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Thomas J. Millar Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast, Antrim, UK

Vincent Minier CEA, Saclay, France

Shin Miyakawa Kamagaya, Chiba, Japan

Department of Chemistry and Biotechnology, Faculty of Engineering, Yokohama National University, Chiba, Japan

A. M. Mloszewska Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

Robert Mochkovitch Institut d'Astrophysique de Paris, Paris, France

Ralf Moeller German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Christine Moissl-Eichinger Department of Internal Medicine, Medical University of Graz, Graz, Austria

Diagnostic and Research Institute of Hygiene, Microbiology and Environmental Medicine, Medical University of Graz, Graz, Austria

Stephen Mojzsis University of Colorado, Boulder, CO, USA

Pierre-Alain Monnard FLinT Center, Institute for Physics and Chemistry, University of Southern Denmark, Odense, Denmark

Francisco Montero Department of Biochemistry and Molecular Biology I, Facultad de Ciencias Químicas, Universidad Complutense de Madrid, Madrid, Spain

Thierry Montmerle Institut d'Astrophysique de Paris, CNRS/Université Paris 6, Paris, France

Lluís Montoliu National Centre for Biotechnology (CNB-CSIC), Madrid, Spain

Lilia Montoya Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Maximilian Mora Department of Internal Medicine, Medical University of Graz, Graz, Austria

Michel Morange Centre Cavaillès, USR 3308 CIRPHLES, Ecole normale supérieure, Paris Cedex 05, France

Alessandro Morbidelli Laboratoire Lagrange, Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, Nice, France

David Moreira Unité d'Ecologie, Systématique et Evolution CNRS UMR8079, Université Paris-Sud 11, Paris, Orsay Cedex, France

Alvaro Moreno Departamento de Lógica y Filosofía de la Ciencia, Universidad del País Vasco, San Sebastián, Spain

Miguel Moreno Centro de Astrobiología, CSIC, Madrid, Spain

Harold Morowitz George Mason University, Fairfax, VA, USA

Penny L. Morrill Memorial University of Newfoundland, St. John's, NL, Canada

Stefano Mottola German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Denis J. P. Moura Centre national d'études spatiales, Toulouse, France

Jean-François Moyen Université de Lyon, LGL-TPE, UJM-UCLB-ENSL-CNRS, Saint Etienne, France

Armen Y. Mulkidjanian School of Physics, University of Osnabrueck, Osnabrueck, Germany

Moscow State University, Moscow, Russia

Holger S. P. Müller I. Physikalisches Institut, Universität zu Köln, Köln, Germany

Sami Nabhan Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Kazumichi Nakagawa Sanken, Osaka University, Ibaraki City, Osaka, Japan

Stephanie A. Napieralski University of Wisconsin–Madison, Madison, WI, USA

Hiroshi Naraoka Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

Gopal Narayanan Five College Radio Astronomy Observatory, University of Massachusetts, Amherst, MA, USA

Christian Naulin Univ. Bordeaux, CNRS, Bordeaux INP, ISM, Talence, France

Thomas Navarro McGill Space Institute, McGill University, Montréal, QC, Canada

Alicia Negrónk-Mendoza Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Circuito Exterior s/n, Ciudad Universitaria, Coyoacán, Mexico

Gerhard Neukum Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Silvia E. Newell Wright State University, Dayton, OH, USA

Wayne L. Nicholson Space Life Sciences Laboratory, University of Florida, Merritt Island, FL, USA

Space Life Sciences Laboratory, Kennedy Space Center, University of Florida, Gainesville, FL, USA

Peter E. Nielsen The Panum Institute, ICMM, University of Copenhagen, Copenhagen, Denmark

Jennifer Noble PIIM, CNRS/Aix-Marseille Universite, Marseille, France
School of Physical Sciences, University of Kent, Canterbury, UK

Nora Noffke Old Dominion University, Norfolk, VA, USA

Joseph Andrew Nuth III Solar System Exploration Division, NASA's Goddard Space Flight Center, Greenbelt, MD, USA

Karin I. Öberg Center for Astrophysics, Harvard-Smithsonian, Cambridge, MA, USA

Conel Michael O'Donel Alexander Earth and Planets Laboratory, Carnegie Institution for Science, Washington, DC, USA

Jonathan O'Neil University of Ottawa, Ottawa, ON, Canada

Shohei Ohara Carnegie Institution of Washington, Geophysical Laboratory, Washington, DC, USA

Hiroshi Ohmoto NASA Astrobiology Institute and Department of Geosciences, The Pennsylvania State University, University Park, PA, USA

José Olivares Estación Experimental del Zaidín. CSIC, Granada, Spain

Marc Ollivier Institut d'Astrophysique Spatiale, CNRS, Université de Paris-Sud, Orsay, France

Hans Olofsson Department of Earth and Space Sciences, Chalmers University of Technology, Gothenburg, Sweden

Silvano Onofri Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

Tullis C. Onstott Department of Geosciences, Princeton University, Princeton, NJ, USA

Gian Gabriele Ori Int'l Research School of Planetary Sciences, Univ. d'Annunzio, Pescara, Italy

Ibn Battuta Centre, Université Cadi Ayyad, Marrakech, Morocco

Vincenzo Orofino Dipartimento di Matematica e Fisica "E. De Giorgi", Università del Salento, Lecce, Italy

Gordon R. Osinski University of Western Ontario, Department of Earth Sciences/Institute for Earth and Space Exploration, London, ON, Canada

Sijbren Otto Stratingh Institute for Chemistry, University of Groningen, Groningen, The Netherlands

Corinna Panitz German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Etienne Pariat Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris-PSL, CNRS, Laboratoire de Physique des Plasmas (LPP), Paris, France

LESIA, Observatoire de Paris, Université PSL, Sorbonne Université, Université Paris Cité, CNRS, Meudon, France

Víctor Parro Molecular Evolution Department, Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Robert Pascal Institut des Biomolécules Max Mousseron CC1706, Université de Montpellier II, Montpellier, France

Matthew A. Pasek University of South Florida, Tampa, FL, USA

Mercedes Moreno Paz Molecular Evolution Department, Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Ernesto Pecoits Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada

Els Peeters Department of Physics and Astronomy & Institute for Earth and Space Exploration, The University of Western Ontario, London, ON, Canada
SETI Institute, Mountain View, CA, USA

Ivanka Pelivan Institute of Planetary Research, German Aerospace Center, Berlin, Germany

Francesco A. Pepe Department of Astronomy, University of Geneva, Versoix, Switzerland

Juli Peretó Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Institute for Integrative Systems Biology I²SysBio, Universitat de València-CSIC, València, Spain

Nicolas Peretto School of Physics & Astronomy, Cardiff University, Cardiff, UK

Jérôme Perez Applied Mathematics Laboratory, ENSTA ParisTech, Paris Cedex 15, France

Erik Persson Department of Philosophy, Lund University, Lund, Sweden

Jean-Robert Petit Univ. Grenoble-Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France

Daniel A. Petrash Environmental Geochemistry and Biogeochemistry, Czech Geological Survey, Prague, Czech Republic

Pascal Philippot Equipe Géobiosphère Actuelle et Primitive, Institut de Physique du Globe de Paris (IPGP), Paris, France

Raymond Pierrehumbert Department of Physics Clarendon Laboratory, University of Oxford, Oxford, OXON, UK

Göran L. Pilbratt Science Directorate Science Division (SCI-SC), European Space Agency, Noordwijk, The Netherlands

Samanta Pino Department of Biology and Biotechnologies “Charles Darwin”, University of Rome “Sapienza”, Rome, Italy

Daniele L. Pinti Geotop, Research Centre on the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Sandra Pizzarello Department of Chemistry & Biochemistry, Arizona State University, Tempe, AZ, USA

Noah J. Planavsky Department of Geology and Geophysics, Yale University, New Haven, CT, USA

Raphaël Plasson Department of Earth and Planetary Science, Harvard University, Cambridge, MA, USA

Ana-Catalina Plesa Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

Franck Poitrasson Géosciences Environnement Toulouse, CNRS, Toulouse, France

Simon W. Poulton School of Earth and Environment, University of Leeds, Leeds, UK

Nikos Prantzos Institut d'Astrophysique de Paris, Paris, France

Lawrence Pratt Tulane University, New Orleans, LA, USA

Jorge Enrique Bueno Prieto Instituto de Astrobiología de Colombia, Bogotá, Colombia

Daniel Prieur Université de Bretagne Occidentale (University of Western Brittany), Brest, France

Institut Universitaire Européen de la Mer (IUEM), Technopôle Brest-Iroise, Plouzané, France

Alexander J. Probst Department of Chemistry, Institute for Environmental Microbiology and Biotechnology, University of Duisburg-Essen, Essen, Germany

Addy Pross Ben Gurion University of the Negev, Be'er Sheva, Israel

José Cernicharo Quintanilla Laboratory of Molecular Astrophysics, IFF-CSIC, Madrid, Spain

Ahmed Ragab Harvard Divinity School, Cambridge, MA, USA

Nisha K. Ramkissoon Faculty of Science, Technology, Engineering and Mathematics, The Open University, Milton Keynes, UK

Heike Rauer German Aerospace Center (DLR), Berlin, Germany

François Raulin LISA – UMR CNRS/IPSL, Faculté des Sciences et Technologie, Université Paris Est-Créteil & Denis Diderot, Créteil, France

Florence Raulin-Cerceau Maître de Conférences, Centre Alexandre Koyré (UMR 8560-CNRS/EHESS/MNHN/CSI) Muséum National d'Histoire Naturelle, Paris, France

Sean N. Raymond Laboratoire d'Astrophysique de Bordeaux, CNRS, Université de Bordeaux, Bordeaux, France

Laboratoire d'Astrophysique de Bordeaux, CNRS, Université de Bordeaux, Floirac, France

Laboratoire d'Astrophysique de Bordeaux, CNRS, Université de Bordeaux, Pessac, France

Jacques Reisse Université Libre de Bruxelles, Brussels, Belgium

Anthony J. Remijan National Radio Astronomy Observatory, Charlottesville, VA, USA

Laurent Remusat Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, Muséum National d'Histoire Naturelle, Sorbonne Université, UMR CNRS 7590, Paris, France

Petra Rettberg Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne, Germany

Alonso Ricardo Ra Pharmaceuticals, One Kendall Square, Cambridge, MA, USA

Antonio J. Ricco NASA Ames Research Center, on Assignment from Stanford University, Moffett Field, CA, USA

Víctor M. Rivilla Centro de Astrobiología (CSIC/INTA), Madrid, Spain
Osservatorio Astrofisico di Arcetri, INAF, Florence, Italy

Hanika Rizo Carleton University, Ottawa, ON, Canada

Leslie J. Robbins University of Alberta, Edmonton, AB, Canada
Yale University, New Haven, CT, USA

Wayne G. Roberge New York Center for Astrobiology, Rensselaer Polytechnic Institute, Troy, NY, USA

François Robert Institut de Minéralogie, Physique des Matériaux et Cosmochimie (IMPMC), Sorbonne Université et Muséum National d'Histoire Naturelle, UMR 7590 CNRS, Cedex 05 Paris, France

Institut Origine et Evolution (O&E), Muséum National d'Histoire Naturelle, Sorbonne Université, IMPMC-UMR 7590 CNRS, Paris, France

Laboratoire de Minéralogie et Cosmochimie du Muséum (LMCM), Muséum National d'Histoire Naturelle, UMR 7202 CNRS, Paris, France

Michael P. Robertson Department of Molecular Biology MB42, The Scripps Research Institute, La Jolla, CA, USA

Océane Rocher Faculté des Sciences et Technologies, GeoRessources – UMR 7359, Université de Lorraine, Vandoeuvre-Les-Nancy, France

Bernd Michael Rode Institute for General, Inorganic and Theoretical Chemistry, Leopold-Franzens University, Universität Innsbruck, Innsbruck, Austria

Eric E. Roden University of Wisconsin-Madison, Madison, WI, USA

Francisco Rodriguez-Valera Microbiologia, Universidad Miguel Hernandez, San Juan, Alicante, Spain

Françoise Roques Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Meudon, France

Minik T. Rosing Nordic Center for Earth's Evolution, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark

Ramon Rosselló-Móra IMEDEA (CSIC-UIB), Esporles, Mallorca, Balearic Islands, Spain

Daniel Rouan LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Kepa Ruiz-Mirazo Department of Logic and Philosophy of Science, FICE, UPV-EHU, Biophysics Research Unit (CSIC – UPV/EHU), Donostia, San Sebastián, Spain

Sara Russell Natural History Museum, London, UK

Hassan Sabbah Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse (UPS), CNRS, CNES, Toulouse Cedex 4, France

Jan W. Sadownik Stratingh Institute for Chemistry, University of Groningen, Groningen, The Netherlands

Nita Sahai Department of Polymer Science, University of Akron, Akron, OH, USA

A. Marco Saitta IMPMC, UMR 7590, Sorbonne Université, CNRS, Muséum National d'Histoire Naturelle, Paris, France

Raffaele Saladino Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

Agustín Sánchez-Lavega Escuela de Ingeniería de Bilbao, Universidad del País Vasco UPV/EHU, Bilbao, Spain

Cristina Sánchez-Porro Department of Microbiology and Parasitology, Faculty of Pharmacy, University of Sevilla, Sevilla, Spain

Leopoldo G. Sancho Faculty of Pharmacy, Section of Botany, Universidad Complutense, Madrid, Spain

Juan Sanjuán Estación Experimental del Zaidín. CSIC, Granada, Spain

José Luis Sanz Departamento de Biología Molecular, Universidad Autónoma de Madrid, Madrid, Spain

Kohei Sasaki Graduate School of Science, Tohoku University, Sendai, Japan

Pierre Savaton Université de Caen Basse-Normandie, Caen, France

Kevin Schindler Lowell Observatory, Flagstaff, AZ, USA

Nicola Schneider I. Physik. Institut, University of Cologne, Cologne, Germany

Karel Schulmann Ecole et Observatoire de Science de la Terre, Institute de Physique de Globe, Université de Strasbourg, Strasbourg, France

Peter Schuster Institut für Theoretische Chemie der Universität Wien, Wien, Austria

Alan W. Schwartz Radboud University Nijmegen, Nijmegen, The Netherlands

Petra Schwill Max Planck Institute of Biochemistry, Martinsried, Germany

Sabrina Schwinger German Aerospace Center (DLR) Institute for Planetary Research, Berlin, Germany

William G. Scott Department of Chemistry and Biochemistry, The Center for the Molecular Biology of RNA, University of California at Santa Cruz, Santa Cruz, CA, USA

Burckhard Seelig Department of Biochemistry, Molecular Biology and Biophysics & BioTechnology Institute, University of Minnesota, St. Paul, MN, USA

Elliot Sefton-Nash European Space Agency – ESA/ESTEC (SCI-S), Noordwijk, The Netherlands

Antigona Segura Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Franck Selsis Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Floirac, France

CNRS, LAB, Floirac, France

CNRS, Laboratoire d'astrophysique de Bordeaux, Passac, France

Dmitry Semenov Max Planck Institute of Astronomy, Heidelberg, Germany

O. Sharaf Mohammed Bin Rashid Space Centre (MBRSC), Dubai, United Arab Emirates

M. A. Shea Air Force Research Laboratory (Emeritus), Bedford, MA, USA

Friedrich C. Simmel Technical University Munich, Garching, Bavaria, Germany

Aleksandr Slabunov Institute of Geology, Karelian Research Centre, RAS, Petrozavodsk, Russia

Greg Slater McMaster University, Hamilton, ON, Canada

Don F. Smart Air Force Research Laboratory (Emeritus), Bedford, MA, USA

Alexander Smirnov Department of Earth and Marine Science, Dowling College, Oakdale, NY, USA

David J. Smith Space Biosciences Research Branch, NASA Ames Research Center, Moffett Field, CA, USA

Derek Smith Case Western Reserve University, Cleveland, OH, USA

Ian W. M. Smith Chemistry Laboratory, University of Cambridge, Cambridge, UK

Ronald L. Snell Department of Astronomy, 517 K Lederle Graduate Research Center, University of Massachusetts, Amherst, MA, USA

Colin Snodgrass University of Edinburgh, Edinburgh, UK

Frank Sohl DLR, Institute of Planetary Research, Berlin, Germany

Gordon Southam The University of Queensland, St. Lucia, QLD, Australia

Alessandro Sozzetti Istituto Nazionale di Astrofisica (INAF) – Osservatorio Astrofisico di Torino, Pino Torinese, Italy

Tilman Spohn International Space Science Institute, Bern, Switzerland

Jiří Šponer Institute of Biophysics of the Czech Academy of Sciences, Brno, Czech Republic

Judit E. Šponer Institute of Biophysics of the Czech Academy of Sciences, Brno, Czech Republic

Greg Springsteen Furman University, Greenville, SC, USA

J. Andy Spry SETI Institute, Mountain View, CA, USA

Steven W. Stahler Department of Astronomy, University of California, Berkeley, CA, USA

Lucas J. Stal Department of Marine Microbiology, Royal Netherlands Institute of Sea Research (NIOZ), Yerseke, The Netherlands

Vlada Stamenković Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA

Kenneth Mark Stedman Department of Biology, Center for Life in Extreme Environments, Portland State University, Portland, OR, USA

Lisa Y. Stein Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada

Jennifer C. Stern Planetary Environments Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Barbara Stracke Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

Harald Strauss Westfälische Wilhelms-Universität Münster, Institut für Geologie und Paläontologie, Münster, Germany

Kenichiro Sugitani Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

Håkan Svedhem European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Ewa Szuszkiewicz CASA, Faculty of Mathematics and Physics, University of Szczecin, Szczecin, Poland

Makoto Tabata Department of Physics, Graduate School of Science, Chiba University, Chiba, Japan

Kamal Taj-Eddine Int'l Research School of Planetary Sciences, Univ. d'Annunzio, Pescara, Italy

Ibn Battuta Centre, Université Cadi Ayyad, Marrakech, Morocco

Jun-ichi Takahashi Faculty of Engineering, Yokohama National University, Yokohama, Japan

Motohide Tamura The University of Tokyo and Astrobiology Center, Mitaka, Tokyo, Japan

Olga Taran Chemistry and Chemical Biology, Harvard University, Cambridge, MA, USA

Inge Loes ten Kate Department of Earth Sciences, Utrecht University, Utrecht, Netherlands

Christophe Thomazo UMR CNRS 5561 Biogéosciences, Université de Bourgogne, Dijon, France

Institut Universitaire de France, Paris, France

Phil Thurston Laurentian University, Sudbury, ON, Canada

Simon Tillier Département Systématique et Evolution, UMR 7138 CNRS-MNHN-UPMC-IRD, Muséum National d'Histoire Naturelle, Paris, France

Giovanna Tinetti Department of Physics & Astronomy, University College London (UCL), London, UK

Stéphane Tirard Faculté des Sciences et des Techniques de Nantes, Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Nantes, France

Daniela Tirsch German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

Dmitrij Titov European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Marco Tomassini Information Systems Department, University of Lausanne, Lausanne, Switzerland

Carmen Tornow Institute of Planetary Research, German Aerospace Center, Berlin, Germany

Nicola Tosi German Aerospace Center (DLR) Institute for Planetary Research, Berlin, Germany

Rosalie Tostevin Department of Geological Sciences, University of Cape Town, Rondebosch, South Africa

Department of Earth Sciences, University of Oxford, Oxford, UK

Melissa G. Trainer NASA Goddard Space Flight Center Code 699, Greenbelt, MD, USA

Pascal Tremblin CEA, Saclay, France

Cecilia Tubiana Istituto di Astrofisica e Planetologia Spaziali – IAPS/INAF,
Via del Fosso del Cavaliere, 100, Roma, Italy

Martin Turbet Observatoire Astronomique de l'Université de Genève,
Sauverny, Switzerland

Department of Astronomy, Université de Genève, Versoix, Switzerland

Jorge L. Vago European Space Agency – ESA/ESTEC (SCI-S), Noordwijk,
The Netherlands

Veronica Vaida University of Colorado, Boulder, CO, USA

Stephan van Gasselt Planetary Sciences and Remote Sensing, Institute of
Geological Sciences, Freie Universität Berlin, Berlin, Germany

Martin J. Van Kranendonk School of Biological, Earth and Environmental
Sciences, University of New South Wales, Sydney, NSW, Australia

Iris van Zelst Institute of Planetary Research, German Aerospace Center
(DLR), Berlin, Germany

Ashwin R. Vasavada Jet Propulsion Laboratory, California Institute of Tech-
nology, Pasadena, CA, USA

Charlotte Vastel Institut pour la Recherche en Astrophysique et
Planétologie, Toulouse, France

Antonio Ventosa Department of Microbiology and Parasitology, Faculty of
Pharmacy, University of Sevilla, Sevilla, Spain

Eric P. Verrecchia IDYST, Faculty of Geosciences and the Environment,
University of Lausanne, Lausanne, Switzerland

Enrique Viguera Genetics Department Sciences Faculty, University of
Malaga, Malaga, Spain

Michel Viso Innovaxiom, Paris, CX, France

Günter von Kiedrowski Lehrstuhl für Organische Chemie I, Ruhr-
Universität Bochum, Bochum, Germany

Jeff Wagg Square Kilometre Array Observatory, Macclesfield, UK

Roland J. Wagner German Aerospace Center (DLR), Institute of Planetary
Research, Berlin, Germany

Sara Imari Walker School of Earth and Space Exploration, Arizona State
University, Tempe, AZ, USA

Beyond Center for Fundamental Concepts in Science, Arizona State Univer-
sity, Tempe, AZ, USA

Michaela Walterová Deutsches Zentrum für Luft- und Raumfahrt (DLR),
Institut für Planetenforschung, Berlin, Germany

Samantha M. Waters Universities Space Research Association, Space Biosciences Research Branch, NASA Ames Research Center, Moffett Field, CA, USA

Frances Westall Centre de Biophysique Moléculaire, CNRS, Rue Charles Sadron, Orléans, France

Hubert Whitechurch Ecole et Observatoire de Science de la Terre, Institute de Physique de Globe, Université de Strasbourg, Strasbourg, France

William B. Whitman University of Georgia, Athens, GA, USA

Douglas Whittet Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY, USA

New York Center for Astrobiology, Rensselaer Polytechnic Institute, Troy, NY, USA

Simon Wilde School of Earth & Planetary Sciences, Curtin University, Perth, WA, Australia

Steven W. Wilhelm University of Tennessee Knoxville, Knoxville, TN, USA

Ian S. Williams Research School of Earth Sciences, ANU College of Science, The Australian National University, Canberra, ACT, Australia

Jonathan P. Williams Institute for Astronomy, University of Hawaii, Honolulu, HI, USA

Loren Dean Williams School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, USA

Ross H. Williams CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology/University of Maryland, College Park, MD, USA

NASA Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, MD, USA

Colin Wilson European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Olivier Witasse European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Charles T. Wolfe Département de philosophie, Université de Toulouse Jean-Jaurès, Toulouse, France

Mark G. Wolfire Astronomy Department, University of Maryland, College Park, MD, USA

C. W. V. Wolner Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA

Alexander Wolszczan Department of Astronomy & Astrophysics and Center for Exoplanets & Habitable Worlds, The Pennsylvania State University, University Park, PA, USA

Paul M. Woods Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast, Antrim, UK

Robin Wordsworth School of Engineering and Applied Sciences, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA

Ci Xue University of Virginia, Charlottesville, VA, USA

Kosei E. Yamaguchi Geochemical Laboratory, Department of Chemistry, Toho University, Funabashi, Chiba, Japan

Masamichi Yamashita Institute of Space and Astronautical Science (ISAS)/ JAXA, Sagamihara, Kanagawa, Japan

Bruce Yardley School of Earth and Environment, University of Leeds, Leeds, UK

Reika Yokochi Department of Geophysical Sciences, The University of Chicago, Chicago, IL, USA

Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL, USA

Philippe Zarka LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France

LESIA, Observatoire de Paris, CNRS, PSL, SU, UPC, Meudon, France

Annie Zavagno CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, Aix Marseille Université, Marseille, France

Institut Universitaire de France, Paris, France

Tanja Elsa Zegers Paleomagnetic Laboratory, Institute of Earth Sciences, Utrecht University, Utrecht, The Netherlands

Aubrey L. Zerkle School of Earth and Environmental Sciences and Centre for Exoplanet Science, University of St Andrews, St Andrews, UK

Mingyu Zhao Department of Geology and Geophysics, Yale University, New Haven, CT, USA

Linna Zhou Department of Chemistry, University of Oxford, Oxford, UK

Michael E. Zolensky ARES, NASA Johnson Space Center, Houston, TX, USA

Astrobiology by Discipline

Field - Astrophysics & Astrochemistry: *M. Gerin, D. Rouan*

Section - Stars and Nucleosynthesis: *J. Isern*

Abundances of Elements
Astroseismology
Asymptotic Giant Branch Star
Big Bang Nucleosynthesis
Black Holes
CNO Cycle
Cosmochemistry
Diffusion
Drake Equation
Dwarf Star
Faint Young Sun Paradox
Fermi Paradox
Galactic Archaeology
Galactic Habitable Zone
Galaxy
Globular Cluster
Hertzsprung-Russell Diagram
High-Mass Star
Horizontal Branch
Initial Mass Function
Isochrone
Low Mass Star
Main Sequence, Star
Mass-Luminosity Relation
Metallicity
Milky Way
Neutron Star
Nova
Nuclear Reaction
Nuclear Stability

Nucleosynthesis, Explosive
Nucleosynthesis, Neutrino
Nucleosynthesis, Stellar
Opacity
Open Cluster
P-P Chains
Planetary Nebula
Pulsar
R-Process
Red Dwarf
Red Giant
S-Process
Solar Neighborhood
Spallation Reaction
Spectral Type
Stars
Stellar Evolution
Stellar Populations
Stellar Pulsation
Stellar Rotation
Stellar Yield
Sun (and Young Sun)
Supernova
Supernova Remnant
Supernova Types
White Dwarf
Zero Age Main Sequence

Section - Stars – Formation: *M. Beltran*

Accretion, Stellar
Ambipolar Diffusion
Binary Stars, Young
Bipolar Flow
Birthline
Brown Dwarf

Convection, Stellar
 Debris Disk
 Dense Core
 Fragmentation of Interstellar Clouds
 Free-Fall Time
 FU Orionis (Object)
 Gravitational Collapse, Stellar
 Hot Core
 Hot Corino
 Infrared Dark Cloud
 Infrared Excess
 Initial Mass Function, Origin of
 Interstellar Filaments
 Jeans Criterion
 Kelvin-Helmholtz Timescale
 Larson's Law
 Lithium Absorption
 Magnetic Fields and Star Formation
 Molecular Cloud
 OB Association
 Pillars
 Pre-main-sequence Star
 Protobinary Star
 Protoplanetary Disk
 Protostars
 Protostellar Envelope
 Skumanich Law
 Spectral Classification of Embedded Stars
 Spectral Veiling of Young Stars
 Star Formation Rate
 Star Formation, Feedback
 Star Formation, Observations
 Star Formation, Theory
 Star Formation, Triggering
 Stellar Cluster
 Stellar Winds
 T Association
 T Tauri Star
 Thermal Radio Jets
 Ultracompact HII Regions
 YY Orionis Star

Section - Astrophysics: General **Definitions: D. Rouan**

Ablation
 Accretion Shock

Activity, Magnetic
 Adaptive Optics
 Alignment of Dust Grains
 Anatexis
 Angular Diameter
 Angular Momentum
 Aphelion
 Astrometry
 Atomic Fine Structure Cooling
 AU
 Background
 Bandpass
 Blackbody
 Bolometer
 Bolometric Magnitude
 Bremsstrahlung Radiation
 CCD
 Celestial Equator
 Center of Mass Velocity
 Chandrasekhar's Limit
 Cirrus Cloud
 Coagulation, Interstellar Dust Grains
 Color Excess
 Color Index
 Column Density
 Continuum
 Coordinate Systems
 Coronagraphy
 Cosmogony
 Declination
 Dense Cloud
 Diffraction
 Diffuse Cloud
 Diffuse Galactic Light
 Doppler Shift
 Dust Cloud, Interstellar
 Eccentricity
 Ecliptic
 Effective Temperature
 Electromagnetic Radiation
 Electromagnetic Spectrum
 Emission Nebula
 Emissivity
 Ephemeris
 Equation of State
 Equinox
 Exozodiacal Light
 Extinction, Interstellar or Atmospheric

Flux, Radiative	Plasma
Gas Giant Planet	Polar Axis
Gneiss	Precession
Gravitation	Proper Motion
Grey Body	Protoplanetary Nebula
Heavy Element	Q (Orbital Parameter)
HII Region	Radiative Processes
Hydrodynamic Flow	Radiative Transfer
Hydrostatic Equilibrium	Radio Astronomy
Imaging	Red Rectangle
Impact Parameter	Reddening, Interstellar
Inclination (Astronomy)	Redshift
Infrared Astronomy	Reflection Nebula
Interferometry	Right Ascension
Interstellar Cloud	Roche Limit
Interstellar Dust	Rotational Velocity
Interstellar Medium	Semimajor Axis
Jeans Escape	Semiminor Axis
Johnson UVB Bandpasses	Shock, Interstellar
Lagrangian Points	Solar Constant
Light-Year	Solar Luminosity
Limb Darkening	Solar Mass
Limb, Astronomical	Solar Radius
Line Emission	Spectral Line
Line of Sight	Spectrometer
Line Profile	Spectroscopy
Linewidth	Star Counts
Local Standard of Rest	Suprathermal
Luminosity	Surface Gravity
Lyman Alpha	Synchrotron Radiation
Magnetic Field	Telescope
Magnetohydrodynamics	Thermodynamical Chemical Equilibrium
Magnitude	Time Series
Magnitude, Absolute	Titius-Bode Law
Maser	Translucent Interstellar Clouds
Mass Loss Rate	Turbulence, Interstellar
Mean Free Path	Ultraviolet Radiation
Nadir	UV Radiation
Noise	Vacuum Ultraviolet
Nulling Interferometry	Variability, Stellar
Occultation	Vernal Point
Optical Depth	Visible Light
Orbital Resonance	VLBI
Parallax	VLT
Parsec	X-Rays (Stellar)
Photodissociation Region	XDR
Photon	Z (Astrophysics)
Photosphere	Zenith

Section - Astrochemistry: Models and Observations: V. Wakelam

Absorption Spectroscopy

Abundances

Acetamide

Acetone (CH_3COCH_3)

Acetylene (C_2H_2)

Adsorption

Amino Radical

Aminoacetonitrile ($\text{NH}_2\text{CH}_2\text{CN}$)

Ammonium (NH_3D^+)

Anion

Apolar Molecule

Argonium (ArH^+)

Benzene (C_6H_6)

Benzonitrile ($\text{C}_6\text{H}_5\text{CN}$)

Butadiynyl Radical (C_4H)

C_3N^- Anion

C_5N^- Anion

Carbene

Carbodiimide (HNCNH)

Carbon Monosulfide (CS)

Chemical Bistability

Chlorine Hydrides in the Interstellar Medium

Chloromethane (CH_3Cl)

Circumstellar Chemistry

Clathrate Hydrate

Cosmic Ray, Ionization Rate

Cosmic-Ray-Induced Desorption

Cyanide Anion (CN^-)

Cyanobutadiynyl Radical (C_5N)

Cyanoethynyl Radical (C_3N)

Cyanogen Radical (CN)

Cyanomethanimine

Cyanopolyynes

Cyclopropenylidene (C_3H_2)

Desorption

Diacetylene (C_4H_2)

Diazenylium (N_2H^+)

Diffuse Interstellar Bands

Dihydroxyacetone

Dimethyl Ether (CH_3OCH_3)

Dust Grain

Elemental Depletion

Ethanimine

Ethyl Cyanide ($\text{CH}_3\text{CH}_2\text{CN}$)

Ethyl Formate

Ethyl Methyl Ether ($\text{C}_2\text{H}_5\text{OCH}_3$)

Ethylene Glycol ($\text{HOCH}_2\text{CH}_2\text{OH}$)

Ethylene Oxide ($\text{C}_2\text{H}_4\text{O}$)

Ethynyl Radical (C_2H)

Extended Red Emission

Formamide (NH_2CHO)

Formyl Cation (HCO^+)

Fullerane

Fullerene

Gas-Grain Chemistry

Glycolaldehyde (HOCH_2CHO)

HC_3O^+

HC_4NC

HC_5NH^+

Hydrogen Chloride (HCl)

Hydrogen Isocyanide (HNC)

Hydrogenated Amorphous Carbon

Hydroxyl Radical (OH)

Imidogen (NH)

Interstellar Chemical Processes

Interstellar Ices

Interstellar Molecule

IRAS16293-2422

IRC+10216

Isotopic Fractionation (Interstellar Medium)

Isotopolog

Ketenyl Radical (HCCO)

L1544

Line Shielding

Macro Monte Carlo Models

Master Equation Models

Metal Compounds in Circumstellar

Envelopes

Methanethiol (CH_3SH)

Methanimine (CH_2NH)

Methoxy Radical (CH_3O)

Methoxymethanol ($\text{CH}_3\text{OCH}_2\text{OH}$)

Methyl Acetate ($\text{CH}_3\text{COOCH}_3$)

Methyl Formate (HCOOCH_3)

Methyl Isocyanate (CH_3NCO)

Methyl Radical (CH_3)

Methyl Triacetylene ($\text{CH}_3\text{C}_6\text{H}$)

Methylamine (CH_3NH_2)

Methylene (CH_2)

Methylidyne (CH)

Methylidyne Cation (CH^+)

Micro-Monte-Carlo Models
Molecular Depletion
Molecular Line Cooling
Molecular Line Map
Molecular Line Survey
Molecules in Space
Nanodiamond
Nitrogen Sulfide (NS)
Nucleation of Dust Grains
Organic Dust, Synthesis by Stars
Phosphaethyne (HCP)
Phosphorus Chemistry
Phosphorus Monoxide (PO)
Polar Molecule
Polycyclic Aromatic Hydrocarbon
Prasad-Tarafdar Mechanism
Propyl Cyanide ($\text{C}_3\text{H}_7\text{CN}$)
Propylene (CH_3CHCH_2)
Propylene Oxide ($\text{CH}_3\text{CHCH}_2\text{O}$)
Propynylidyne (C_3H)
Propynylidynium (C_3H^+)
Radical
Rate Equation Models
Reaction Rate Coefficient
Scattering
SgrB2
Silane (SiH_4)
Silicon Monosulfide (SiS)
Silicon Monoxide (SiO)
Silicon Nitride (SiN)
Sputtering
Star Dust
Sulfur Chemistry
Sulfur Hydrides in the Interstellar Medium
Sulfur Monoxide (SO)
Thioformaldehyde (H_2CS)
Titanium Dioxide (TiO_2)
Titanium Monoxide (TiO)
TMC-1 Molecular Cloud
Unidentified Infrared Emission Bands
UV Absorption Bump
Vinyl Cyanide (CH_2CHCN)
VY CMa
Water in the Universe
Water, Formation and Photodissociation
Water, Related Interstellar Radicals
and Ions
Water, Vibrational and Rotational Transitions

Section - Astrochemistry: Laboratory Experiments: *F. Dulieu, A Canosa*

Amorphous Solid
Bimolecular Reaction
Binding Energy
Charge Transfer
Chemisorption
Condensation Temperature
Electron Attachment
Electron Dissociative Recombination
Electron Radiative Recombination
Eley-Rideal Mechanism
Interstellar Dust Spectroscopy
Interstellar Ice Spectroscopy Experiments
Ion-Neutral Reaction
Isotopic Exchange Reaction
Laboratory Astrophysics, General Definition of
Laboratory Characterization of Meteorites
Laboratory Dust Analogs
Langevin Rate Coefficient
Langmuir-Hinshelwood Mechanism
Molecular Beams
Molecular Spectroscopy
Mutual Neutralization
Neutral-Neutral Reaction
Photochemistry
Photodesorption
Photodetachment
Photodissociation
Photoionization
Photolysis
Physisorption
Plasma Chemistry, Laboratory
Plasma, High-Energy Density in Laboratory
Predissociation
Proton Transfer
Quenched Carbonaceous Composite
Radiation Chemistry
Radiative Attachment
Radiolysis
Refractory Molecule
Spectroscopy, Electronic (UV-Vis Astronomy)
Spectroscopy, Rotational
Spectroscopy, Vibrational
Sticking Coefficient
Supersonic Jet Expansions
Unimolecular Reaction

Field - Planetology; *T. Spohn*

Section - Planetary Formation and Dynamics; *Y. Alibert, R. Helled*

Apsidal Angle
 Atmosphere, Primitive Envelope
 Cassini State
 Coagulation in Planetary Disks
 Condensation Sequence
 Core Accretion, Model for Giant Planet Formation
 Corotation Torque
 Critical Core Mass (Giant Planet Formation)
 Disk Instability, Model for Giant Planet Formation
 Dynamical Friction
 Dynamical Instability
 Ejection, Hyperbolic
 Escape Velocity
 Feeding Zone
 Formation of Planetesimals: The Building Blocks of Planets
 Gas Drag
 Giant Impact
 Gravitational Collapse, Planetary
 Gravitational Focusing
 Hill Radius/Sphere
 Hill/Lagrange Stability
 Impact, Hit and Run
 Isolation Mass
 Kozai Mechanism
 Laplace Resonance
 Late Heavy Bombardment
 Late-Stage Accretion
 Libration
 Lindblad Resonance
 Magnetic Fields and Planetary Systems Formation
 Mean Motion Resonance
 Meter-Size Catastrophe
 Moon, Origin of
 Nice Model
 Oligarchic Growth
 Orbit
 Orbital Period
 Photoevaporation of Protoplanetary Disks
 Planet Formation

Planet V Hypothesis
 Planetary Embryo
 Planetary Evolution
 Planetary Migration
 Planetesimals
 Protosun Composition
 Protoplanetary Disk Dead Zone
 Protoplanetary Disk Instability
 Protoplanetary Disk Midplane
 Protoplanetary Disk of Second Generation
 Protoplanetary Disk, Chemistry
 Protosolar Nebula, Minimum Mass
 Q (Tidal Quality Factor)
 Q (Toomre Parameter)
 Q* (Specific Energy to Destroy an Object)
 Radial Drift
 Rotation Planet
 Runaway Gas Accretion
 Runaway Growth
 Secular Dynamics
 Secular Resonance
 Shepherding
 Snow Line
 Solar Nebula
 Solar System
 System Solar Formation, Chronology of
 Turbulence (Planetary Disks)
 Viscosity
 Viscous Stirring
 Vortex, Vortices
 Water in the Solar System

Section - Inner Solar System: *G. Alemanno*

Aquifer (Mars)
 Areology
 Carbonate on Mars
 Carbonate, Extraterrestrial
 Concretions (Mars)
 Cosmic Spherules
 Deimos
 Dynamo, Planetary
 Gegenschein
 Habitability on Mars
 Interplanetary Dust Particle
 Jarosite

Mars
 Mars Stratigraphy
 Mars, Delta
 Mars, Erosion Rate
 Mars, Hydrated Minerals
 Mars, Paleo Ocean
 Mars, Paleoclimate
 Mars, Paleolakes
 Mercury
 Moon, The
 Nanoparticle
 Obliquity and Obliquity Variations
 Olympus Mons
 Phobos
 Planet
 Planetary Mapping
 Poynting-Robertson Drag
 Psyche
 RQ36
 Satellite or Moon
 Selenology
 Serpentinization (Mars)
 Sol
 Solar System, Inner
 Space Weathering
 Spectral Parameters, Solar System Planets
 Terrestrial Planet
 Tessera, Tesserae
 Tharsis
 Valles Marineris
 Valley Networks
 Venus
 Zeolites

Section - Outer Solar System: *T. Cavalie*

Callisto
 Cassini
 Cassini Division
 Cryovolcanism
 Dione
 Enceladus
 Europa
 Galileo Galilei
 Ganymede
 Giant Planets
 Huygens

Iapetus
 Io
 Jupiter
 Magnetosphere
 Mimas
 Miranda
 Neptune
 Nereid
 Phoebe
 Planetary Rings
 Rhea
 Saturn
 Solar System, Outer
 Tethys
 Titan
 Titania
 Triton
 Umbriel
 Uranus
 Zodiacal Light

Section - Small Bodies and Dwarf Planets: *H. Cottin*

6 Hebe
 67P/Churyumov–Gerasimenko
 Achondrite
 Active Asteroid
 ALH 84001
 Annefrank
 Apollo Asteroid
 Apophis Asteroid
 Arrokoth
 Asteroid
 Asteroid Belt, Main
 Bennu Asteroid
 C-Asteroid
 CAIs
 Carbonaceous Chondrite
 Centaurs (Asteroids)
 Ceres
 Charon
 Chassignites
 Chassigny
 Chiron
 Chondrite
 Chondrule

Comet
 Comet (Nucleus)
 Comet Borrelly
 Comet Encke
 Comet Giacobini-Zinner
 Comet Hale-Bopp
 Comet Halley
 Comet Hartley 2
 Comet Hyakutake
 Comet Mc Naught
 Comet Shoemaker-Levy 9
 Comet Shower
 Comet Tempel 1
 Comet Wild 2
 Daughter Molecule, Comet
 Dwarf Planet
 Eros Asteroid
 Fusion Crust
 Gaspia
 GEMs
 Hygiea
 Ida
 Itokawa Asteroid
 Kuiper Belt
 Lightcurve
 Lutetia
 Mathilde
 Meteor
 Meteorite, Allende
 Meteorite, Murchison
 Meteorite, Orgueil
 Meteorites
 Meteoroid
 Micrometeorites
 Nakhla
 Nakhilites
 Near-Earth Objects
 Oberon
 Oort Cloud
 Organic Refractory Matter
 Pallas
 Panspermia
 Parent Body
 Parent Molecule, Comet
 Pluto
 Quaoar
 Ryugu Asteroid
 Sedna

Shergottites
 Shergotty
 Small Solar System Body
 SNC Meteorites
 Toutatis
 Trans-Neptunian Object
 Trojans (Asteroids)
 Ultra-carbonaceous Antarctic Micrometeorites
 Vesta
 Šteins
 'Oumuamua

Section - Exoplanetary Systems: *E. Bolmont*

51 Pegasi B
 55 Cancri
 Alpha Centauri Bb
 Astrometric Orbit
 Astrometric Planets
 Barycenter
 Beta Pictoris b
 Circumbinary Planet
 Circumprimary Planet
 CoRoT 7b
 Direct-Imaging, Planets
 Eclipse
 ESPRESSO
 Eta-Earth
 Exomoon
 Exoplanet, Detection, and Characterization
 Exoplanets, Discovery
 Fomalhaut b
 Gamma Cephei
 GJ 667C: First System with Multiple Super-Earth
 Candidates in the Habitable Zone
 Habitable Zone Around Binary Star Systems
 Habitable Zone in Binary Stars Systems
 Habitable Zone in Multi-star Systems
 HARPS
 HATNet
 HD 189733b
 HD 209458b
 HIRES
 Hot Jupiters
 Hot Neptunes
 Kepler 11: Multiple Transiting Planet System

Kepler 16b: First Circumbinary Planet
 Kepler 186f: First Earth-Sized Planet in Habitable Zone
 Kepler 47: First Multi-circumbinary Planet System
 Kepler 9: First Transiting System Confirmed by TTV
 Kepler-10
 Kepler-37b: A Moon-Sized Planet
 Kepler-444
 Keplerian Orbits
 LHS-1140b
 Light Travel Time Effect
 MEarth
 Microlensing Follow-Up Network
 Microlensing Observations in Astrophysics
 Mini-Neptunes
 Modelling Terrestrial Planetary Atmospheres
 Ocean Planet
 OGLE-2005-BLG-390Lb
 OGLE-2006-BLG-109Lb,c
 Optical Gravitational Lensing Experiment
 Periastron
 Period
 Phase, Orbital
 Planet Characterization: Emitted and Reflected Light
 Planet Characterization: High-Resolution Spectroscopy
 Planet Characterization: Transmitted
 Planet Detection: Transit Timing Variation
 Planet Detection: Eclipse Timing Variation
 Planets in Binary Star Systems
 Probing Lensing Anomalies Network
 Proxima-b
 Pulsar Planets
 Radial Velocity
 Radial-Velocity Planets
 Ross-128b
 Rossiter-McLaughlin Effect
 SETI
 Spectroscopic Orbit
 SPECULOOS
 Super-Earths
 Transit
 Transiting Planets
 TRAPPIST-1 System
 TrES

Section - Planetary and Exoplanetary Atmospheres: *S. Lebonnois*

Absorption Cross Section
 Adiabatic Processes
 Albedo
 AOGCM
 Atmosphere, Structure
 Atmosphere, Temperature Inversion
 Atmospheric Circulation
 Atmospheric Modeling, Gray Gas Model
 Atmospheric Modeling, Non-gray Gas Model
 Atmospheric Modeling, Radiative-Convective Equilibrium
 Atmospheric Modeling: 1D Model
 Atmospheric Processes, Escape
 Atmospheric Retrieval for Exoplanets
 Biomarkers (Atmosphere)
 Biomarkers Atmospheric, Evolution over Geological Time
 Biomarkers, Spectral
 Climates, Diversity in the Solar System
 Climates, Exoplanets
 Climates, Terrestrial Planets
 Clouds
 CO₂ Ice Clouds (Mars)
 Dust Devils
 Earth-Like Atmosphere
 False Negative
 False Positive
 GCM
 Greenhouse Effect
 Habitability of the Solar System
 Habitability, Effect of Eccentricity
 Habitability, Effects of Stellar Irradiation
 Habitability, Role of the Atmosphere
 Habitable Planet, Characterization
 Habitable Zone
 Habitable Zone, Effect of Tidal Locking
 Hadley Cells
 Latent Heat
 Mesosphere
 Mie Scattering
 Photochemical Hazes
 Radiative Transfer (Atmospheres)
 Raman Scattering
 Rayleigh Scattering

Scale Height
 Stratosphere
 Superrotation
 Synchronous Rotation
 Thermosphere
 Troposphere
 Venus Clouds
 Venus Clouds, Potential for Life

Section - Planetary Surfaces: *J. Helbert*

Albedo Feature
 Amazonian
 Arachnoid
 Catena, Catenae
 Cavus, Cavi
 Chaotic Region
 Chasma, Chasmata
 Chronostratigraphy
 CO₂ Ice Cap (Mars)
 Corona, Coronae
 Crater Lakes (Mars)
 Crater, Impact
 Dark Streaks (Mars)
 Dichotomy, Planetary
 Facula, Faculae
 Fossa, Fossae
 Fumarole
 Gullies
 Hesperian
 Interior Structure, Planetary
 Juno
 Labyrinthus, Labyrinthi
 Lacus
 Landing Site
 Landslide (Mars)
 Lava Tubes
 Lenticula, Lenticulae
 Linea, Lineae
 Lingula, Lingulae
 Macula, Maculae
 Mare, Maria
 Mars Analogues
 Mensa/Mensae
 Meridiani (Mars)
 Mons, Montes

Nitrates on Mars
 Noachian
 Oceanus, Oceani
 Opaline Silica on Mars
 Outflow Channels
 Palus, Paludes
 Patera, Paterae
 Perchlorates on Mars
 Phosphates on Mars
 Phyllosilicates, Extraterrestrial
 Planitia
 Planum
 Polar Caps (Mars)
 Polar Layered Deposits (Mars)
 Regio
 Regolith, Planetary
 Rille
 Rima, Rimae
 Rupes, Rupēs
 Slope Lineae, Recurrent
 Slope Streaks (Mars)
 Solid-State Greenhouse Effect
 Sulcus, Sulci
 Sulfates, Extraterrestrial
 Terra, Terrae
 Tholus
 Vallis, Valles
 Vastitas, Vastitates

Section - Planetary Interiors: *A-C. Plesa*

Core, Planetary
 Differentiation, Planetary
 Heat Flow, Planetary
 Heat Transfer, Planetary
 Impact Basin
 Interior Degassing
 Interior Structure of Low-Mass Exoplanets
 Magma Oceans
 Magnetic Field, Planetary
 Plume
 Primordial Heat
 Radioactive Heating
 Rheology, Planetary Interior
 Stagnant Lid Convection
 Tides, Planetary

Field - Space Sciences: *M. Viso*

Section - Space Missions: *O. Witasse*

Ariel Space Mission
 Beagle 2
 BepiColombo
 Biopan
 Cassini-Huygens Space Mission
 CHEOPS
 COMET (Experiment)
 Comet Interceptor Mission
 CoRoT Satellite
 Deep Impact
 EnVision
 EPOXI Mission
 ERA
 EURECA
 Exobiologie Experiment
 ExoMars
 EXPOSE
 Exposure Facilities
 Foton Capsule, Spacecraft
 FRIPON
 Gaia Mission
 Galileo Mission
 Giotto Spacecraft
 Hayabusa Missions
 Herschel Mission
 Hipparcos
 HOPE Mission
 HST
 Huygens Probe
 Infrared Astronomical Satellite
 Infrared Space Observatory
 Ingenuity
 International Space Station
 Jupiter Icy Moon Explorer Mission
 JWST
 Kepler
 Large Millimeter Telescope
 Long Duration Exposure Facility
 Mars 2020
 Mars Express
 Mars Global Surveyor
 Mars Odyssey

Mars Orbiter Mission
 Mars Pathfinder
 Mars Reconnaissance Orbiter
 Mars Sample Return Mission
 Mars Science Laboratory
 Martian Moon Exploration
 MER, Spirit, and Opportunity (Mars)
 Messenger
 New Horizons
 Odin
 OSIRIS-REx
 Parker Solar Probe
 Perseverance
 Philae Lander
 Phobos-Grunt
 Phoenix
 Pioneer Spacecraft
 PLATO 2.0 Satellite
 Rosetta Spacecraft
 ESA Solar Orbiter Mission
 Spitzer Space Telescope
 Stardust Mission
 Stone
 Submillimeter Wave Astronomy Satellite
 TESS
 Tianwen-1
 TPF/Darwin
 Ulysses Mission
 Vega 1 and 2 Spacecraft
 Venus Express
 Venus Missions (History of)
 Viking
 Voyager, Spacecraft
 WASP
 Yinghuo-1

Section - Planetary Protection: *A. Spry*

Aerobic Mesophilic Bacterial Spore
 Aseptic Process
 Assay
 Biobarrier
 Bioburden
 Bioburden Controlled Environment
 Bioburden Reduction
 Biodiversity (Planetary Protection)

Biological Efficacy
 Biological Indicator
 Biological Safety Level
 Cleanliness
 Cleanroom
 Coleman-Sagan Equation
 Contamination, Probability
 D-Value
 Depyrogenation
 DHMR
 Disinfection
 Encapsulated Bioburden
 Exposed Surface Bioburden
 Hard Landing
 Heat Shock
 HEPA Filters
 Impact, Probability of
 Inactivation
 Mated Bioburden
 Organic Material Inventory
 Outer Space Treaty
 Parametric Release
 Pasteurization
 Perennial Heat Source
 Planetary Protection
 Planetary Protection Category
 Quarantine
 Sample Receiving Facility
 Sample Safety Assessment Protocol
 Special Region (Mars)
 Sporicide
 Sterile
 Sterility Assurance Level
 Sterilization
 Terminal Sterilization
 Z-Value

Section - Ground Facilities: *J-P de Vera, M. Baqué*

ALMA
 Curation Facilities and Sample Receiving Facilities
 Simulation Chambers
 Square Kilometre Array

Field - Earth Sciences: *P. Claeys*

Section - Geology: General Definitions: *D. Pinti*

Accretion
 Alunite
 Amphibolite Facies
 Anorthosite
 Antarctica, Natural Analogue Site
 Askja Caldera, Lunar Natural Analog
 Asthenosphere
 Atacama Desert
 Atacama Desert, Natural Analog
 Barite
 Basalt
 Black Smoker
 Breccia
 Chert
 Chicxulub Crater
 Craton
 Crust
 Cryosphere
 Deccan Trapps
 Degassing
 Deuterium/Hydrogen Ratio
 Diamictite/Diamicton
 Diapirism
 Earth
 Ejecta
 Evaporite
 Fluid Inclusions
 Ga
 Gabbro
 Geological Timescale
 Geotherm
 Geothermal Gradient
 Geothermobarometers
 Geyser
 Glaciation
 Goethite
 Granite
 Graphite
 Greenschist Facies
 Hematite

Hydrosphere
Hydrothermal Alteration
Hydrothermal Environments
Igneous Rock
Impact Melt Rock
Impactite
Iridium
Jaspilite
KT Boundary
Lithosphere, Planetary
Ma
Mafic and Felsic
Magma
Magnetic Anomaly
Magnetite
Mantle
Mantle Plume, Planetary
Mantle Volatiles
Mars Analogue Sites
Mass Extinctions
Metamorphic Rock
Metamorphism
Metasediment
Metasomatism
Mid-Ocean Ridge
Mineral
Moho
Monomictic Breccia
MORB
Mud Volcanism
Natron
Noble Gases
Obduction
Oceans, Chemical Evolution of
Oceanic Crust
Olivine
Ophiolite
Paleomagnetism
Paleosols
Peridotite
Permafrost
Pillow Lava
Plate Tectonics
Plate, Lithospheric
Polymictic Breccia
Pyrite
Quartz
Radiative Forcing

Rock
Sedimentary Rock
Self-Shielding Effects on Isotope Fractionation
Serpentine
Serpentinization
Shale
Shield
Shocked Quartz
Siderite
Silicate Minerals
Soda Lake
Spherules
Stable Isotopes
Stratigraphy
Subduction
Subglacial Environments
Suevite
Sulfate Minerals
Supercontinent
Tektite
Theia
Thermonatrite
Trapps
Trona
True Polar Wander, Theory of
Ultramafic Rocks
Ultrastructure
Uraninite
Volcaniclastic Sediment
Volcano, Planetary
Vostok, Subglacial Lake
Weathering Profile
White Smoker
Yellowstone National Park, Natural Analogue Site
Zircon

Section - Early Earth Geochemistry: ***H. Rizo-Garza***

Absolute and Relative Ages
Boron Isotopes
Bulk Silicate Earth
Carbonation
Cerium, Anomalies of
Chalcophile Elements
Decay Constant

Delta, Isotopic
 Distillation, Rayleigh
 Earth's Atmosphere, Origin and Evolution of
 Earth, Age of
 Extinct Radionuclides
 Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation
 Fractionation, Mass Independent and Dependent
 Geochronology
 Great Oxidation Event
 Hadean Mantle
 Half-Life
 Hydrodynamic Escape
 Hydrogen Isotopes
 Impact Degassing
 Isochron
 Isotope
 Isotopic Fractionation (Planetary Process)
 Isotopic Ratio
 KREEP
 Late Veneer
 Lithophile Elements
 Lomagundi Carbon Isotope Excursion
 Mantle, Oxidation of
 Oxygen Fugacity
 Oxygen Isotopes
 Ozone
 Phosphates
 Platinum Group Elements
 Radioactivity
 Radiogenic Isotopes
 Rare Earth Elements
 Red Beds
 Siderophile Elements
 Water, Delivery to Earth
 Weathering

Section - Traces of Life: *N. McLoughlin*

Acid Maceration
 Acritarch
 Apex Chert, Microfossils
 Archaean Traces of Life
 Barberton Greenstone Belt, Traces of Early Life
 Belcher Group, Microfossils
 Biogenicity
 Biomarkers

Biomarkers, Morphological
 Bioprecipitation
 Biosignatures, Effect of Metamorphism
 Bitumen
 Cap Carbonates
 Carboxylic Acids, Geological Record of
 Dresser Formation, Traces of Life
 Dubiofossil
 Endogenicity
 Eukaryotes, Appearance and Early Evolution of
 Fatty Acids, Geological Record of
 Fossil
 Fossilization, Process of
 Gunflint Formation
 Gunflint Microbiota
 Hopanes, Geological Record of
 Iron Oxides, Hydroxides, and Oxyhydroxides
 Isoprenoids
 Isotope Biosignatures
 Kerogen
 Microbially Induced Sedimentary Structures
 Microfossils
 Microfossils, Analytical Techniques
 Molecular Fossils
 Prokaryotes, Origin of
 Pseudofossil
 Steranes, Rock Record
 Stirling Range Biota
 Stirling Range, Australia
 Strelley Pool Formation
 Stromatolites
 Syngeneticity
 Traces of Life in Basaltic Crust

Section - Hadean-Archean Geology: *H. Martin, P. Claeys, F. Albarede*

Acasta Gneiss
 Adakite
 Akilia
 Amitsoq Gneisses
 Apex Basalt, Australia
 Apex Chert
 Archean Drilling Projects
 Archean Environmental Conditions
 Archean Eon
 Archean Mantle

Archean Tectonics
 Banded Iron Formation
 Barberton Greenstone Belt
 Barberton Greenstone Belt, Sedimentology
 Barberton Supergroup
 Campbellrand-Malmani Platform, South Africa
 Canadian Precambrian Shield
 Continental Crust
 Continents
 Cool Early Earth
 Coonterunah Subgroup, Australia
 Devon Island
 Dharwar Craton
 Dixon Island Formation, Western Australia
 Earth, Formation, and Early Evolution
 Earth, Surface Evolution
 Evaporites, Archean
 Fennoscandia
 Fig Tree Group
 Fortescue Group
 Gondwana
 Greenstone Belt
 Hadean
 Huronian Glaciation
 Isua Supracrustal Belt
 Jack Hills (Yilgarn Craton, Western Australia)
 Kaapvaal Craton, South Africa
 Komatiite
 Laurasia
 Magnetic Pole
 Moodies Group
 Moodies Group, Microbial Mats
 Mount McRae Shale
 North Pole Dome (Pilbara, Western Australia)
 Nuvvuagittuq Greenstone Belt
 Oceans, Origin of
 Onverwacht Group
 Pangea
 Pilbara Craton
 Precambrian
 Precambrian Oceans, Temperature of
 Proterozoic Eon
 Regolith, Terrestrial
 Rodinia
 Sagduction
 Saglek-Hebron Complex (Northern Labrador, Canada)
 Sanukitoid

Snowball Earth
 Tides, Archean
 Tonalite-Trondhjemite-Granodiorite
 Transvaal Supergroup, South Africa
 Tumbiana Formation (Pilbara, Western Australia)
 Turbidite
 Warrawoona Group

Section - Geomicrobiology:

K. Konhauser

Aerobic Respiration
 Alginate
 Amoebae
 Anaerobic Photosynthesis
 Biomineralization
 Biopolymer
 Biostabilization
 Carbon Isotopes in the Solar System
 Chemocline
 Chromium Isotopes
 Copper Isotopes
 Cyanobacteria, Diversity and Evolution of
 Diagenesis
 Exopolymers
 Fungal Weathering
 Iron Isotopes
 Iron Oxidation
 Iron Reduction
 Manganese Oxidation
 Manganese Reduction
 Methane Oxidation
 Methanogenesis
 Microbial Mats
 Mucin
 Nitrate Reduction
 Nitrogen Isotopes
 Nutrient Cycling
 Oxic Sediments
 Oxygen Minimum Zone
 Oxygenation of the Earth's Atmosphere
 Oxygenic Photosynthesis
 Photoferrotrophy
 Phytoplankton
 Redox Zonation
 Rio Tinto
 Shark Bay, Stromatolites of

Silicon Isotopes
 Suboxic
 Suboxic Sediments
 Sulfate Reduction
 Sulfide Oxidation
 Sulfidic Oceans
 Sulfur Isotopes
 Trace Metals
 Zinc Isotopes

Field - Chemistry: *J. Cleaves*

Section - Chemistry: General Definitions: *K. Kobayashi*

Achiral
 Acid Hydrolysis
 Activation Energy
 Active Site
 Activity
 Aerogel
 Affinity Chromatography
 Affinity Constant
 Alcohol
 Aliphatic Hydrocarbon
 Alpha Rays
 Alteration
 Amide
 Amine
 Amorphous Carbon
 Aqueous Alteration
 Arrhenius Plot
 Asymmetric Reaction, Absolute
 ATP
 Automaton, Chemical
 Beta Rays
 Branching Ratio
 Carbon
 Carbonyl
 Carboxylic Acid
 Catalyst
 Chromatographic Coelution
 Chromatography
 Chromophore
 Circular Dichroism
 Clathrate
 Concentration Gradients

Corona Discharge
 Cosmic Rays
 Covalent Bonds
 Cryostat
 D/L-Ratio
 Decarboxylation
 Disproportionation
 Electrophoresis
 Endergonic
 Endothermic
 Enthalpy
 Entropy
 Ester
 Ethane
 Ethanol
 Ether
 Exergonic
 Exothermic
 Extreme Ultraviolet Light
 Fischer Projection
 Fluorescence
 Fluorometry
 Fluorophore
 Fractionation
 Free Energy
 Gamma Rays
 Gas Chromatography
 GC/MS
 Halogen
 Heterocycle
 Homolysis
 HPLC
 Hydrocarbons
 Hydrogen
 Hydrolysis
 Hydrothermal Reaction
 Hydroxy Acid
 Hydroxyl Group
 Ice
 Infrared Spectroscopy
 Ion-Exchange Chromatography
 Ionization Constant
 Isoelectric Point
 Ketose
 Kinetic Isotope Effect
 Liquid Chromatography-Mass Spectrometry
 Liquidus
 Mass Spectrometry

Moiety
Mole
Molecular Weight
Organic Molecule
Organometallic
Oxygen, Atomic
pH
Polarized Electron
Polymer
Precursor
Proton Irradiation
Pyrolysis GC/MS
Quenching
Racemic Mixture
Radiochemistry
Rotatory Power
Sarcosine
Shock Wave
Solidus
Specific Activity
Steric Effect
Sulfur
Supercritical Fluid
Surface Plasmon Resonance
Svedberg Unit
Synchrotron Accelerator
Tautomer
Thermolysis
Thiol
Vacuum Ultraviolet Light
Volatile
Wave Number
Wavelength
Weak Bonds
X-Rays (Organic Synthesis)
XANES
Xanthine
Zwitterion

Section - Prebiotic Chemistry:

R. Saladino

Abiotic Photosynthesis
Abiotic Recombination
Acetaldehyde
Acetic Acid
Acetonitrile

Adenine
Aerosols
Alanine
Aldehyde
Aldose
Amino Acid
Amino Acid N-Carboxy Anhydride
Amino Acid Precursors
Aminobutyric Acid
Aminoisobutyric Acid
Aminomaleonitrile
Aminonitrile
Ammonia
Aqueous Interfaces
Aromatic Hydrocarbon
Atomistic Computer Simulation
Autocatalysis
Biomorphs
Black Smoker, Organic Chemistry
Borate
Bücherer-Bergs Synthesis
Cahn Ingold Prelog Rules
Carbohydrate
Carbon Dioxide
Carbon Monoxide
Carbonaceous Chondrites, Organic Chemistry of
Chemical Gardens
Chirality
Clay
Combustion
Complex Organic Molecules
Cyanamide
Cyanoacetylene
Cyanogen
Cyclic Nucleotide Monophosphate
Cysteine
Cystine
Cytosine
D-Amino Acids
Deamination
Deoxyribose
Derivatization
Deuterium
Diamino Acid
Diaminomaleonitrile
Diastereomers
Dicarboxylic Acid
Diketopiperazine

Dinitrogen	Methionine
Dioxygen	Mildly Reducing Atmosphere
Dissolved Inorganic Carbon Equilibrium	Mineral Vesicles
Electric Discharge	Molecular Beacon
Enantiomeric Excess	Molecular Simulations
Enantiomers	Monosaccharide
Extraterrestrial Delivery of Organic Compounds	Montmorillonite
Fischer-Tropsch-Type Reaction	N-Carbamoyl Amino Acid
Flow Reactor	Neutral Atmosphere
Formaldehyde	Nitrile
Formamido Pyrimidines	Nitrogen
Formic Acid	Nonprotein Amino Acids
Formose Reaction	Nucleic Acid Base
Free Amino Acid	Nucleon
FRET	Nuclide
Furanose	O/OREOS Nanosatellite
Globule, Nanoglobule	Origin of Life
Glutamic Acid	Ornithine
Glutamine	Oxidizing Atmosphere
Glyceraldehyde	PAH Hypothesis
Glycerol	Phase Transition
Glycine	Phenylalanine
Glycolic Acid	Phosphine
Guanine	Phosphite
Hapten	Phosphoric Acid
HCN Polymer	Photochemistry, Atmospheric
HCNO Isomers	PIXE
Heavy Atom Beams	Polarized Light and Homochirality
Hexamethylenetetramine	Polyoxymethylene
Histidine	Postimpact Plume
Hydantoin	Prebiotic Chemistry
Hydrogen Cyanide	Prebiotic Phosphorylation
Hydrogen Sulfide	Primordial Soup
Hypoxanthine	Proline
Insoluble Organic Matter	Propionaldehyde
Isoleucine	Purine Bases
Isomer	PVED
Isotopomer	Pyranose
Isovaline	Pyrimidine Base
Kaolinite	Pyrolysis
L-Amino Acids	Pyrophosphate
Lactic Acid	Pyruvate
Leucine	Quencher
Lysine	Racemization
Melanins	Radiation Pressure
Metabolism, Prebiotic	Raman Spectroscopy
Methane	Redox Potential
Methanol	Refractory Organic Polymer

Ribose
Rice-Ramsperger-Kassel-Marcus
Selenocysteine
Serine
Spark Discharge
Stereochemistry
Stereoisomers
Strecker Synthesis
Sublimation
Substrate
Succinic Acid
Systems Chemistry
Thiocyanate
Thioester
Tholins
Threonine
Thymine (T)
Trace Elements
Triple Point
Tryptophan
Tyrosine
Uracil (Ura)
Urea
Valine
Van der Waals Forces
Water

**Section - Origins of Life: R. Saladino,
J. Pereto**

Activated Nucleotide
Alpha Helix
Amphiphile
Amphiphilicity
Amphoteric Compounds
Arginine
Asparagine
Aspartic Acid
Atmosphere, Organic Synthesis
Cell Models
Chicken or Egg Problem
Combinatorial Library
Composomes
Denaturation
Disulfide Bond
DNA
Double Helix

Dynamic Kinetic Stability
Endogenous Synthesis
Evolution, Chemical
Genetic Code
Heme
Heterotrophic Hypothesis
Homochirality
Hoogsteen Pair
Hydrogen Bond
Hydrophobic Effect
Hydrophobicity
Hydrothermal Vent Origin of Life Models
Hypercycle
Ligand
Ligase
Lipid Bilayer
Membrane Potential
Micelle
Molecular Recognition
mRNA Display
Nucleic Acids
Nucleoside
Nucleoside Phosphoimidazolidine
Nucleotide
Oligomer
Oligomerization
Oligonucleotide
Oligopeptide
Organic Dust, Influence on the Origin of Life
p-RNA
Permeability
PNA
Polynucleotide
Polypeptide
Polysaccharide
Porphyrin
Protein
Proteinoid Microsphere
Proteins, Primary Structure
Proteins, Quaternary Structure
Proteins, Secondary Structure
Proteins, Tertiary Structure
Protocell
Ribonucleoside
Ribonucleotide
Ribozyme
RNA
RNA Ligase

RNA Replicase Ribozyme
 RNA World
 Self-Assembly, Biological
 Self-Replication, Chemical
 Template-Directed Polymerization
 Transferase
 Vesicle
 Water, Solvent of Life
 Watson-Crick Pairing
 Wobble Pair

Section - Artificial Life: *K. Adamala*

Artificial Cell Division
 Artificial Chemistries
 Artificial Life
 Artificial Organelles
 Biological Networks
 Cellular Automata
 Chemical Reaction Network
 Code
 Complexity
 Evolution, Molecular
 Scale-Free Networks
 Self-Replication
 Self-Assembly
 Synthetic and Hybrid Tissues
 Synthetic Biology

Field - Life Sciences: *R. Amils*

Section - Extremophiles: *R. Amils*

Alkaliphile
 Anoxic
 Antibiotic
 Archaea
 Asgard, Archaea
 Bacteria
 Bacteriorhodopsin
 Biogeochemical Cycles
 Biosensor
 Biosphere
 Biotope
 Carboxysomes, Structure and Function
 Chaotropicity

Chemoautotroph
 Chemolithoautotroph
 Chemolithotroph
 Chemoorganotroph
 Chemotaxis
 Chemotroph
 Chloroplast
 Compatible Solute
 Crenarchaeota
 Dark Biosphere
 Denitrification
 DPANN, Archaea
 Eukarya
 Euryarchaeota
 Fungi
 Gaia Hypothesis
 Genus
 Geomicrobiology
 Glove Box
 Gram-Negative Bacteria
 Gram-Positive Bacteria
 Green Bacteria
 Hydrogenosomes
 Iron
 Iron Cycle
 Korarchaeota
 Lithotroph
 Macronutrient
 Margulis, Lynn
 Membrane
 Methanogens
 Methanotroph
 Micronutrients
 Motility
 Multicellular Organisms
 Nanoarchaeota
 Nucleoid
 Osmotic Pressure
 Outer Membrane
 Oxidic
 Peroxisome
 Photoautotroph
 Pili
 Planetary Ecosynthesis
 Ploidy
 Prokaryote
 Protists
 Protoplast

Quorum Sensing
Species
Species (Prokaryote)
TACK, Archaea
Taq Polymerase
Taxonomy
Transport, Biological
Ultrasmall Bacteria, CPR, and Patescibacteria
Unicellular Organisms
Water Activity
Xerophile

Section - General Biology: *F. Gomez*

Abiotic
Acidophile
Aerobe
Algae
Anaerobe
Biofilm
Carbon Cycle, Biological
Carbon Source
Cell
Cell Wall
Colonization, Biological
Cryptoendolithic
Cyanobacteria
Deep Biosphere
Deep-Sea Microbiology
Deep Subsurface Microbiology
Dormant State
Ecological Niche
Ecosystem
Endogenous
Endolithic
Energy Sources
Environment
Europa Analogues
Exogenous
Extreme Environment
Extremophiles
Habitat
Halophile
Halotolerance
Heterotroph
Homeostasis
Hot Spring Microbiology

Hot Vent Microbiology
Hypersaline Environment
Hyperthermophile
Intelligence
Intelligence, Evolution of
Magnetosome
Magnetotactic Bacteria
Mesophile
Metabolic Diversity
Microorganism
Nitrification
Nucleus
Organelle
Osmolite
Oxidation
Oxygenase
Peptidoglycan
Periplasm
Piezophile
Plankton
Proteobacteria
Proton Motive Force
Proton Pump
Psychrophile
Reducing Agent
Reduction
Sulfate Reducers
Sulfur Cycle
Symbiosis
Terrestrial Analog
Thermophile
Yeast

Section - Genetics and Evolution: *C. Briones*

Adaptation
Amplification (Genetics)
Aptamer
Aptasensor
Biodiversity
Bioinformatics
Cell Membrane
Cenancestor
Combinatorial Nucleic Acid Library
Common Ancestor
Conjugation

CRISPR
 DNA Sequencing
 Domain (Taxonomy)
 Endosymbiosis
 Error Rate
 Evolution, Biological
 Evolution, In Vitro
 Fidelity
 Fitness
 Gene
 Gene Expression
 Genetic Map
 Genetics
 Genome
 Genome Editing
 Genomics
 Genotype
 Homology
 Hybridization
 Last Universal Common Ancestor
 Lateral Gene Transfer
 Metagenome
 Metatranscriptome
 Metavirome
 Molecular Clock
 Monophyletic
 Mutagen
 Mutagenesis
 Mutant
 Mutation
 Natural Selection
 Operon
 Orthologous Gene
 Paralogous Gene
 Phenetics
 Phenotype
 Phylogenetic Tree
 Phylogeny
 Phylotype
 Phylum
 Plasmid
 Polymerase Chain Reaction
 Proteome, Proteomics
 Quasispecies
 Recombination
 Replication (Genetics)
 Ribosome
 Selection
 Sequence

Sequence Analysis
 Splicing
 Systems Biology
 Template
 Virion
 Viroid
 Virology
 Virus

Section - Biochemistry: *J Pereto*

Anabolism
 Anaerobic Respiration
 Anoxygenic Photosynthesis
 Antibody
 Anticodon
 Assimilative Metabolism
 ATP Synthase
 ATPase
 Autopoiesis
 Autotroph
 Autotrophy
 Bacteriochlorophyll
 Base Pair
 Bioenergetics
 Buffer
 Calvin-Benson Cycle
 Catabolism
 Cell, Minimal
 Chlorophylls
 Chromosome
 Citric Acid Cycle
 Cloning
 Codon
 Coenzyme
 Cofactor
 Cytochromes
 Cytoplasm
 Diazotrophy
 Dissimilative Metabolism
 DNA Polymerase
 Electrochemical Potential
 Electron Acceptor
 Electron Carrier
 Electron Donor
 Electron Transport
 Embden-Meyerhof-Parnas Pathway
 Energy

Energy Conservation
 Entner-Doudoroff Pathway
 Enzyme
 Exon
 Fermentation
 Genome, Minimal
 Gluconeogenesis
 Glycolysis
 Intron
 Life
 Metabolism
 Metabolism, Secondary
 Mitochondrion
 NADH, NADPH
 Nitrogen Cycle, Biological
 Nitrogen Fixation
 Photosynthesis
 Photosynthetic Pigments
 Phototroph
 Primer
 Prion
 Respiration
 Restriction Enzyme
 RNA Polymerase
 Rubisco
 Transcription
 Transduction
 Transformation
 Translation
 Wobble Hypothesis (Genetics)

Section - Earth Analogues Field Sites: *F. Gomez*

Dallol Geothermal System
 Devon Island's Houghton Impact Structure
 Ibn Battuta Desert
 Sudbury Impact Structure
 Tirez Lagoon System

Section - Microbiology in Space: *K. Beblo-Varnesevic*

Aerobiology
 Apollo Mission
 Arrhenius Svante

Biostack
 Cosmic Rays in the Heliosphere
 Desiccation
 DNA Damage
 DNA Repair
 Endospore
 Epilithic
 Gravitational Biology
 Hypolithic
 HZE Particle
 Ionizing Radiation, Biological Effects
 Lichens
 Life Support Systems
 Linear Energy Transfer
 Lithopanspermia
 MEED
 Microbiome of the International Space Station
 Microgravity
 'Omics Technologies
 Ozone Layer
 Photobiology
 Planetary and Space Simulation Facilities
 Radiation Biology
 Radiation Dose
 Solar Particle Events
 Solar UV Radiation, Biological Effects
 Space Biology
 Space Environment
 Space Vacuum Effects
 Spallation Zone
 Spore
 Sporulation
 Stratosphere Biology
 Survival
 UV Climate
 UV Radiation Dose
 UV Radiation, Biological Effects

Field - History and Philosophy of Astrobiology: *S. Tirard*

Section - History: From Antiquity to 1800: *D. Duner*

Al-Andalus, Cosmological Ideas
 al-Bīrūnī, Abū Rayḥān
 al-Tūsī, Nasir al-Dīn

Anaximander
 Animalcules
 Bruno, Giordano
 Buffon's Conception of Origins of Life
 Cassini, Giovanni Domenico
 Copernican Principle
 Cosmogony: Greece
 Cosmogony: Mesopotamia
 Cosmogony: Rome
 Cosmology: Native American
 De Maillet's Conception of Origins of Life
 Diderot's Conception of Origins of Life
 Evolution of Species, Islamic Ideas
 Fossils (from Antiquity to the Eighteenth Century)
 Galilean Satellites
 Geocentric Worldview
 Great Chain of Being
 Heliocentric Worldview
 Ikhwan al-Safa
 Imaginary Voyages (from Antiquity to the Eighteenth Century)
 Kant-Laplace Nebular Hypothesis
 Kepler, Johannes
 Leeuwenhoek, Antony van
 Life, Concept of (from Antiquity to the Eighteenth Century)
 Lucretius
 Planetary Theories and Cosmology, Islamic Theories
 Principle of Plenitude

Section - History: From 1800 to Present: **S. Tirard**

Abiogenesis
 Astrobiology
 Baly's Experiment
 Bathybius Haeckelii
 Bernal's Conception of Origins of Life
 Calvin's Conception of Origins of Life
 Cellular Theory, History of
 Coevolution
 Comets, History of
 Cosmic Background Radiation

Cuvier's Conception of Origins of Life
 Darwin's Conception of the Origins of Life
 De Duve, Christian
 Dirac, Paul
 Earth's Atmosphere, History of the Origins
 Ecology, History of
 Enzymology, History of
 Evo-devo
 Fermi, Enrico
 Gene, Selfish
 Genetics, History of
 Geological Time Scale, History of
 Goldschmidt, Viktor Moritz
 Haeckel's Conception of Origins of Life
 Haldane's Conception of Origins of Life
 Halley, Edmond
 Herschel, William
 Hoyle, Fred
 Hubble, Edwin
 Huxley's Conception on Origins of Life
 Lamarck's Conception of Origins of Life
 Lemaître's Theory of Expanding Universe (History)
 Life in the Solar System (History)
 Louis Pasteur
 Lowell, Percival
 Meteorites, History of
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CNSA, China
 CONAE, Argentina
 COSPAR
 COST
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 DLR, Germany
 DTU Space, Denmark
 EANA
 ECSS
 ESTEC
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 European Space Agency
 Geobiology Society
 IAC, Colombia
 IAF
 IAU
 IKI
 ISO (Normative Organization)
 ISRO, India
 ISSI
 ISSOL
 Italian Society of Astrobiology
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 JABC, Japan
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 Socioeconomic Benefits of Space

Field - Institutions and Organizations:

W. Irvine

Section - Institutions and Organizations: W. Irvine

AbGradE
 AEB, Brazil
 ASA, Austria
 ASI
 ASPAST, Peru
 Astrobiology (IAU Commission)
 Astrobiology Society of Britain
 Australian Centre for Astrobiology
 Bioastronomy
 BNSC
 CAB, Spain
 CAN, Canada
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 Chemical and Biological Data
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 General Data
 Geological Data

A

51 Pegasi B

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Radial-velocity planet · Exoplanet · Hot Jupiters

Definition

51 Pegasi b is an extrasolar planet orbiting the solar-type star 51 Pegasi.

History

51 Pegasi b is the first Jupiter-type planet, with a minimum mass slightly smaller than half of that of Jupiter, discovered around a sunlike star. It was detected by ► [radial-velocity](#) observations obtained with the Elodie ► [spectrometer](#) on the 1.93-m telescope at the Observatoire de Haute Provence in France (Mayor and Queloz 1995). The extraordinarily short ► [period](#) of 4.230785 ± 0.000036 days was completely unexpected for a planet with a mass close to that of

Jupiter and led to some initial skepticism that the unseen companion of 51 Pegasi could be a gas ► [giant planet](#) (e.g., Gray 1997). However, the subsequent announcement of several other ► [radial-velocity planet](#) candidates soon convinced most people of the reality of ► [extrasolar planets](#). This historic discovery and the subsequent emergence of the vibrant field of exoplanetology allowed Michel Mayor and Didier Queloz to receive the Nobel Prize of Physics in 2019.

Overview

51 Pegasi is classified as a G dwarf similar to the Sun but slightly cooler, at a distance of 15.6 parsecs (50.9 light years). A periodic variation in the ► [radial velocity](#) of the star indicates an unseen companion with minimum mass of 0.472 ± 0.039 Jupiter masses, if the orbit is viewed edge-on, but the actual orbital inclination is not well established. The ► [orbit](#) is nearly circular, with an ► [eccentricity](#) of 0.013 ± 0.012 , presumably the result of circularization by tidal forces. The proximity of the planet to its star, 20 times closer than the Earth to the Sun, implies a temperature on the order of 1200 K. 51 Pegasi b is the prototype for a population of ► [hot Jupiters](#) that probably formed much farther from their parent stars, where conditions were cool enough for a gas giant planet

to form, followed by migration into a much tighter orbit around the host star.

Cross-References

- [Dwarf Star](#)
- [Eccentricity](#)
- [Extrasolar Planets](#)
- [Giant Planets](#)
- [Hot Jupiters](#)
- [Inclination \(Astronomy\)](#)
- [Planetary Migration](#)
- [Radial-Velocity Planets](#)

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55 Cancri

Brice-Olivier Demory
 Centre for Space and Habitability, University of
 Bern, Bern, Switzerland

Keywords

Transits · Radial-velocity · Exoplanet systems

Synonyms

[Brahe \(55 Cancri c\)](#); [Galileo \(55 Cancri b\)](#); [Harriot \(55 Cancri f\)](#); [Janssen \(55 Cancri e\)](#); [Lipperhey \(55 Cancri d\)](#)

Definition

55 Cancri is a bright ($V = 5.95$), nearby ($D = 12.3$ pc) G8V star part of a resolved binary system with a mid M-dwarf companion located at a projected separation of 1062 AU. Five exoplanets orbiting 55 Cancri are currently known. The properties of the planets in the 55 Cancri system are very diverse, with masses ranging between 8 Earth masses and 3 Jupiter masses and orbital periods as

short as 18 h and as long as 15 years. While all five planets have been discovered using the radial-velocity technique, the innermost one (55 Cancri e) has been found to transit its host star, providing additional insights into the nature of this extreme super-Earth.

History

The first exoplanet discovered in the system was 55 Cancri b (Butler et al. 1997), a Jupiter-mass companion on a 15-day orbit, which was published 2 years after the announcement of the first exoplanet orbiting a sun-like star (51 Pegasi b). Two more, longer-period planets orbiting 55 Cancri (c and d) were announced shortly thereafter (Marcy 2002). The discovery of the once smallest known exoplanet at the time, 55 Cancri e, was published by McArthur (2004), which rendered 55 Cancri the most populated planetary system at the time. With a published orbital period of 2.8 days and a minimum mass of 14 Earth masses, the discovery of 55 Cancri e prompted independent analyses of the radial-velocity dataset on which the announcement was based. In 2005, Wisdom found evidence for a Neptune-mass planet on a 260-day orbital period but also questioned whether the 2.8-day signal of 55 Cancri e could be an alias of the 44-day planet c. Fischer (2008) confirmed both the presence of a planet at 260 days (55 Cancri f) and the 2.8-day period of 55 Cancri e. Two years later, Dawson and Fabrycky (2010) found that the 2.8-day periodicity signal was in fact an alias of a significantly shorter 18-h (0.74 days) orbital period companion with a minimum mass of 8.2 Earth masses. A confirmation of this late reanalysis came a few months afterward with the transit discovery of 55 Cancri e (Winn 2011; Demory 2011), which eventually resulted in a refined radius of $1.88 \pm 0.03 R_{\text{Earth}}$ and a density of $6.7 \pm 0.4 \text{ g/cm}^3$ (Bourrier 2018).

Overview

The super-Earth 55 Cancri e has attracted considerable attention compared to the other planets of

the system because of several striking characteristics. First, it is one of the largest and most-massive exoplanets with orbital periods less than 1 day (Sanchis-Ojeda et al. 2014). Second, 55 Cancri e is located right at the upper edge of the so-called “radius valley” (Owen and Wu 2013; Fulton 2017) that separates super-Earths with negligible atmospheres to those with massive H/He envelopes. Therefore the innermost planet of the 55 Cancri system is key in better understanding the formation and evolution pathways of small close-in exoplanets through constraints on its bulk structure and atmospheric properties.

Thanks to the brightness of its host star, multiple observations of 55 Cancri e have been gathered from the extreme UV to the mid-infrared in the past decade. Despite these efforts, the nature of this super-Earth has not been entirely elucidated yet. Among the most notable conundra lie the interannual observations obtained with the MOST satellite in the visible, which have revealed a large amplitude modulation (Sulis 2019) phased on 55 Cancri e’s orbital period that is an order of magnitude larger than expected from the planet’s elevated dayside temperature (~2400 K). Another surprising observation is the variability of 55 Cancri e’s occultation signal measured by the Spitzer Space Telescope in the infrared (Demory et al. 2016a; Tamburo et al. 2018). The planetary thermal phase-curve obtained with the same facility (Demory et al. 2016b) revealed an Eastward offset suggestive of a significant atmosphere (Angelo and Hu 2017; Hammond and Pierrehumbert 2017). High-resolution spectroscopy observations of 55 Cancri e have shown tentative detection of neutral Sodium and singly ionized calcium lines, which may be the signpost of an exosphere. Ultraviolet observations gathered with the Hubble Space Telescope have further shown variability in several emission lines, possibly resulting from interactions between 55 Cancri e and the stellar corona (Bourrier 2018).

It has recently been shown that 55 Cancri e was orbiting inside the Alfvén surface of the host star stellar wind (Folsom 2020), which motivates a better accounting of potential star-planet interactions in the system. An ongoing monitoring of 55 Cancri with the CHEOPS satellite (Benz 2020) should soon reveal the

extent of the phase modulation variability observed in the visible and, hopefully, pinpoint its origin and unveil the nature of the enigmatic 55 Cancri e.

Cross-References

- CHEOPS
- Eclipse
- Exoplanet, Detection, and Characterization
- HARPS
- HIRES
- Hubble Space Telescope
- Planet Characterization: Emitted and Reflected Light
- Planet Characterization: High-Resolution Spectroscopy
- Radial-Velocity Planets
- Spitzer Space Telescope
- Super-Earths
- Transiting Planets

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67P

- [67P/Churyumov–Gerasimenko](#)

AAN

- [Aminoacetonitrile \(NH₂CH₂CN\)](#)

Ab Initio = First-Principles

- [Atomistic Computer Simulation](#)

AbGradE

William M. Irvine

Department of Astronomy, University of Massachusetts Amherst, Amherst, MA, USA

Synonyms

[Astrobiology Graduates in Europe](#)

Definition

AbGradE is an independent association, initiated by the European Astrobiology Network Association (EANA), which promotes scientific networking primarily among PhD students and postdoctoral researchers in Europe. A principal activity of AbGradE is organizing biennial symposia in astrobiology, with the first symposium taking place in Edinburgh in 2014 and the second in Athens in 2016. In the intervening years, 1 day workshops are organized, for example, on “mission proposal writing” in 2015 at the European Space Research and Technology Centre (ESTEC) in the Netherlands.

Cross-References

- [EANA](#)
- [ESTEC](#)

Abiogenesis

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, BPNantes, France

Definition

Thomas Huxley (1825–1895) used the term *abiogenesis* in an important text published in 1870. He strictly made the difference between spontaneous generation, which he did not accept, and the

possibility of the evolution of matter from inert to living, without any influence of life.

Since the end of the nineteenth century, *evolutive abiogenesis* means increasing complexity and evolution of matter from inert to living state in the abiotic context of evolution of primitive Earth.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [Huxley's Conception on Origins of Life](#)
- [Origin of Life](#)

Abiogenic Photosynthesis

- [Abiotic Photosynthesis](#)

Abiotic

David C. Fernandez-Remolar
State Key Laboratory of Lunar and Planetary
Sciences, Macau University of Science and
Technology, Taipa, China
CNSA Macau Center for Space Exploration and
Science, Macau, PR China

Definition

Abiotic refers to the ongoing physical and chemical processes in natural environments driven by different mechanisms that deviate from any biological activity. Although primary physical and chemical cycles on Earth can hardly escape the activity of the biosphere, some processes do not depend on biological activities. For example, this is the case of hydrothermal deposits resulting from reactions equilibrated at high temperature and driven by the circulation of hot fluids commonly through a silica-rich host rock. Under those conditions, the redox, volatile fugacity, and mineral saturation are fully conducted by physical and chemical processes that are independent of the biological processes. Interestingly, while the

hydrothermal processes are mostly unbound from the biological activity, they can produce organic compounds (McCollom and Seewald 2007) or replicate chemical reactions that are mimicked some way by some metabolic pathways (Huber and Wächtershäuser 1997). In analogous conditions, different organics could also be produced through the impact of large planetary impact of chondritic bodies on the Early Earth oceanic masses (rc). Therefore, some abiotic pathways have likely been essential to originate the primary biochemical materials and pathways that might have driven the emergence of life on Earth. Some abiotic processes are involved in producing surface oxidants through photochemical reactions in planet atmospheres, as proposed to explain the presence of different inorganic compounds on Mars like sulfates and perchlorates (Catling et al. 2010; Hurowitz et al. 2010). Those processes could be also associated with the production of different organic compounds showing a high oxidation degree like oxalates (Cheng et al. 2016). Furthermore, the detection of different organics in different planetary surfaces strongly support that they are actively produced or have been produced through abiotic processes in far different planetary bodies of the Solar System (e.g., Mars, Titan, Enceladus, etc.) since its formation (Eigenbrode et al. 2018; Waite et al. 2005). Different abiotic pathways (thermal, radiolytic, or photochemical) are essential to promote the emergence of a chemical disequilibrium and production of essential chemicals for life to transform a given area of the Universe into potentially habitable.

Cross-References

- [Hydrothermal Environments](#)
- [Origin of Life](#)
- [Photochemistry](#)
- [Prebiotic Chemistry](#)

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Abiotic Phosphorylation

► Prebiotic Phosphorylation

Abiotic Photosynthesis

Armen Y. Mulikidjanian
School of Physics, University of Osnabrueck,
Osnabrueck, Germany
Moscow State University, Moscow, Russia

Keywords

Bacterial photosynthesis · Carbon fixation · Photochemistry · Semiconductors · Anoxic geothermal fields

Synonyms

Abiogenic photosynthesis; Prebiotic photosynthesis

Definition

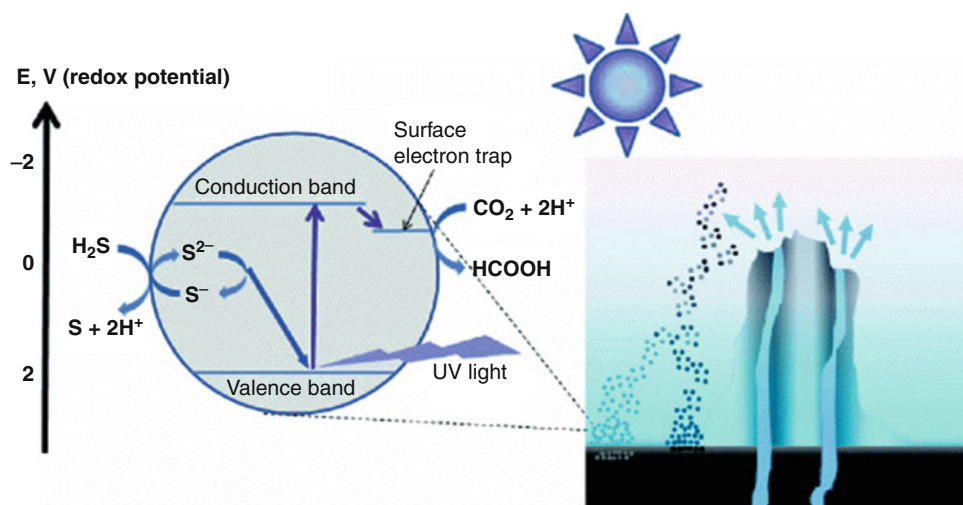
Abiotic or abiogenic photosynthesis is the synthesis of organic compounds with the aid of radiant energy and various inorganic or organic catalysts.

History

In September 1912, Benjamin Moore suggested at a discussion on the origin of life, held by the joint sections of Zoology and Physiology of the British Association for the Advancement of Science, that “the first step towards the origin of life must have been the synthesis of organic matter from inorganic by the agency of inorganic colloids acting as transformers or catalysts for radiant solar energy” (Moore and Webster 1913).

Overview

In spite of Haldane’s well-known idea that UV light may have served as a driving force for formation of the first viruslike organisms (Haldane 1929), the idea of directly driving abiogenesis by solar energy had not won much support at that time, despite the fact that the Sun is by far the most powerful energy source on Earth. The limited acceptance of the idea was partly due to the low quantum yield of abiotic photosynthetic reactions and the poor reproducibility of experimental results. Abiotic photoproduction of hydrogen, in the presence of ions of divalent iron, has been observed (Mauzerall et al. 1993). It has been shown atmospheric photochemistry can produce aldehydes from CO (Bar-Nun and Chang 1983). Only in the 1980s, were robust procedures of producing colloidal nanoparticles of photoactive semiconductors, such as zinc sulfide (ZnS) or cadmium sulfide (CdS), developed (Henglein 1984). These particles (see Fig. 1), due to their



A

Abiotic Photosynthesis, Fig. 1 Abiogenic photosynthesis on the primordial Earth. *Left panel:* light-induced reactions in a ZnS particle combined with an energy diagram. The absorption of a UV quantum by a minute crystal of ZnS, an *n*-type semiconductor, leads to the separation of electric charges and to the transition of the excited electrons into the conducting zone. The electrons can migrate inside the crystal until they are trapped at the surface,

where they can be picked up by appropriate acceptors, e.g., molecules of CO_2 . The residual electron vacancies (holes) are initially reduced by the S^{2-} ions of the crystal, which then eventually can be replenished by external electron donors, e.g., H_2S (cf with the mechanism of anoxygenic photosynthesis). *Right panel:* the precipitation of ZnS particles (gray dots) around a Hadean continental hot spring (Figure from Mulkidjanian 2009)

high surface-to-volume ratio, provided experimental systems in which the photoreduction of CO_2 to diverse organic compounds could be studied. The photoreduction proceeded with high and reproducible quantum yield (up to 80% for CO_2 reduction to formate at the surface of colloidal ZnS particles (Henglein 1984)). Recent studies have demonstrated high-yielding ZnS- and MnS-mediated photosynthesis under simulated primeval conditions (Zhang et al. 2004, 2007; Guzman and Martin 2009). In the modern oceans, ZnS and MnS are found at the sites of geothermal activity, where minute particles of these minerals continuously precipitate around hot, deep-sea hydrothermal vents; thereby, particles of ZnS and MnS, slowly precipitating sulfides, make rings around black throats of such vents that are covered by promptly precipitated particles of FeS (Tivey 2007). On the primordial Earth, hot metal-enriched geothermal fluids and vapor may have discharged to the surface of the first continents, so that particles of ZnS and MnS could have precipitated within regions exposed to solar radiation (Mulkidjanian 2009). These sulfide minerals could have been

present in shallow waters (Guzman and Martin 2009) and should have precipitated around continental thermal springs (Mulkidjanian 2009). Since Zn^{2+} ions are much more volatile than Fe^{2+} ions, the vapor of continental geothermal systems would be particularly enriched in ZnS (Mulkidjanian et al. 2012). On the primordial Earth, ZnS could not be oxidized by atmospheric oxygen, so that photosynthesizing and habitable rings may have persisted around terrestrial thermal springs and fumaroles. The development of the first life forms within photosynthesizing, ZnS-containing precipitates at such anoxic geothermal fields, where Zn^{2+} ions would be continuously released as by-products of abiogenic photosynthesis, might explain cellular enrichments in Zn^{2+} , the equilibrium concentration of which in the primordial ocean should have been extremely low (Mulkidjanian and Galperin 2009; Mulkidjanian et al. 2012). Several proteins shared by all extant organisms and believed to form the core of the last universal common ancestor (LUCA) are particularly enriched in Zn and Mn; this may also support the notion of a role for

abiogenic photosynthesis in the earliest stages of evolution (Mulkey and Galperin 2009; Mulkey et al. 2012). Since these ubiquitous proteins are depleted in iron, it remains to be established whether and to what extent iron (II), the predominant transition metal in geothermal exhalations, was involved in abiogenic photosynthesis. It has also been shown that titanium dioxide particles can drive photosynthetic organic chemistry inside cell membrane-like vesicles (Summers et al. 2009). Titanium dioxide (both rutile and anatase) particles could have been formed by precipitation or released (directly or from alteration of other titanium minerals) by weathering. This energy transduction could have provided pathways to new compounds in a prebiotic system or support early biochemical reactions.

Cross-References

- ▶ [Anoxygenic Photosynthesis](#)
- ▶ [Black Smoker](#)
- ▶ [Carbon Dioxide](#)
- ▶ [Charge Transfer](#)
- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Electron Acceptor](#)
- ▶ [Electron Donor](#)
- ▶ [Energy Sources](#)
- ▶ [Extreme Ultraviolet Light](#)
- ▶ [Formic Acid](#)
- ▶ [Haldane's Conception of Origins of Life](#)
- ▶ [Hot Spring Microbiology](#)
- ▶ [Hydrothermal Vent Origin of Life Models](#)
- ▶ [Iron](#)
- ▶ [LUCA](#)
- ▶ [Origin of Life](#)
- ▶ [Photochemistry](#)
- ▶ [Photosynthesis](#)
- ▶ [UV Radiation](#)
- ▶ [White Smoker](#)

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Abiotic Recombination

Giovanna Costanzo
Institute of Molecular Biology and Pathology
(IBPM)- National Research Council (CNR),
Rome, Italy

Keywords

RNA · RNA origin · RNA world · Ribozymes · Origin of life

Synonyms

Non-enzymatic rearrangement; Primitive RNA catalysis; Self-catalytic activity

Definition

The RNA world hypothesis (Gilbert 1986) states that systems based on an RNA genome and RNA catalysts preceded current forms of life and several model systems have been described for auto-replication (Cech 1986; Meyer et al. 2012) and metabolism (Nissen et al. 2000). According to this model, long catalytically active RNA molecules (*ribozymes*) had to evolve from short RNA fragments through the reactions of cleavage and/or intermolecular ligation (named collectively “recombination”). Both reactions involve transesterification, which implies the involvement of 2'-OH group of ribose in the cleavage site for the ester bond transfer. This is the main reason for most likely participation of RNA rather than DNA in evolution under prebiotic conditions.

History (Optional)

RNA nonenzymatic recombination reactions are of great interest within the hypothesis of the “RNA world” (Gilbert 1986) which argues that, at some stage of prebiotic life development, proteins were not yet engaged in biochemical reactions and RNA carried out both the information storage task and the full range of catalytic roles necessary in primitive self-replicating systems. In the same year of the pivotal paper of Gilbert, Cech (1986) described an RNA enzyme able to convert pentacytidylic acid (pC₅) to poly(C) with multiple turnover, using the same recombination activity that it employs in the self-splicing and autocyclization reactions (Kruger et al. 1982). This RNA enzyme or *ribozyme* acts as a poly(C)polymerase, synthesizing RNA in a 5'-to-3' direction. Using the method known as in vitro selection (Tuerk and Gold 1990; Ellington and Szostak 1990) more than a dozen research groups

have demonstrated that ribozymes have the potential to catalyze the diverse chemical reactions required to sustain a metabolism, reactions that include RNA ligation, peptide coupling, Diels-Alder bond formation, redox reactions, decarboxylation, and transphosphorylation (reviewed in Chen et al. 2007). With the advancement of knowledge in nonenzymatic oligomerization (Lohrmann et al. 1980), recombination, the swapping of large blocks of polymeric information through near energy-neutral reactions, offered a facile means to accomplish a supply of polymers long enough to possess phenotypic function and diverse enough to provide raw material for natural Darwinian selection (Riley and Lehman 2003).

Overview

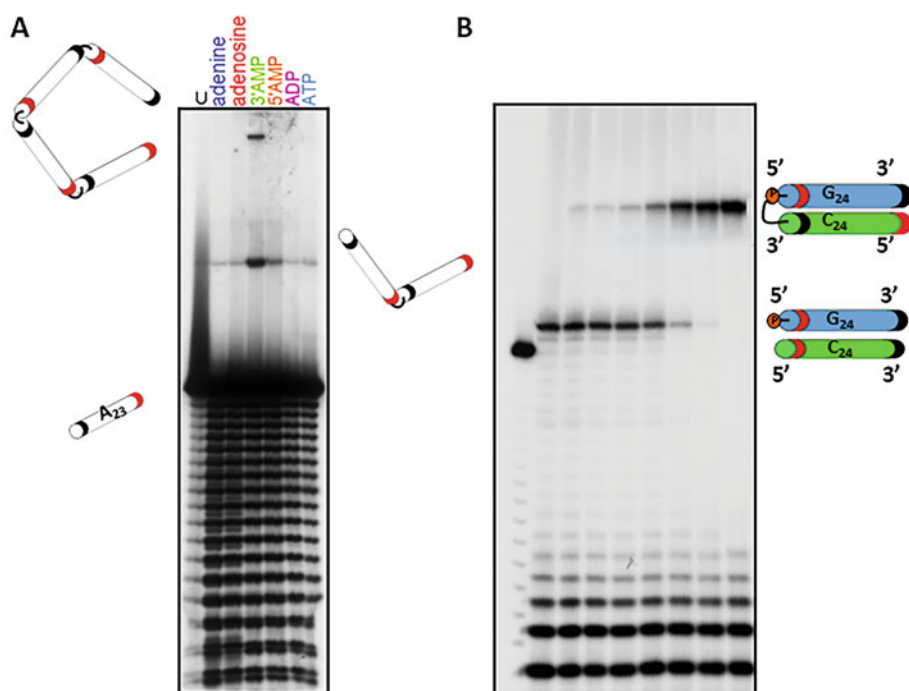
The origin of life journey may have started with chemical replication of simple linear polymers. Molecular variants capable of faster replication would come to dominate a population, and the development of cycles in which templates could foster one another's replication would have led to increasingly complex replicators and from thence to the initial genomes. The appearance of long RNA molecules under prebiotic conditions is not self-evident. Recombination seems to be a plausible way of creating RNA diversity, resulting in the appearance of functional RNAs, capable of self-replication. The nonenzymatic polymerization process, studied for decades (Yadav et al. 2020), seems to be slow, so that an equilibrium between synthesis and degradation of the polymer would rapidly be reached, preventing the accumulation of sufficiently long (pre)genetically meaningful information. Polymer elongation by successive condensation steps adding one monomer at the time is not a likely mechanism for the accumulation of (pre) genetic information. A series of studies published by Lehman's group revealed fascinating phenomena of RNA recombination. They demonstrated that four special RNA fragments of 40–60 nucleotides can self-assemble with the formation of the *Azoarcus* intron I, the latter, in

turn, catalyzes RNA oligonucleotide recombination (Riley and Lehman 2003; Hayden et al. 2005). Moreover, motivated by the discovery that RNA oligomers stored for long periods of time in the freezer expand their lengths, they systematically investigated RNA–RNA recombination processes and discovered at least three new mechanisms. In these, one RNA oligomer acts as a splint to catalyze the hybridization of two other oligomers and facilitates the attack of a 5'-OH, a 3'-OH, or a 2'-OH nucleophile of one oligomer onto a target atom of another (Smail et al. 2019).

Pino et al. (2008) observed RNA multimerization by simply leaving ribooligonucleotides in water in the presence of an adenine-based nucleotide cofactor (Fig. 1, panel

A). The reaction was dependent upon time, type of cofactor, oligonucleotide length and sequence, temperature, and pH through a mechanism of a double-stranded structure as the initial step of the ligation reaction (Pino et al. 2011a). Sequence complementarity-driven terminal ligation of polyG on polyC and, complementarily, of polyC on polyG was demonstrated to occur non-enzymatically in water in the absence of any added organic or inorganic cofactor (Pino et al. 2011b) (Fig. 1, panel B).

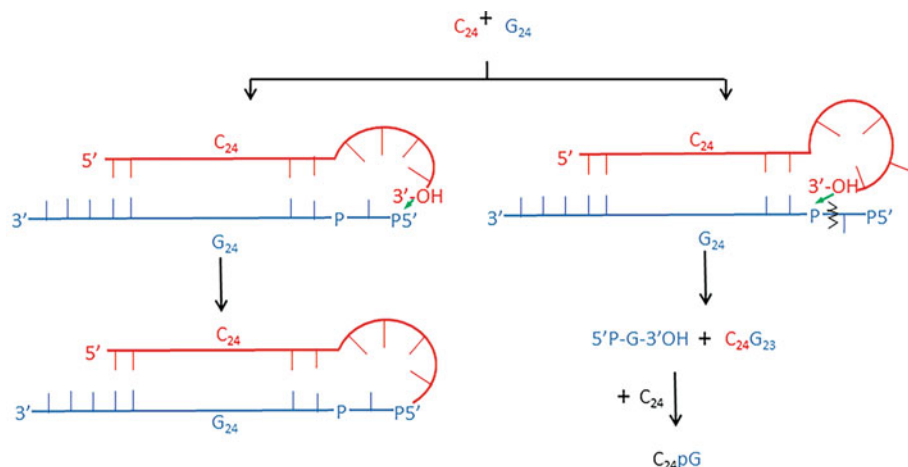
In the same paper, a reaction consisting of the ligation of cytosine-containing mixed sequences with no internal sequence complementarity in the presence of a cyclic guanosine nucleotide was described. Both terminal ligation and terminal growth result in the generation



Abiotic Recombination, Fig. 1 Abiotic synthesis of oligonucleotides

Panel A: Formation of dimer- and tetramer-sized multimers from a γ - ^{32}P 5'-labeled A_{23} -mer as a function of different cofactors. First lane: the untreated (U) sample. RNA monomer was reacted in Tris-HCl- buffered water at 60 °C at pH 6.2 for 12 hrs. Active ligation was favored by 3'-AMP and 5'-AMP. Adenine, adenosine, ADP, and ATP only showed minor stimulation of the reaction.

Panel B: Terminal ligation of poly G_{24} to poly C_{24} . Poly G_{24} γ - ^{32}P -phosphorylated at the 5'-end was reacted with increasing amounts of unphosphorylated poly C_{24} . The following cartoons are shown at the right: G sequences (blue), C sequences (green), 3'-extremity (black), 5'-extremity (red), filled dots for [^{32}P]phosphate groups. The G_{24} - C_{24} dimer is shown. The reaction was conducted for 30 min at 60 °C in water (pH 5.3).



A

Abiotic Recombination, Fig. 2 Ligation-cleavage mechanism

Simultaneous ligation-cleavage mechanism shown on the example of the reaction between C_{24} and 5'-phosphorylated G_{24} . On the left: ligation assuming loop formation at the 3'-end of C_{24} and attack at the phosphorylated 5'-end of G_{24} leading to the formation of

$C_{24}G_{24}$. On the right: simultaneous cleavage reaction initiated by the attack of the 3'-end of C_{24} at the last but one phosphate of the 5'-phosphorylated G_{24} . The products of this reaction are $C_{24}G_{23}$ and 5'-phosphorylated guanosine-phosphate, which readily combines with C_{24} leading to the formation of $C_{24}pG$. (From: Pino et al. 2013).

of complex and controlled sequence combinations dictated by the sequences themselves. A reaction carried out by nonenzymatically generated oligoG RNAs when challenged with a base-pair complementary sequence is also possible (Pino et al. 2013). In this reaction (dubbed LIC: Ligation following Intermolecular Cleavage) two complementary sequences ligate and self-cleave through the nucleophilic attack of an acceptor 3'-hydroxyl group on the phosphorus of a donor 3',5' phosphodiester bond. The mechanism of the LIC reaction requires a tetraloop-like transient but sufficiently stable overhang structure due to imperfect pairing of the donor and acceptor strands (Šponer et al. 2016) (Fig. 2).

Staroseletz et al. (2018) explored the RNA recombination process by modeling it with a simple system which included two RNA fragments and Mg^{2+} as a catalyst, showing that oligomers which form the most stable intermediate complex (due to formation of a duplex with a template or some kind of intramolecular duplex) and achieve the optimal orientation of the ligation reacting groups (2',3'-cyclophosphate and 5'-OH) will be the most selected. RNA ligation

occurs mostly in the internal loops, bulge-loops, and the end of stem structures, definitively indicating that both RNA sequence and structure play a role in the evolution of the genetic material.

Cross-References

- Abiotic
- Autocatalysis
- Cyclic Nucleotide Monophosphate
- Evolution, Molecular
- Intron
- Metabolism, Prebiotic
- Nucleic Acids
- Oligomer
- Oligonucleotide
- Origin of Life
- Polynucleotide
- Recombination
- Replication (Genetics)
- Ribonucleotide
- Ribozyme
- RNA
- RNA World

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Ablation

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Ablation is the erosion of the surface of a solid object in a flow (e.g., during the entrance of an object into the atmosphere) through some physical process, such as formation of a ► [fusion crust](#), vaporization, or friction.

Absolute Age Dating

► [Absolute and Relative Ages](#)

Absolute and Relative Ages

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Montréal, QC, Canada

Keywords

Geochronology · Stratigraphy · Geological time scale · Radioactive decay

Synonyms

[Absolute age dating](#); [Geochronology](#); [Numerical ages of rocks](#); [Radiometric dating](#); [Relative age dating](#); [Relative ages of rocks](#)

Definition

In geochronology, the “absolute age” of a rock is the age obtained from the measurement of the spontaneous decay of radioactive nuclides contained in the rock, or its constituent minerals, into their radiogenic daughter isotopes. It differs from the “relative age” of a rock, which is determined from spatial relations between rock formations (stratigraphy), giving only qualitative information on the period when the rock formed.

History

Relative dating of rocks is a method known since the foundation of the principles of stratigraphy by Nicolas Steno (1638–1686), a Danish scientist and Catholic Bishop who was a pioneer in both anatomy and geology. In his major contribution to geology – *Dissertationis prodromus* of 1669 – Steno is credited with three of the five defining principles of stratigraphy, the Earth science’ discipline which studies the order and relative position of geological strata of rocks and their relation to the geological timescale. James Hutton, considered the father of modern geology, later introduced the two remaining principles of stratigraphy. It is only from the beginning of the twentieth century, with the discovery of the radioactivity, that absolute dating of rocks was made possible. The first radiometric dating of rocks and the first absolute geological timescale was proposed by a young brilliant English scholar, Arthur Holmes (1890–1965). In his famous text, “The age of the Earth” published in 1913, he presents the first absolute rock dating using different methods (U-⁴He, U-Pb method) and measured ages that spanned from the Archean (dated at 710 Ma against 4–2.5 Ga today) to the Pleistocene (1 Ma). Holmes is thus considered the father of the geochronology.

Overview

The relative age of rock strata is usually determined based on their spatial relationships. These relationships are governed by the five principles of

stratigraphy which can be resumed as follows: (1) the *Principle of Superposition*, which states that in a sequence of strata, any stratum is younger than the sequence of strata on which it rests, and is older than the strata that rest upon it; (2) the *Principle of Initial Horizontality* which states that strata are deposited horizontally and then deformed later; (3) the *Principle of Strata Continuity*, which states that strata can be assumed to have continued laterally far from where they presently end; (4) *Principle of Cross-Cutting Relationships*, which tells that any geological body that cross-cut strata probably post-dates them; (5) and finally the *Principle of Inclusions*, if eroded chunks of one material are incorporated within another, then the eroded material must be older. These five principles are still used today to spatially order the different sedimentary-deposited strata. Although approximate, the addition of information from fossilized species (based on the Darwinian evolution) and radiometric ages of datable material (such as magmatic intrusions or metamorphic layers) help anchor these spatially ordered layers into age periods.

The discovery of sedimentary layers on Mars has brought scientists to use the same methodology described above. Mars has a simplified Geological Time Scale based on crater counting. Sedimentary stratified layers filling the bottom of Gale crater as observed by the Mars Science Laboratory mission and the Curiosity rover mission, or river-incised valleys crosscutting craters are a good example of applying the same principles of relative dating than on Earth. In both cases, deposited sediments and erosional features postdate the surface cratering, giving relative ages to those surface’s features.

Radiometric or absolute ages are based on the measurement of radioactive elements (parent elements) present in a rock or in its constituting minerals, and their decay products (daughter elements). Because the decay of radioactive elements is constant and unaffected by temperature, pressure, or oxygen fugacity conditions, an age can be obtained, assuming that the decay constant is known and that the mineral(s) containing both the parent and the daughter elements act as closed systems (no addition or loss of parent or daughter elements). Radiometric ages were available to date geological strata since the start of the twentieth century. In

1956, Clair Patterson at Caltech age-dated meteorites, which led to the first absolute age proposed for the Earth. Lunar samples brought to Earth by the first Apollo missions in the 1970s were age-dated with the Rb-Sr method. The *in situ* absolute dating of rocks directly on the surface of a planet, other than the Earth, is a very recent endeavor. In 2013, the team of Ken Farley at Caltech obtained a K-Ar age of 4.21 ± 0.35 Ga on a powder from the Gale crater (Mars) obtained using the drill of the Curiosity rover. The obtained age lacks precision, and it is likely a mixed age between that of older detrital (i.e., transported over a distance) sediments and younger authigenic (i.e., precipitated *in situ*) sediments. Yet, the age is compatible with that of 3.8–3.6 Ga obtained by relative dating for the Gale crater. Improvement in dating planetary distant surfaces will depend on the capacity of developing small portable automated laboratories able to separate minerals and by refining onboard analytical instrumentation. Yet, the potential of dating far planetary surfaces is enormous, even with the actual limitations.

Cross-References

- [Earth, Age of](#)
- [Geochronology](#)
- [Mars Stratigraphy](#)
- [Stratigraphy](#)

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Absorption Cross Section

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Keywords

Absorption

Definition

When a parallel, monochromatic beam of light traveling in some specific direction encounters a medium of finite extent, a certain amount of the flux will be absorbed and a certain amount will be scattered into other angles. The rate at which energy is taken out of the beam by absorption and scattering can be characterized in terms of coefficients with dimensions of area, which are known as cross sections. The term absorption cross section is often used to include both the portion due to scattering and that due to true absorption (loss of the photon into another form of energy, such as heat). For atmospheric gases, this total absorption cross section is defined by the Beer's law expression:

$$I = I_0 \exp(-\sigma n l)$$

where I_0 and I are the incident and transmitted light intensities, respectively, σ is the absorption cross section ($\text{cm}^2 \text{ molecule}^{-1}$), n is the molecular density, and l is the pathlength in cm.

Absorption Spectroscopy

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

In absorption ► [spectroscopy](#), the spectral features of interest appear in absorption with respect to a background continuous spectrum. In the interstellar medium, the background continuum may be supplied by a radiation source, such as a star, located behind the region of interest. The absorbing material may be either in the gas or the solid phase (e.g., interstellar dust or ices). Solid state features are much broader than atomic or molecular absorptions and are consequently more difficult to assign to a specific carrier. Much of the solar (Fraunhofer) spectrum is seen in absorption,

as the outer cooler layers of the solar atmosphere absorb radiation from the deeper photosphere. Spectral lines in planetary atmospheres are typically seen in absorption, against the continuous thermal spectrum from the planetary or satellite surface.

History

The first person to notice a number of dark features in the solar spectrum was the English chemist William Wollaston in 1802. This absorption spectrum was first systematically investigated by Joseph von Fraunhofer, starting in 1814, and the spectral features are now known as Fraunhofer lines.

Cross-References

► [Spectroscopy](#)

Abundances

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Fractional abundances](#)

Definition

Relative molecular abundances measure the chemical composition of an astronomical source or object. Such abundances can be either by mass or by number of molecules. For interstellar clouds, molecular abundances are typically presented as fractional abundances constructed from the measured molecular ► [column density](#), divided by the estimated H_2 column density of the source (Irvine et al. [1987](#)). For planetary or

satellite atmospheres, abundances are usually given in terms of the “volume mixing ratio”, the fractional number of molecules or atoms in a given volume relative to the total number of particles in the volume (de Pater and Lissauer [2001](#)).

Cross-References

► [Abundances of Elements](#)
► [Column Density](#)
► [Molecular Cloud](#)

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Abundances of Elements

Nikos Prantzos
Institut d’Astrophysique de Paris, Paris, France

Keywords

Chemical composition · Nucleosynthesis · Nuclide

Definition

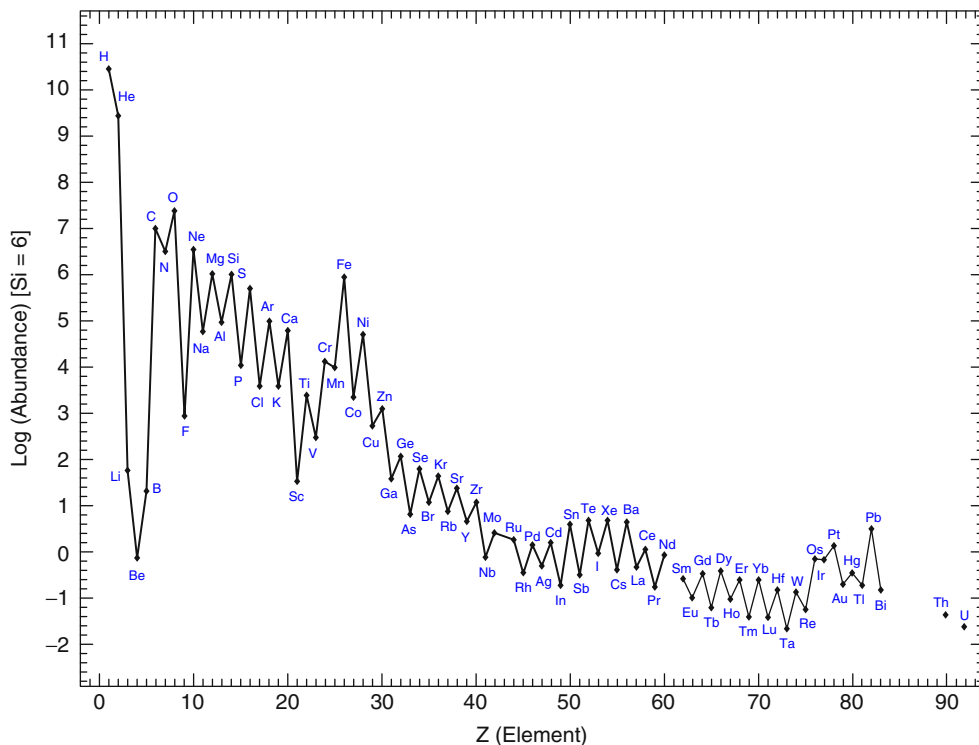
The relative amount (or fraction) of a given nuclide in a sample of matter is called the *abundance* of that nuclide. It can be expressed either in absolute terms (i.e., with respect to the total amount of matter in the sample) or in relative terms (with respect to the amount of some key element, e.g., the most abundant one, in the sample). Similarities and differences in the elemental and isotopic composition of ► [stars](#) and galaxies are key ingredients for understanding their origin and evolution.

Overview

The composition of remote objects (the Sun, ► [stars](#), interstellar gas, and galaxies) is determined through spectroscopy, which usually allows the determination of elemental abundances; in rare cases, particularly for interstellar clouds, some isotopic abundances may be determined in those objects. For Earth, lunar, and meteoritic samples, nuclear mass spectroscopy allows precise determination of most isotopic abundances; this is also the case for cosmic rays, albeit only for the most abundant nuclides at present. Hydrogen (H) being the most abundant element in the Universe, spectroscopists express the abundance of element i as the number ratio of its nuclei with respect to those of H: $n_i = N_i/N_H$, and they use a scale where $\log(N_H) = 12$. In the meteoritics community, the silicon scale of $\log(-N_{Si}) = 6$ is used. Theoreticians use the *mass fraction* $X_i = N_i A_i / \sum N_j A_j$, where A_j is the mass number of nuclide j ; obviously, $\sum X_i = 1$. Conversion of mass fractions to abundances by number

requires use of the quantity $Y_i = X_i / A_i$ called the *mole fraction* (notice that $\sum Y_i \neq 1$).

According to our current understanding, the material of the proto-solar nebula had a remarkably homogeneous composition, as a result of high temperatures (which caused the melting of nearly all the dust grains) and thorough mixing. This composition characterizes the present-day surface layers of the Sun, which remain unaffected by nuclear reactions occurring in the solar interior (with a few exceptions, e.g., the fragile D and Li). Furthermore, after various physicochemical effects are taken into account, it appears that the elemental composition of the Earth and meteorites matches extremely well with the solar photospheric composition. The composition of stars in the Milky Way presents both striking similarities and considerable differences with the solar composition. The universal predominance of H (90% by number, but $\sim 70\%$ by mass) and He (9% by number, but $\sim 25\%$ by mass) and the relative abundances of “metals” (to astronomers, elements heavier than He) is the most important similarity. On the other hand, the



Abundances of Elements, Fig. 1 Solar system abundances (by number) of the 92 chemical elements, in a logarithmic scale where $\log(N) = 6$ for Silicon. (From a compilation in Lodders [2003](#))

fraction of metals (*metallicity*, about 1.5% in the Sun) appears to vary considerably within the solar neighborhood (where the oldest stars have a metallicity of 0.1 solar), across the Milky Way disk (with young stars in the inner Galaxy having three times more metals than the Sun), or in the galactic halo (with stellar metallicities ranging from 0.1 to 0.00001 solar). These variations in composition reflect the history of “chemical evolution” of the Milky Way (Fig. 1).

Cross-References

- [Nucleosynthesis, Explosive](#)
- [Nucleosynthesis, Neutrino](#)
- [Primordial Nucleosynthesis](#)
- [S-process](#)
- [Stars](#)

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1989 AC

- [Toutatis](#)

Acasta Gneiss

Samuel A. Bowring¹ and Hervé Martin²

¹Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

²Laboratoire Magmas et Volcans, Université Clermont Auvergne, Aubière Cedex, France

Keywords

Geochronology · Oldest rocks · Zircon

Samuel A. Bowring: deceased.

Synonyms

[Gneiss](#)

Definition

The Acasta Gneisses are the oldest rocks so far discovered on the surface of the Earth. They are exposed in northern Canada, north of Great Slave Lake, east of Great Bear Lake with the approximate position of 65° 10' N and 115° 30' W. They are granitic (*s.l.*) in composition and are interpreted to have formed, at least partly, from even older rocks that may be as old as 4.2 Ga.

Overview

The Acasta Gneisses are the oldest dated rocks on Earth. They are exposed in northwestern Canada (65° 10' N and 115° 30' W) along the western margin of the Archean Slave craton (>2.5 Ga), in the core of a north-trending fold in the foreland of the Wopmay orogen, a 2.02–1.84 Ga-old orogenic belt. The ages of Acasta Gneisses range from 4.03 to ca. 3.6 Ga, which group into three age clusters: 4.03–3.94 Ga, 3.74–3.72 Ga, and 3.66–3.58 Ga (Bowring et al. 1990; Bowring and Housh 1995). In each of these chronological groups, rock composition ranges from tonalite to granite through granodioritic. Since their genesis, these rocks have been deformed several times resulting in well-developed foliations (planar fabric present in metamorphic rocks and produced by reorientation of minerals). Lens-shaped boudins (cylinder-like structures making up a layer in a deformed rock) of serpentinized ultramafic rocks, up to several hundred meters long, occur throughout the gneisses. ca. 4.0–3.6-Ga-old metasedimentary rocks are lacking although sparse outcrops of locally tightly folded quartzite, iron formation, and pelite are found in the older gneisses. Many outcrops are cut by weakly deformed, ca. 3.6 Ga-old granitic dikes. During the 1.88 Ga Calderian orogeny to the west, sheets

of 1.9–2.5 Ga-old rocks were thrust over the western edge of the Slave craton, resulting in a set of north-trending folds and metamorphism of underlying Archean rocks. Ar-Ar biotite and U-Pb apatite dates record complex reheating during this event at ca. 1.77 Ga.

Most of the Acasta Gneiss protoliths have TTG (Tonalite-Trondhjemite-Granodiorite) composition, characterized by high light- and low heavy-rare earth element contents, which points to the involvement of residual garnet in their source (Martin 1987). On the other hand, several zircons crystals contain older xenocrystic cores with ages up to 4.2 Ga, which demonstrate that Hadean crust has been involved in the genesis of the Acasta protoliths through partial melting or assimilation (Iizuka et al. 2006, 2007).

Radiogenic isotope systematics in whole rocks (Sm-Nd) and zircon (Lu-Hf) are also consistent with the involvement of older ► [continental crust](#) (Guitreau et al. 2014; Reimink et al. 2018). The metamorphic imprint at ca 3.65 Ga, 3.6 Ga, and 3.4 Ga appears as zircon thin overgrowths.¹⁴² Nd signatures indicate that the oldest Acasta Gneisses were generated by partial melting of a hydrated, Hadean-age mafic crust at relatively shallow depths.

The formation and preservation of ► [continental crust](#) early in Earth's history is of broad interest to Earth scientists; indeed, the oldest continental crust provides information on the petrogenetic mechanisms as well as on the role played by water in generating granitic (*s.l.*) magmas 4 Ga ago. The ca. 4.0 Ga granitoids are very similar to those formed much later in Earth's history by plate-tectonic processes. No evidence of the late heavy bombardment is preserved in the Acasta Gneisses.

Cross-References

- [Canadian Precambrian Shield](#)
- [Continental Crust](#)
- [Earth, Formation, and Early Evolution](#)
- [Geochronology](#)
- [Granite](#)

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Accretion

Daniele L. Pinti

Geotop, Research Centre on the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Continental accretion](#); [Landmass accretion](#); [Planetary formation](#); [Plate accretion](#)

Definition

In planetary sciences, accretion is the process in which solid particles agglomerate together to form larger objects and eventually planets (*planetary accretion*). The initial conditions are a disc of gas and ca. 1% in mass of microscopic solid particles rotating around a young star. In geology, accretion is the process by which geological materials such as sediments, volcanic arcs, and pieces of continental crust, split from other continental plates, are added to a tectonic plate or to a landmass (*continental accretion*) participating in their growth with time.

Cross-References

- [Formation of Planetesimals: the Building Blocks of Planets](#)
- [Late-Stage Accretion](#)
- [Planet Formation](#)
- [Planetesimals](#)
- [Plate Tectonics](#)
- [Plate, Lithospheric](#)

Accretion Shock

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Generally, an accretion shock is a shock wave occurring at the surface of a compact object or dense region that is accreting matter supersonically from its environment. In the context of astrophysics, an accretion shock is normally understood to mean the shock wave present at the surface of the protosolar nebula or the corresponding nebula surrounding a ► [protostar](#), as it accretes interstellar matter from the surrounding molecular cloud.

Cross-References

- [Protoplanetary Disk](#)
- [Protosolar Nebula, Minimum Mass](#)
- [Protostars](#)
- [Shock, Interstellar](#)

Accretion, Stellar

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

Stellar accretion refers to the inflow of ambient gas onto the surface of a star. During the process of star formation, accretion builds up the object to its final mass. The infalling gas is the interior portion of a ► [dense core](#), a small ► [molecular cloud](#) that collapses under the influence of its own gravity. The object being built up in this manner is a protostar and represents the first phase of stellar evolution. Some infalling gas impacts the protostar directly. Much of the gas, however, has sufficient angular momentum that it goes into orbit around the young star. The accreting gas thus creates a circumstellar disk. Matter spirals in through the disk onto the surface of the protostar. The remaining part of the disk eventually gives rise to planets.

Cross-References

- [Dense Core](#)
- [Free-Fall Time](#)
- [Gravitational Collapse, Stellar](#)
- [Molecular Cloud](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Protostellar Envelope](#)
- [Star Formation, Theory](#)

Acetaldehyde

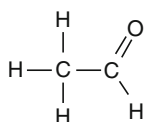
Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[Acetic aldehyde](#); [Ethanal](#)

Definition

Acetaldehyde is an organic compound with the chemical formula CH_3CHO



It is the smallest aldehyde after formaldehyde. It is a colorless liquid at room temperature with an irritating odor. It can be obtained by the oxidation of ► [ethanol](#) or by the reduction of ► [acetic acid](#). When we drink alcohol, the ethanol is oxidized to acetaldehyde, by alcohol dehydrogenase, which is then oxidized to acetic acid by aldehyde dehydrogenase in the liver. It can be formed easily from gas mixtures containing methane by ultraviolet light and electric discharges, among others. It reacts with hydrogen cyanide and ammonia to give 2-aminopropionitrile, which gives ► [alanine](#) (amino acid) after hydrolysis. It has been detected in extracts from carbonaceous chondrites. Melting point: $-123.5\text{ }^{\circ}\text{C}$, boiling point: $-20.2\text{ }^{\circ}\text{C}$, density: 0.788 g cm^{-3} .

Cross-References

- [Acetic Acid](#)
- [Alanine](#)
- [Aldehyde](#)
- [Chondrite](#)
- [Formaldehyde](#)

Acetamide

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Keywords

Molecules · Interstellar

Synonyms

[Acetic acid amide](#); [Ethanamide](#)

Chemical Formula

CH_3CONH_2

Definition

Acetamide is an organic molecule with potential astrobiological significance, since it includes an amide bond, $-\text{NHCO}-$, which makes it potentially a marker of hydrolytic activity. Acetamide has been detected in the interstellar medium in the Galactic Center molecular cloud SgrB2, in carbonaceous chondrites (e.g., Halfen et al. 2011), and also apparently in the nucleus of comet 67P/Churyumov–Gerasimenko by the Philae lander as part of the Rosetta mission of the European Space Agency (Goesmann et al. 2015).

Cross-References

- [Amino Acid](#)
- [Carbonaceous Chondrite](#)
- [Comet](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Philae Lander](#)
- [SgrB2](#)

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2-(Methylamino) Acetic Acid

- [Sarcosine](#)

Acetic Acid

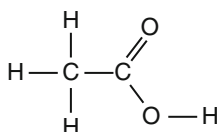
Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[Ethanoic acid](#)

Definition

Acetic acid is a ► [carboxylic acid](#) with the chemical formula CH₃COOH



It is a colorless liquid at room temperature with an irritating odor. Pure anhydrous acetic acid is sometimes called glacial acetic acid. It can be obtained by oxidation of ► [acetaldehyde](#), which occurs in human liver catalyzed by the enzyme aldehyde dehydrogenase, or by the hydrolysis of acetonitrile. It is easily formed in chemical

evolution experiments, e.g., it was found among the products of spark discharge experiment in a gas mixture of methane, ammonia, hydrogen, and water by S. L. Miller in 1953. It has been found in extracts from carbonaceous ► [chondrites](#) and has also been identified in ► [molecular clouds](#). Melting point: 16.6 °C, boiling point: 117.8 °C, density: 1.0492 g cm⁻³, acidity constant (p*K*_a): 4.76.

Cross-References

- [Acetaldehyde](#)
- [Aldehyde](#)
- [Carboxylic Acid](#)
- [Chondrite](#)
- [Miller, Stanley](#)
- [Molecular Cloud](#)

Acetic Acid Amide

- [Acetamide](#)

Acetic Aldehyde

- [Acetaldehyde](#)

Acetone (CH₃COCH₃)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Propanone](#)

Definition

The organic compound acetone (CH₃COCH₃) is the simplest example of a ketone. Under standard

conditions, it is a colorless, flammable liquid. Acetone is naturally produced by normal metabolic processes in the human body. Since it is miscible with water, it serves as an important laboratory solvent. Rotational transitions in both the ground vibrational state and in the first excited torsional state have been detected by radio astronomers in ► [molecular clouds](#).

History

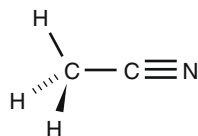
Although detection of acetone in a molecular cloud toward the center of our ► [Milky Way](#) galaxy was reported by radio astronomers in 1987, secure confirmation of its presence in interstellar clouds was not achieved until some 15 years later.

Cross-References

- [Milky Way](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

References and Further Reading

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It is a colorless liquid at room temperature with an ether-like odor. It can be obtained by dehydration of acetamide or by hydrogenation of a mixture of carbon monoxide and ammonia. It gives ► [acetic acid](#) and ammonia after hydrolysis and gives ethylamine after reduction. Acetonitrile itself is only slightly toxic but gives extremely toxic ► [hydrogen cyanide](#) by metabolism in the body. It is detected in ► [molecular clouds](#) as an interstellar molecule and also found in cometary comas. When aminated on the methyl group, aminoacetonitrile is produced, which is an important precursor of ► [glycine](#). It is completely miscible with water and often used as an eluant in high-performance liquid chromatography (HPLC), with melting point, -45.7°C ; boiling point, 82°C ; and density, 0.786 g cm^{-3} .

Cross-References

- [Acetic Acid](#)
- [Comet](#)
- [Glycine](#)
- [Hydrogen Cyanide](#)
- [Molecular Cloud](#)
- [Nitrile](#)

Acetonitrile

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

CH_3CN ; [Cyanomethane](#); [Methyl cyanide](#)

Definition

Acetonitrile is the simplest organic ► [nitrile](#) with the chemical formula CH_3CN .

Acetylene (C_2H_2)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Ethyne](#), [HCCH](#)

Definition

Acetylene is the simplest alkyne (hydrocarbons that have a triple bond between two carbon

atoms, with the formula C_nH_{2n-2}). Under standard conditions in the laboratory, it is a colorless but unstable gas. Because of its symmetry, linear of the form HCCH, it lacks a permanent electric dipole moment and hence has no allowed pure rotational transitions, making it undetectable at millimeter wavelengths. Astronomers have observed its vibrational transitions in the infrared, in both ► [molecular clouds](#) and in the envelopes of evolved stars. It is an important link in the chemistry of heavier carbon chain molecules and related species in these regions. Acetylene is also found as a minor component in the atmospheres of gas giants like the planet ► [Jupiter](#), in the atmosphere of Saturn's satellite ► [Titan](#), and in ► [comets](#).

History

Acetylene was discovered in 1836 by Edmund Davy and then rediscovered in 1860 by French chemist Marcellin Berthelot, who coined the name "acetylene." It was first observed in the interstellar medium by Lacy et al. (1989) and in ► [Comet Hyakutake](#) and ► [Comet Hale-Bopp](#) (Brooke et al. 1996).

Cross-References

- [Comet](#)
- [Comet Hale-Bopp](#)
- [Comet Hyakutake](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Stellar Evolution](#)

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Achiral

Robert Hazen

Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Synonyms

[Mirror symmetric](#)

Definition

The term "achiral" is applied to any object – in astrobiology most commonly a molecule, a two-dimensional crystal surface, or a three-dimensional crystal structure – that is invariant (i.e., superimposable) with its mirror image. Achiral objects possess a plane of symmetry, either a mirror or a glide plane symmetry operator. Common achiral objects include a soccer ball, a pencil, and the letter "X," in contrast with chiral objects such as a snail shell, your left hand, and the letter "R." Common achiral molecules are H_2O , CH_4 , and NH_3 in contrast with such chiral biomolecular species as alanine and ribose. In chemistry, achiral should not be confused with racemic, although in neither case is the optical rotation of polarized light affected.

Cross-References

- [Chirality](#)
- [Enantiomeric Excess](#)
- [Homochirality](#)
- [Racemic Mixture](#)
- [Stereoisomers](#)

Achondrite

Frank Sohl^{1,2} and Tilman Spohn¹

¹Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

²International Space Science Institute, Bern, Switzerland

Definition

Achondrites are differentiated stony ► [meteorites](#) and constitute a minority among the stony meteorites. The term literally means “without ► [chondrules](#)” and therefore underlines the main difference with ► [chondrites](#). Achondrites are igneous ► [rocks](#) or ► [breccias](#) of igneous rock fragments and thus their parent body has experienced partial melting and recrystallization. The class of achondrites includes the primitive achondrites (e.g., ureilites) and achondrites in general (e.g., aubrites, eucrites, howardites, diogenites, Martian meteorites, and lunar meteorites).

Cross-References

- [Breccia](#)
- [Chondrite](#)
- [Chondrule](#)
- [Meteorites](#)
- [Rock](#)

Acid Hydrolysis

Mark Dörr

University of Southern Denmark, Odense M, Denmark

Definition

Hydrolysis (Greek: υδωρ [hydor] = “water” and λύσις [lýsis] = “solution”) is a chemical reaction

in which a compound is cleaved by water. If a proton-donating compound (Brønsted acid) catalyzes the reaction, it is called “acid hydrolysis.” Formally one part of the cleaved reaction product receives a proton (H^+), the other a hydroxyl (OH^-) moiety of a water molecule. Hydrolysis can also be catalyzed by a base. The reverse reaction is called a “condensation reaction.”

Acid Maceration

Emmanuelle J. Javaux

Palaeobiogeology-Palaeobotany-Palaeopalynology, Geology Department, Université de Liège, Liège, Belgium

Definition

Acid maceration is a technique used to extract organic-walled ► [microfossils](#) or kerogen from rock. A rock sample is cleaned to remove external contamination and crushed into small pieces. About 25 mg is macerated in chlorhydric acid solution (HCl) to remove carbonate minerals, rinsed with distilled water, and then macerated in fluorhydric acid solution (HF) to remove silicate minerals. A following step of boiling the macerate in hot HCl removes fluorides formed during the previous acid step. This protocol may vary according to the nature of the rock, of the fossils, and of their degree of preservation. After neutralization of the final macerate with distilled water, the residue is filtered on sieves of desired size fractions, then mounted on microscopic slides or kept in vials for other analyses.

Cross-References

- [Acritarch](#)
- [Biomarkers, Morphological](#)
- [Fossil](#)
- [Kerogen](#)

Acidophile

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Keywords

Archaea · Chemolithoautotroph · Eukaryote · Iron cycle · Prokaryote · Sulfur cycle

Definition

Acidophiles are ► [microorganisms](#) that thrive under acidic conditions, usually at very low pH (<3). Natural niches where acidophiles can be found are volcanic areas (Yellowstone), hydrothermal sources, deep-sea vents, metal mining activities (Iron Mountain, Rio Tinto), or in the stomachs of animals. Acidophilic organisms can be found in the different domains of the tree of life (► [Archaea](#), Bacteria, and ► [Eukarya](#)).

Overview

The best characterized acidophiles belong mainly to Bacteria and Archaea domains (Madigan and Martinko 2005). These microorganisms normally are associated to sulfuric pools, acid mine drainage, or hydrothermal sources, that is, environments where sulfur compounds are present. The origin of extreme acidic conditions is related with the ► [oxidation](#) of reduced sulfur compounds which determines the strong relationship between acidophiles and sulfur chemistry. But also some eukaryotes as the green algae *Dunaliella acidophila* and the red algae *Cyanidium caldarium* (both organisms can live below pH 1.5) and some fungi are acidophiles. Surprisingly, eukaryotic microbes are the principal contributors of biomass in some low-pH environments as ► [Rio Tinto](#), a Spanish river which has a pH of around 2 and contains much higher concentrations

of heavy metals than are typically found in fresh waters (López-Archilla et al. 2001). Some interesting results from Rio Tinto are related with evolutionary distances between acidophilic species that occur in the river and their neutrophilic relatives. Authors reported some results that offer insight into adaptation to an extremely acidic environment. Adaptations associated with the transition from a neutral to an acidic environment must occur relatively rapidly when measured on evolutionary timescales (Amaral-Zettler et al. 2002). Authors detected clones from the Rio Tinto that are closely related to neutrophilic species such as *Chlamydomonas noctigama*, *Chlorella minutissima*, and *Colpidium campylum*. From microscopic observations, rotifers were also identified as inhabitants of Rio Tinto, as well as heliozoans and other types of amoeba.

Acidophiles belonging to different orders of the archaeal domain have been identified, such as Sulfolobales (a particular order in the Crenarchaeota branch) and some facultative anaerobic thermoacidophilic microorganisms as *Acidianus brierleyi* and *A. infernus* and other thermophilic as *Metallosphaera sedula*, all of them related with metal mobilization in natural environments and mining processes, Thermoplasmatales (order included in Euryarchaeota branch), and some others groups as nanoorganisms associated to Iron Mountain Mine and called ARMAN (Archaeal Richmond Mine Acidophilic Nanoorganisms). The ARMAN group is composed by three different lineages deeply branched in the Euryarchaeota subgroup.

Acidophiles belonging to the bacterial domain are the phylum Acidobacteria, the order Aciditobacillales of ► [Proteobacteria](#), the genus *Acidithiobacillus* and *Leptospirillum*, and some other related microorganisms as *Acetobacter aceti*, a bacterium that belongs to the *Acetobacter* genus of Proteobacteria that produces acetic acid (vinegar) from the oxidation of ethanol.

Studies of mechanisms used for adaptation at low pH by acidophiles reported interesting results about efficient apparatus for pumping protons out of the intracellular space as a way of maintaining

cytoplasm at or near neutral pH (Kelch et al. 2007). Therefore, intracellular proteins are not forced to develop acid stability through evolution. However, some acidophiles, as *Acetobacter aceti*, have an acidified cytoplasm. In the case of acidophiles with acidic cytoplasm, all proteins are forced to evolve acid stability. *Acetobacter* has become as a good model for studying acid stability mechanisms. Several authors have studied proteins adapted to low pH and revealed that in acid-stable proteins there is an overabundance of acidic residues which minimizes low-pH destabilization induced by a buildup of positive charge. The relocation of acid-sensitive salt bridges to regions with important functions in the unfolding process is a very specialized case of acid stability for some proteins of acidophiles. But some others mechanisms for protein stabilization in acid conditions have been reported.

- ▶ [Chemolithotroph](#)
- ▶ [Deep-Sea Microbiology](#)
- ▶ [Eukarya](#)
- ▶ [Eukaryote](#)
- ▶ [Euryarchaeota](#)
- ▶ [Extremophiles](#)
- ▶ [Hot Spring Microbiology](#)
- ▶ [Hot Vent Microbiology](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Iron Cycle](#)
- ▶ [Microorganism](#)
- ▶ [Oxidation](#)
- ▶ [Prokaryote](#)
- ▶ [Proteobacteria](#)
- ▶ [Pyrite](#)
- ▶ [Rio Tinto](#)
- ▶ [Sulfur Cycle](#)
- ▶ [Yellowstone National Park, Natural Analogue Site](#)

Applications

Acidophiles have industrial applications as in biomining and bioremediation. Among the methods used for acid mine drainage treatment, there are several which involve also metal-immobilizing bacteria as a way for metal sequestering. An important biotechnological application of acidophiles is the process known as bioleaching for metal extraction and exploitation of extremely low-grade ores. Not only bacteria but also fungi have been used in related projects (Mohapatra et al. 2007; Botuyan et al. 1996). Projects include nickel extraction with *A. ferrooxidans* and *Aspergillus* sp. fungi (Mohapatra et al. 2007) and sulfur removal from coal with *Acidithiobacillus* sp. or naturally present population bacteria on fossil fuels as coal (Gómez et al. 1997).

Cross-References

- ▶ [Autotroph](#)
- ▶ [Autotrophy](#)
- ▶ [Biodiversity](#)
- ▶ [Chemoautotroph](#)
- ▶ [Chemolithoautotroph](#)

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Acritarch

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Keywords

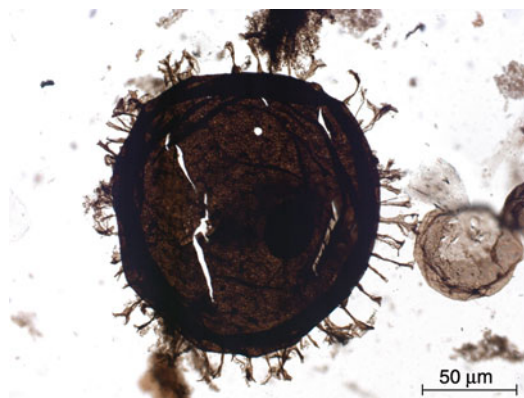
Organic-walled microfossils

Definition

An acritarch is a microscopic organic-walled hollow vesicle with an unknown biological affinity. The term comes from two Greek words: “acritos” (unknown) and “arche” (origin). Acritarchs are found in marine sediments from most of the geological timescale, from the Archean to the present, but were more abundant and diversified in the Proterozoic and the Paleozoic. Their diversity decreased in the Mesozoic.

Overview

The term “acritarch” was coined by Evitt (1963) to define any organic-walled ► [microfossils](#) that cannot be assigned to a known biological group. The acritarchs form a polyphyletic artificial group that may represent many different types of organisms, from bacteria to unicellular (protists) or multicellular eukaryotes (e.g., fungi, algae, animal eggs). Their size ranges from a few microns to a few millimeters, although most are microscopic. They are classed into several artificial morphogroups based on the morphology and presence and type of ornamentation of the vesicle. Filamentous organic-walled microfossils of unknown biological affinities are not included among acritarchs. In the Paleozoic, most acritarchs are assumed to represent cysts of marine planktonic algae (phytoplankton). Acritarchs are very useful to date and correlate marine sedimentary rocks (biostratigraphy), especially in the late Proterozoic and the Paleozoic, to



Acritarch, Fig. 1 Two acritarchs from the Mesoproterozoic (1.65 Ga Ruyang Group, China). *Left*, a spiny acritarch (acanthomorph); *right*, a smooth-walled acritarch (sphaeromorph). (Photograph: E Javaux)

reconstruct paleoenvironments, and to assess the thermal maturity of the organic matter (paleothermometer) and their potential as a source of hydrocarbon. Moreover, the detailed study of acritarch morphology, wall ultrastructure, and microchemistry gives precious information on the early evolution of eukaryotes in the Precambrian.

The oldest acritarchs known so far have smooth walls (sphaeromorphs) and are preserved in 3.2 Ga fine-grained detritic rocks deposited in tidal shallow marine waters (Mesoarchean). The oldest ornamented acritarchs (with concentric striations) are 1.9 Ga and interpreted as probable eukaryotes. The oldest spiny acritarchs (acanthomorphs) are unambiguously eukaryotic and 1.65 Ga. Acritarchs can be preserved as flattened vesicles in fine-grained detritic sediments (shales, siltstones) or in three dimensions by permineralization (partial or complete replacement by minerals) in cherts or phosphorites. They are studied in thin sections or extracted from the rock by ► [acid maceration](#), depending on their state of preservation (Fig. 1).

Cross-References

- [Acid Maceration](#)
- [Eukaryotes, Appearance and Early Evolution of](#)

- Fossilization, Process of
- Microfossils
- Proterozoic Eon

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Acrylonitrile

- Vinyl Cyanide (CH_2CHCN)

Activated Nucleotide

Kunio Kawamura
Department of Human Environmental Studies,
Hiroshima Shudo University, Hiroshima, Japan

Keywords

Chemical evolution · Nucleotide ·
Oligonucleotide · RNA

Synonyms

Nucleoside 5'-monophosphorimidazolid

Definition

An activated nucleotide is a nucleoside 5'-monophosphate possessing a leaving group, such as imidazole, which provides sufficient energy to form higher oligonucleotides. The activation of nucleoside 5'-monophosphates by N-P bond formation between the phosphate group and a base (such as an amino acid or an imidazole) seems to be essential for the abiotic formation of RNA oligomers. In contrast, DNA oligomers are less readily formed from activated deoxynucleotides.

Overview

The synthesis of ► RNA molecules may have been an essential step for the emergence of lifelike systems on the primitive Earth. In modern organisms, polymerization of RNA monomers only proceeds because thermodynamics and kinetics allow for biochemical polymerization in organisms. In modern biology, nucleoside 5'-triphosphate monomers are used to form RNA polymers. This is thermodynamically favorable, since nucleoside 5'-triphosphates possess high-energy phosphate groups. These by themselves are rather kinetically slow to react in solution; however, their polymerization becomes kinetically favorable due to the involvement of biological catalysts, RNA polymerases. In addition, biological nucleotide polymerization is usually conducted on a DNA template; in the absence of an RNA polymerase or a template, the polymerization of 5'-triphosphate does not proceed.

RNA polymers are also formed in biology from nucleoside 5'-diphosphate in the presence of polynucleotide phosphorylase without a DNA template. This is an exception, although this does show that the polymerization of nucleoside 5'-diphosphates is also thermodynamically possible.

As mentioned above, the polymerization of nucleotide 5'-triphosphates does not proceed in the absence of an enzyme and a polynucleotide template. Since enzymes are fairly complicated biological catalysts, and since the first nucleic

acids must have predated the first nucleic acid templates, primitive pathways to form RNA polymers without an enzyme and a template molecule have been investigated under simulated Earth conditions. The activation of nucleoside 5'-monophosphates is essential thermodynamically, since the nucleoside 5'-monophosphate does not possess sufficient energy to form phosphodiester bonding. These monomers also have the experimental benefit of reacting quite rapidly under laboratory conditions. Furthermore, the activation should have occurred from plausible precursors under primitive Earth conditions. Investigations by Orgel and coworkers have shown that the nucleoside 5'-monophosphate monomers, that is, nucleoside 5'-monophosphoimidazolides and related compounds, can be considered as candidate primitive activated nucleotide monomers, as they can be formed under plausible primitive Earth conditions (Lohrmann and Orgel 1973; Orgel and Lohrmann 1974; Lohrmann 1977; Huang and Ferris 2006). RNA oligomers up to 50 nucleotide units can be formed from the activated nucleotide monomers in the presence of a metal ion catalyst, a clay mineral catalyst, or a polynucleotide template. In contrast, DNA oligomers do not form readily from the activated nucleotides.

Cross-References

- [Nucleoside](#)
- [Nucleoside Phosphoimidazolidine](#)
- [Oligonucleotide](#)
- [RNA](#)
- [RNA World](#)

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Activation Energy

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

E_a

Definition

In chemical kinetics, the activation energy (abbreviated E_a) is the energy barrier which must be overcome for a sufficient number of reactant molecules to acquire enough kinetic energy for a reaction to occur appreciably. The activation energy can generally be achieved by supplying energy, for example, in the form of heat, to the system or through the intervention of a catalyst. The Arrhenius equation gives the temperature dependence of the rate constant k : E_a is obtained from the slope of a plot of $\ln k$ versus $1/T$, where T is the absolute temperature in Kelvin. The activation energy is usually measured in kJ/mol.

E_a is related to the rate (k) via the equation

$$E_a = -RT \ln(k/A)$$

where A is a constant called the frequency or pre-exponential factor, usually given in units of s^{-1} , and R is the universal gas constant.

Cross-References

- [Arrhenius Plot](#)

Active Asteroid

Gerhard Hahn

Asteroids and Comets, DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

Dual status objects; Mainbelt comet

Definition

Objects in typical asteroidal orbits, e.g., located in the main asteroid belt, showing typical cometary activity, such as tails or comae, either temporarily or sporadically. The possible origin of this “cometary” activity may either be intrinsically comet-like, e.g., outgassing, or triggered externally, e.g., by impact events, collisions, etc. Such objects are not confined to the asteroid belt, but exist also in the NEO population, and among Centaurs. A comprehensive recent review can be found in Jewitt (2012).

History

The first observation of such an object was the Centaur asteroid (2060) Chiron = 95P, which was found in 1988–1989 to show unusual brightening that could be related to comet-like activity exhibiting a coma. A member of the NEO group that was observed as both an asteroid and as a comet is (4015) Wilson-Harrington = 107P. Mainbelt asteroid (7968) Elst-Pizarro = 133P shows repeated activity, most likely caused by sublimation of water ice.

Most recent related finding is the detection of water vapor on dwarf planet Ceres = asteroid (1) Ceres.

Cross-References

- Asteroid Belt, Main
- Centaurs (Asteroids)

- Comets, History of
- Near-Earth Objects

References and Further Readings

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Active Site

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In catalysis, an active site is the specific location on the surface of a catalyst where reactions take place. For example, in surface chemistry, this could be a specific set of surface sites, and in biochemistry, it is a particular surface or cleft of a protein ► [enzyme](#) or ► [ribozyme](#) surface where catalysis occurs. In protein enzymes, the active site is generally a pocket or cleft with specific amino acid side chains presented in particular orientations that bind a ► [substrate](#) and facilitate catalysis. Cofactors facilitating catalysis may also be bound in the active site.

Cross-References

- Catalyst
- Cofactor
- Enzyme

- [Ribozyme](#)
- [Substrate](#)

Activity

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry, the activity of a species is a measure of its effective concentration, as distinct from its concentration. This is, by convention, usually presented as a unitless value. Activity can be affected by factors such as pressure, temperature, and the presence of other solutes. The difference in value between concentration and activity is due to the fact that molecules in solution often display non-ideal behavior due to molecular interactions. In the gas phase, activity is called fugacity.

Cross-References

- [Oxygen Fugacity](#)

Activity, Magnetic

Thierry Montmerle
 Institut d'Astrophysique de Paris, Paris, France

Keywords

Magnetic fields, Chromosphere, Corona, and Flares · Dynamo effect · Doppler-Zeeman imaging · UV radiation, X-rays

Definition

Magnetic activity is a characteristic of low-mass stars, with the Sun as a prototype. Its most

spectacular observational manifestation is in the form of stellar flares that can be seen in the optical domain, UV, and X-rays. These flares correspond to the release of magnetic energy, itself temporarily built up as a result of movements of the outer layers of these stars, which are convective (“dynamo” effect). During flares, the stellar luminosity is enhanced by a factor which depends on the energy domain, but which is maximum in X-rays (amplification by a factor of up to 10 or more). The whole phenomenon typically lasts a few hours and may be described by a rapid heating phase (minutes to tens of minutes), followed by a long cooling phase (a few hours).

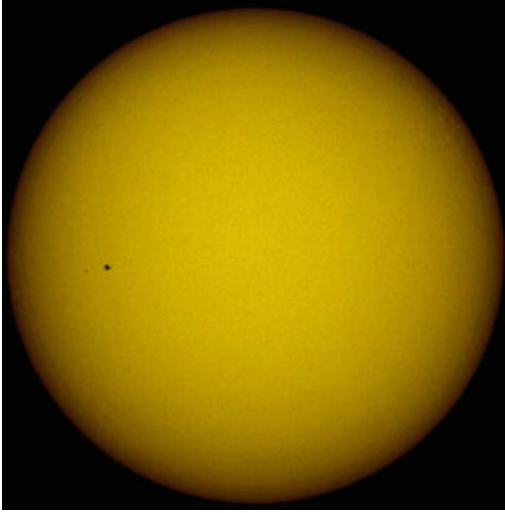
History

The Sun is the first known celestial X-ray source. It was discovered by rocket observations in 1949 by a group of physicists in New Mexico, USA (Friedmann et al. 1951). Since EUV photons and X-rays cannot penetrate the Earth’s atmosphere, studies continued using high-altitude balloons, and finally satellites (50 launched in the world between 1957 and 2021, including satellites hosting also other detectors, like EUV or gamma-rays). The first solar X-ray images were obtained on the *Skylab* space station (1973–1979), establishing the link between X-rays and magnetic fields. The Sun is now continuously monitored by satellites on various orbits, including heliosynchronous. Following the progress in solar X-ray imaging, the X-ray emission from individual stars was discovered by the *Einstein* satellite (1978–1981), already showing “solar-type activity” (flares), hence magnetic in origin. The largest X-ray telescopes, still in operation 22 years after their launch (NASA’s *Chandra* and ESA’s *XMM-Newton*) have detected hundreds of thousands of stars with evidence for magnetic activity.

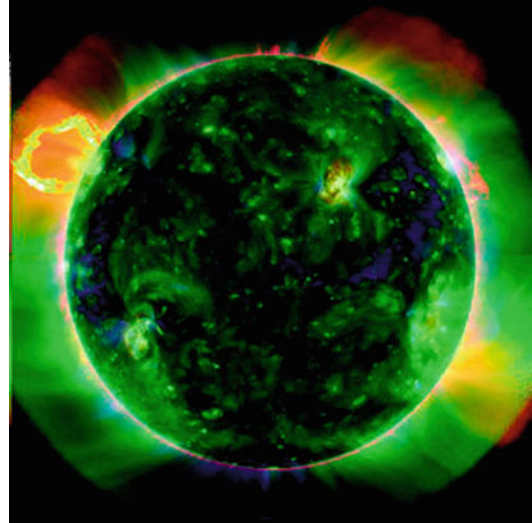
Overview

Solar Activity

The prototype of a “magnetically active star” is the Sun, for which high-resolution images show,



Activity, Magnetic, Fig. 1 The Sun in visible light, during its ultraquiet period of Spring 2009. Note the two minuscule black “spots”: They are the silhouettes of the Space Shuttle servicing the International Space Station (photograph NASA/T. Legaut)



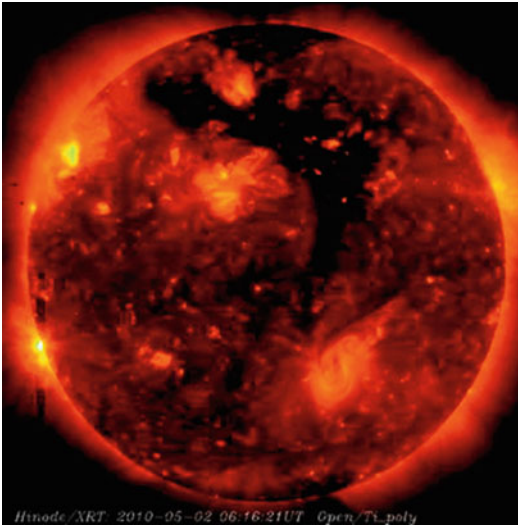
Activity, Magnetic, Fig. 2 The Sun in visible/EUV light, having regained its activity in early 2010. The hot gas is confined by closed magnetic loops in many places, in particular here at the limb (color-coded: bright regions are the hottest, $\sim 10^6$ K). There are also open magnetic field structures, which let the hot gas escape in the form of the solar wind. (*Solar Dynamics Observatory*, NASA)

at all wavelengths, numerous localized “active regions” (the largest ones seen as sunspots in the visible domain). The solar magnetic activity is best seen at “hot” temperatures (10^5 – 10^7 K), i.e., in the EUV and X-ray domains. The corresponding regions are, respectively, called the “chromosphere” and the “corona.” Magnetic activity is also seen in the visible domain, which corresponds to the “photosphere” (the surface of the Sun as we see it with the naked eye). A closer view shows that the solar surface is constantly in motion: This is due to the phenomenon of *convection*, which is the result of energy transport from the interior of the Sun. Figure 1 shows the optically visible Sun in its ultraquiet epoch of Spring 2009, and Fig. 2 shows for comparison the optical/EUV Sun, which regained activity a few months later. These structures evolve with time: on long timescales (days, weeks: starspots, prominences), but more spectacularly on timescales of hours (flares, such as the one seen on the solar limb of Fig. 2). Solar flares reveal material being heated in a few tens of minutes and confined by large magnetic loops; subsequently, the material cools, decays, and eventually flows back to the photosphere after a few hours. The magnetic field

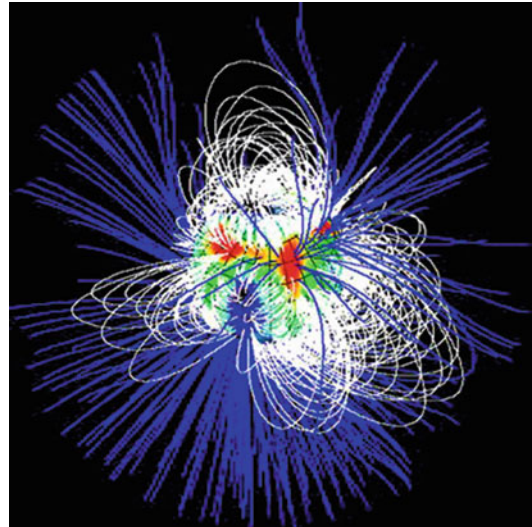
is created via the so-called “dynamo effect,” resulting from the macroscopic movement of electrically charged convective gas. As shown on Fig. 3, the contrast between “active” regions and “quiet” regions is stronger at X-ray energies. This turns out to be a crucial factor for studying stellar magnetic activity.

Stellar Magnetic Activity

The so-called stellar “magnetic activity” is a characteristic of all “solar-type stars” (by extension from the Sun: relatively cool stars with temperatures between 3000 K and 10,000 K, and masses between ~ 0.1 Msol and ~ 2 Msol; for comparison, the surface temperature of the Sun is ~ 6000 K). These stars have convective outer layers and generate their own magnetic field by the dynamo effect like the Sun. The crucial observational difference between these stars and the Sun is that they cannot be resolved; in other words, they appear as points in any imaging device. However, one can reconstitute to some degree the stellar surfaces by using their *rotation*, which modulates the signal: Since active regions (such as spots) are



Activity, Magnetic, Fig. 3 The Sun in X-rays, as seen by the Japanese Hinode satellite. Active regions are again tightly linked with magnetic loops. Here the brightest regions reach a temperature of several $\sim 10^7$ K. (JAXA)



Activity, Magnetic, Fig. 4 Image reconstruction of the active regions and magnetic field topology of the young star SU Aur, observed via Zeeman-Doppler imaging. (@ Wikipedia: P. Petit, Observatoire Midi-Pyrénées)

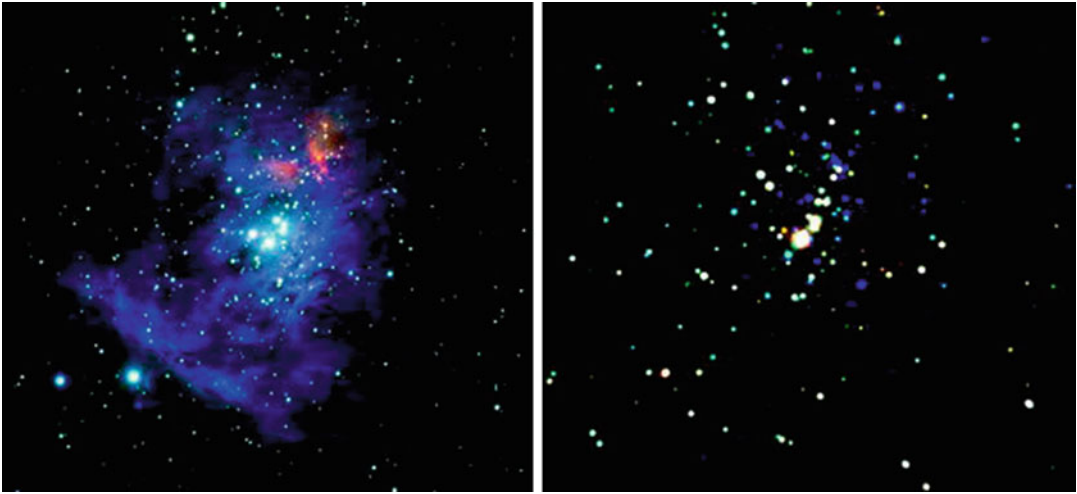
cooler, hence darker than the surrounding surface, their emission is Doppler-shifted when the spots appear to move toward, then away from, the observer, as the star rotates. In favorable cases, it is possible to go one step further, by using the Zeeman effect. This is a physical phenomenon in which, under the influence of magnetic fields, specific spectral lines are slightly splitted into three components, sensitive to polarization, and which are also Doppler-shifted as a result of stellar rotation. Using sophisticated deconvolution methods, one can then reconstruct not only the location and size of active regions, but also the topology of their associated magnetic fields. Figure 4 shows such a reconstruction in the case of a young solar-type star.

A broader view of stellar magnetic activity is provided by X-rays. In particular, the generally large field-of-view of X-ray telescopes allows the simultaneous study of all the stars in the field, especially if they belong to a cluster. This is the case for young, premain sequence stars (“T Tauri” stars): As shown as an example on Fig. 5, over 2000 stars can be observed simultaneously in the Orion star formation region (associated with its famous nebula M42). Long exposures (several

days) reveal the occurrence of ubiquitous X-ray flares, most very similar to solar flares, and a few being of much longer duration and extreme temperatures (up to 10^8 K).

Basic Methodology

Solar and stellar magnetic activity are observed essentially from space. NASA’s solar satellite SDO (*Solar Dynamics Observatory*), launched in February 11, 2010, transmits high-resolution full-disk optical/EUV images at the unprecedented rate of 1 image per second (Fig. 2). Meanwhile, ESA/NASA’s SOHO (*Solar and Heliospheric Observatory*), launched in December 1995, will continue to provide data until 2025 on the Sun activity and solar wind in the same domain, covering in all almost three full solar magnetic cycles of 11 years. The Sun is also imaged in X-rays (Fig. 3), in particular by a series of Japanese-led satellites (*Yohkoh*; now *Hinode* since 2006), providing the best comparison set for stellar magnetic activity studies. Stars are observed using X-ray satellites (NASA’s *Chandra* and ESA’s *XMM-Newton*, both launched in 1999



Activity, Magnetic, Fig. 5 The Orion nebula seen in X-rays. *Left:* Near-IR image of the Orion Nebula cluster, which contains ~ 2000 stars (ESO/VLT/ISAAC). *Right:* X-ray image of the same cluster, obtained with the *Chandra* satellite (NASA). An excellent, one-to-one

correspondence holds between the stars visible on the left, and the point X-ray sources visible on the right. A long exposure of this region shows ubiquitous flares from all the low-mass stars. (From Montmerle et al., *Earth, Moon & Planets*, 98, 39–95, 2006)

and still in operation) that have both a large field of view (a fraction of a square degree) and high spatial resolution. In the case of *Chandra*, the spatial resolution is comparable with that of the best ground-based telescopes ($0.2''$ along the axis), allowing to resolve compact stellar clusters like those found in star-forming regions. In addition to imaging, X-ray satellites also have spectral capabilities, allowing to measure densities, temperatures and composition of the X-ray-emitting plasma, and their dependence with time (for instance, flares and associated coronal emission).

Key Research Findings

The vast majority of “solar-like stars” show evidence for magnetic activity, and observations show that X-rays are an excellent proxy to compare with solar magnetic activity. However, the level of activity is very different depending on stellar type. This level is generally measured by the ratio of the energy output in X-rays (the X-ray luminosity L_X), to the total energy output (the bolometric luminosity L_{bol}). For the Sun, $L_X/L_{\text{bol}} \sim 10^{-7}$, with an amplitude of a factor ~ 10 over magnetic cycles. In contrast, fully convective

stars like “emission-line,” late-type cool stars, and very young T Tauri stars have L_X/L_{bol} reaching $\sim 10^{-3}$. This limiting factor is due to “saturation,” i.e., when active regions cover essentially all the stellar surface, as opposed to 5% for the Sun. For the youngest T Tauri stars (ages less than a few Myr), the magnetic activity is altered by another phenomenon, which is the accretion of material from a circumstellar, protoplanetary disk, along large-scale magnetic field lines connecting the star and the disk. This phenomenon is seen as “soft” X-ray (< 1 keV) emission due to a shock when the accreted material falls onto the stellar surface, superimposed on the “hard” (> 1 keV) coronal emission.

Applications

For present-day human environment, the solar magnetic activity is strongly related to the notion of “space weather,” i.e., the interaction of the solar wind with the Earth’s magnetic field. For astrobiology, X-rays from the young Sun (and from young stars in general) may have had an important influence, via ionization of atoms and molecules, on early planetary atmospheres. More generally,

the study of solar and stellar magnetic activity is related to fundamental plasma physics: low-density plasmas in the corona and (in the case of young stars) interaction with a circumstellar disk; high-density plasmas in motion, leading to the generation of magnetic fields in outer convective zones (dynamo effect). Theoretical developments are now based on sophisticated numerical 3D simulations.

Future Directions

From an astronomical point of view, the similarities between solar and stellar magnetic activity allow two different approaches to the same problem, i.e., the origin of stellar magnetic fields: (i) considering the “Sun as a star,” where proximity allows detailed, localized studies; (ii) considering “stars as suns,” allowing statistical approaches on magnetic activity properties as a function of spectral type (mass, age, and evolutionary status) for thousands of stars, in particular for young stars at the stage of planet formation.

Cross-References

- [Faint Young Sun Paradox](#)
- [Magnetic Field](#)
- [Sun \(and Young Sun\)](#)
- [X-Rays \(Stellar\)](#)

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Adakite

Hervé Martin
Laboratoire Magmas et Volcans, Université
Clermont Auvergne, Aubière Cedex, France

Keywords

Adakite · Archean TTG · Hot subduction · Slab melting

Definition

Adakite is a volcanic rock of dacitic composition (dacite is a rock between intermediate andesite and felsic rhyolite and mainly composed of plagioclase, feldspar, and quartz) which emplaces in ► [subduction](#) zones. While most subduction-related magmas are generated by hydrous melting of the mantle wedge, adakites result from the melting of the subducting slab itself. Their geochemical composition is very similar to that of Archean ► [tonalite-trondhjemite-granodiorite](#) rocks or TTGs, of which they are modern analogues. This similarity supports the hypothesis that Archaean continental crust – dominated by TTG terranes – was generated in subduction-related environments.

Overview

Adakites are present-day volcanic rocks of dacitic composition, only little plutonic equivalents are known today (Bourgeois et al. [2016](#)). Martin ([1999](#)) showed that they are sodium-rich ($3.5\% \leq \text{Na}_2\text{O} \leq 7.5\%$) and relatively potassium-poor ($\text{K}_2\text{O} / \text{Na}_2\text{O} \sim 0.42$). Their Sr

Hervé Martin: deceased.

content is high ($\text{Sr} > 400 \text{ ppm}$, $\text{Sr}_{\text{average}} = 706 \text{ ppm}$), they have fractionated REE (► [Rare Earth Elements](#)) patterns ($(\text{La} / \text{Yb})_{\text{average}} = 20.4$) and typical low HREE contents ($\text{Yb}_{\text{average}} = 0.93 \text{ ppm}$).

Adakitic active volcanoes are only found in subduction zone environments, mainly along the circum-Pacific “Ring of Fire,” which is a belt of active arc volcanoes bordering the Pacific Ocean. They emplace exclusively where the subduction and/or the subducted slab are young ($< 30 \text{ Ma}$). Since pioneer works of Kay (1978), Rogers et al. (1985), and Martin (1986), it has been shown that under specific conditions (hot subduction), the subducted oceanic basalts can melt and give rise to acid and sodium-rich magmas, today known as adakite (Drummond and Defant 1990).

Martin (1999) proposed that adakites could represent the modern effusive equivalents of the Archean TTGs, proposition that was immediately challenged by Smithies (2000). However, in a more recent article, Martin et al. (2005) show that the term adakite in fact covers two families of magmas of different origins:

1. One rich in silica (HSA = High-Silica Adakites) is the product of melting of hydrated basalts in the garnet-stability domain; and whose chemical composition is very similar to that of Archean TTGs;
2. The other with low silica contents (LSA = Low-Silica Adakites) is generated by partial melting of a mantle peridotite previously metasomatized by magmas with HSA composition. LSAs are in no way an analogue of the Archean TTGs.

The very strong similarities that exist between modern HSA and TTGs attest that both have the same source and petrogenesis. Consequently, when Archean-like *Pressure–Temperature* conditions are exceptionally reached in modern subduction zones, Archean-like magmas are generated. This analogy strongly supports the hypothesis that Archean continental crust genesis took place within a subduction geodynamic environment.

Cross-References

- [Mafic and Felsic](#)
- [Tonalite-Trondhjemite-Granodiorite](#)

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Adaptation

Susanna Manrubia
Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Keywords

Ecosystem · Environmental change · Genetic change · Mutation · Phenotype · Selection

Definition

Adaptation is a dynamical process whereby populations become better suited to their habitat. It is promoted by environmental changes, be they abiotic (e.g., climatic change) or biotic (e.g., the appearance of a new trait in a predator or the extinction of a competitor ► [species](#)). Adaptation is the outcome of ► [natural selection](#) acting on heritable variation and leading to a change in the genetic makeup of a population. It may involve changes in any phenotypic trait, among others, in morphology, physiology, dispersal, defense and attack mechanisms, development and growth, reproduction, behavioral patterns, and ecological interactions.

Overview

Adaptation has been an ongoing process ever since the emergence of the first self-replicating molecules. Populations of replicating entities generate continuous variability chiefly due to ► [mutations](#) and (in the case of organisms) to the migration of ► [genes](#) and other mobile genomic sequences. Adaptation is a gradual process that occurs over many generations as the offspring (i.e., the genes) of individuals best suited to the current habitat become increasingly abundant. Under environmental changes, species can react in three different ways. In case of slow change, they (1) perform habitat tracking if the change is exogenous (i.e., the population shifts with the ► [environment](#) to maintain the characteristics of its habitat) or (2) undergo genetic change. Only in the latter case are they truly adapting. If changes are too sudden, species cannot adapt and (3) become extinct. Even if the abiotic environment remains constant, the steady generation of mutants within a population compels related species to change. The appearance of teeth and claws in predators forces a simultaneous improvement in defense organs (as skeletons) to escape extinction. This sustained competition is called the Red Queen effect (Van Valen [1973](#); Stenseth and Maynard Smith [1984](#)).

Many adaptive changes in the history of life are gradual and involve a significant number of sequential modifications, as the evolution of tetrapod limbs from the fins of precursor fish. Some changes (the invention of lungs, of vascular systems in terrestrial plants, or of organs for flight) permitted organisms to colonize new ecological niches (Gould [1993](#)). Certain major transitions in evolution (Maynard Smith and Szathmáry [1995](#)) are probably not the result of adaptation, but of contingency. Such might be the case for the appearance of eukaryotic cells or of multicellular organisms.

Since natural selection acts on the phenotype as a whole, it is impossible to simultaneously improve all its traits in the same degree (Mayr [1982](#)). Also, traits that were once the result of adaptation may turn to be disadvantageous when the habitat changes. Hereditary hemochromatosis causes an excessive absorption of iron that accumulates in human body tissues. This disease is more common among Europeans: it protects against bacterial infections and probably became frequent at the time of the Black Death (Moalem and Prince [2006](#)). This is an example of the many currently nonadaptive traits that were permitted to thrive at some point of time in the history of a species.

Cross-References

- [Colonization, Biological](#)
- [Environment](#)
- [Evolution, Biological](#)
- [Evolution, Molecular](#)
- [Gene](#)
- [Mutation](#)
- [Natural Selection](#)
- [Phenotype](#)
- [Species](#)

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Adaptive Optics

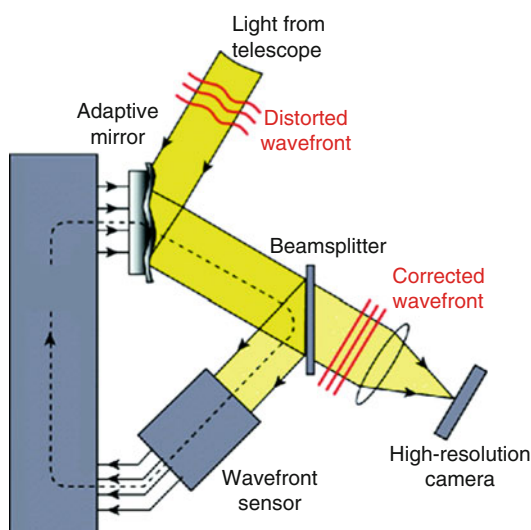
Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Adaptive optics is a technique, used while performing visible or near-infrared imaging from a ground-based telescope, that improves the image quality that is otherwise degraded by the atmospheric turbulence. The wave-front distortions, measured on the studied object or a nearby star, are compensated by deforming a small, thin mirror at a speed higher than turbulence (1 kHz typically) (Fig. 1). The deformable mirror is conjugated to the pupil of the telescope. The use of this technique is mandatory in any method, such as coronagraphy, that aims at a direct imaging of exoplanets.

In the mid of the last decade, adaptive optics systems especially optimized for direct detection of circumstellar disks and exoplanets were installed on several very large telescopes: SPHERE on the VLT, GPI on Gemini South, and SCExAO on SUBARU. Notably they feature what is called extreme adaptive optics (XAO) that allows to reach an effective angular resolution q (angular size of the smallest detail on an image) practically equal to the theoretical limit $q = \lambda/D$ where λ is the wavelength and D the diameter of the telescope.

Adaptive optics should not be confused with active optics that corresponds to corrections



Adaptive Optics, Fig. 1 Cartoon describing the principle of adaptive optics: The wave front deformed by atmospheric turbulence is corrected thanks to a deformable mirror that produces an inverse deformation several hundred times per second, after a device called a wave-front sensor has measured the residual distortion. A real-time computer is used to analyze the residuals and to define the proper surface to give to the mirror. The final improved image is obtained on a camera

applied to the large primary telescope mirror, deformed under gravity, at a much lower frequency (0.1 Hz).

Cross-References

- [Coronagraphy](#)
- [Imaging](#)
- [Telescope](#)

Adenine

Shin Miyakawa
Kamagaya, Chiba, Japan

Definition

Adenine ($C_5H_5N_5$), with molecular weight 135.13, is one of the four nucleic acid bases

found in ► [DNA](#) and ► [RNA](#). Via Watson-Crick base pairing in double-stranded ► [DNA](#) and ► [RNA](#), adenine forms two hydrogen bonds with ► [thymine \(T\)](#) and ► [uracil \(U\)](#), respectively. It is hydrolyzed to give hypoxanthine. The half-life to hydrolysis in aqueous solution at pH 7 is 1 year at 100 °C and 6×10^5 years at 0 °C. It has a UV absorption maximum at 260 nm. It has been found in the Murchison meteorite and can be synthesized in HCN polymerizations, ► [Fischer-Tropsch-type reaction](#), and electric discharges acting on gas mixtures such as $\text{NH}_3\text{-CH}_4\text{-C}_2\text{H}_6\text{-H}_2\text{O}$.

Cross-References

- [DNA](#)
- [Fischer-Tropsch-Type Reaction](#)
- [HCN Polymer](#)
- [Hydrogen Cyanide](#)
- [Hypoxanthine](#)
- [Meteorite, Murchison](#)
- [Nucleic Acid Base](#)
- [RNA](#)
- [Thymine \(T\)](#)
- [Uracil \(Ura\)](#)

Adenosine 5'-Triphosphatase

- [ATPase](#)

Adenosine Triphosphatase

- [ATPase](#)

Adenosine Triphosphate

- [ATP](#)

Adiabatic Processes

Guillaume Chaverot

Observatory of Geneva, University of Geneva,
CH-1290 Versoix, Switzerland

Definition

A thermodynamic process is called *adiabatic* if there is no heat exchange between the considered air or fluid parcel and its surroundings. Consequently, temperature changes are induced by a change in pressure. This process is a key point to determine the temperature gradient of planetary atmospheres and also of oceans.

In planetary atmospheres, an air parcel drifted upward cools and expands due to the decrease in atmospheric pressure. The rate at which the temperature falls is quantified by the *adiabatic lapse rate* (Pierrehumbert 2010; Wallace and Hobbs 2006). If the partial pressure of the condensable gas is below the *saturation pressure*, the process is called *dry adiabatic*, and its lapse rate is $-dT/dz = g/c_p$ where g is gravity acceleration and c_p the heat capacity of the gas. Indicative lapse rate values of different planets are given in Table 1.

When the pressure reaches the saturation pressure, the process is called *moist adiabatic*, and the addition of *latent heat*, by condensation or evaporation of the gas, leads to define a *moist adiabatic lapse rate* different from that of dry air. This is true whatever the considered condensable gas.

Adiabatic processes also play a role to determine the thermal structure of oceans (Stewart 2008) (even on icy moons), but the adiabatic lapse rate depends as well on other physical processes (e.g., salinity).

Adiabatic processes are often considered isentropic, thus reversible, i.e., the entropy remains unchanged. In other words, the system evolves slowly enough to reach the thermodynamic equilibrium at all times.

Although there are thermal exchanges at the surface interface (e.g., atmosphere/ocean

Adiabatic Processes, Table 1 Estimation of the dry adiabatic lapse rate of the atmosphere of different planets. The given value is computed at surface pressure and temperature

	Dry adiabatic lapse rate (K/km)
Earth	9.8 (Zurek 2017)
Venus	10 (Limaye et al. 2018)
Mars	5.0 (Zurek 2017)
Titan	1.3 (McKay et al. 1997)

interface), the surface temperature of a planet is mainly determined through adiabatic processes in planetary atmospheres (and oceans); therefore, they are a key point to study planetary habitability.

Cross-References

- Atmosphere, Structure
- Atmosphere, Temperature Inversion
- Atmospheric Modeling, Gray Gas Model
- Atmospheric Modeling, Non-gray Gas Model
- Earth-like Atmosphere
- Ocean Planet

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Adsorption

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Adsorption is the accumulation of molecules from the gas phase, or more generally from any fluid (adsorption operates in liquids as well as gases), onto a solid surface, e.g., of an ► [interstellar dust](#) grain. The molecules may be bound by physical (van der Waals), electrostatic, or chemical (e.g., hydrogen bonding) forces.

Cross-References

- [Interstellar Dust](#)

AEB, Brazil

Rodrigo Leonardi¹ and Michel Viso²
¹SPO/ Policial Sul, Agência Espacial Brasileira, Brasília, Brazil
²Innovaxiom, Paris, CX, France

Synonyms

[Agência Espacial Brasileira](#); [Brazilian space agency](#)

Definition

Numerous committees since 1961 have been charged with space activities in Brazil. In February 1994, the Brazilian Space Agency was established with the Department of Science and Technology. The agency is partnering with four institutes in

charge of specific missions. The National Institute for Space Research (INPE) in charge of developing satellites and products for civilian use, the Institute of Aeronautics and Space in charge of developing planes and the launch vehicles, and two launching bases in Alcantara and Barreira do Inferno. The space agency is also engaging in international cooperation. For further information: <http://www.aeb.gov.br/>.

- [Electron Acceptor](#)
- [Respiration](#)

Aerobic Mesophilic Bacterial Spore

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Aerobe

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Aerobes are organisms that can tolerate or require the presence of (strict aerobe in this case) oxygen. Oxygen is an extremely strong oxidant and produces very reactive radicals, which react with amino acids or nucleic acids inactivating the functional sites of enzymes or producing lethal mutations. Practically, all animals are aerobes; most fungi and many prokaryotes can survive in the presence of oxygen. To do so, aerobic organisms require the presence of detoxification activities, like catalases and peroxidases. Among aerobes there are different kinds of organisms: obligate aerobes, which require oxygen for growth and use oxygen as final ► [electron acceptor](#) in the ► [respiration](#) process; facultative aerobes, which can use oxygen or not, to obtain energy; micro-aerophiles, which require low levels of oxygen; and aerotolerants, which are not affected by the presence of oxygen.

Cross-References

- [Aerobic Respiration](#)
- [DNA Damage](#)

Definition

The term “spore” as used in planetary protection is a shorthand form for “bacterial endospore,” which is a resistant dormant configuration produced by some ► [microorganisms](#) (principally Gram-positive bacteria) as a response to environmental stressors. Microorganisms are characterized as “aerobic” based on their ability to grow while exposed to oxygen, while “mesophilic” is descriptive for microorganisms that grow (in a lab on nutrient-rich media) at temperatures comfortable for humans (between 15 °C and 40 °C). Outside these preferred conditions (in the absence of oxygen, nutrients, or on exposure to temperature extremes), spore-forming organisms may form spores. In the spore configuration, these bacteria are capable of surviving extreme environmental conditions in dormancy, and then repopulating when reintroduced into a more hospitable environment. This aerobic mesophilic bacterial spore type is commonly used in ► [planetary protection](#) as a reference microorganism for the qualification of ► [bioburden](#) reduction processes, and quantitation of such spores on and in spacecraft is used as a proxy indicator for the cleanliness of spacecraft components and systems.

Cross-References

- [Bioburden](#)
- [Microorganism](#)
- [Planetary Protection](#)

Aerobic Respiration

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

Oxygen respiration

Definition

Aerobic ► [respiration](#) is a respiration in which dioxygen (O₂) serves as the terminal ► [electron acceptor](#) of an electron transport chain.

Cross-References

- [Electron Acceptor](#)
- [Respiration](#)

Aerobiology

Rocco Mancinelli

Bay Area Environmental Research Institute,
NASA Ames Research Center, Moffett Field, CA,
USA

Keywords

Biology, of the atmosphere · Microorganisms,
in the atmosphere · Pollen · Spores

Definition

Aerobiology is the study of the occurrence, movement, and dispersal of living or once-living material through the atmosphere.

Overview

The atmosphere presents a series of challenges for life, from radiation to desiccation. The absolute amount of solar radiation and the proportional contribution of ultraviolet B and ultraviolet C radiation increase with altitude, both of which are particularly hazardous to biomolecules. The low temperature and pressure at 29 km above the surface of the Earth are similar to those on Mars and create problems due to freezing and desiccation. Finally, the lack of nutrient availability in the atmosphere creates an additional challenge for life.

The survival of airborne microbes should not be confused with growth and division while airborne. In fact, one of the critical questions that has yet to be answered unequivocally is “do microbes metabolize and divide while airborne?” If they do, then the atmosphere may be considered a true habitat rather than just a place where they are transient interlopers. Although there are studies that suggest that airborne microbes have the potential to metabolize and divide in the atmosphere, these studies are inconclusive.

Given the hostility of the environment, Earth’s atmosphere just above the surface contains a variety of airborne microorganisms that are thought to originate from the soil, lakes, oceans, animals, plants, as well as any process causing aerosols or dust. The numbers of viable airborne microbes recovered from the atmosphere vary seasonally with the highest numbers obtained during the summer and fall and the lowest in the winter. The distances that airborne organisms may travel range from a few kilometers to thousands of kilometers. There is a statistically significant positive correlation between the total number of viable bacteria isolated from urban air and the concentration of suspended particulate matter in the air. The organisms may be protected from drying by adsorbed water on the surfaces of these suspended particles.

Studies of the biology of the upper troposphere and lower stratosphere (5–20 km) date back to the late 1800s using balloons. But these studies are few in number and not well controlled. The organisms collected included fungi and spore-forming bacteria.

Later studies reported a larger variety of nonspore-forming microbes, especially a variety of pigmented bacteria. However, the composition and prevalence of microorganisms in the middle to upper troposphere (8–15 km altitude) and their role in aerosol–cloud precipitation interactions are unresolved. Using meteorological rockets, fungi and pigmented bacteria have been isolated from as high as 77 km, the highest altitude from which microbes have been isolated. These studies, however, all used culturing methods to determine microbial counts. It has been estimated that those methods allow studying only between 0.1% and 10% of the total microbial flora in any given environment. Therefore, it is speculated that a number of microbes may exist in the upper atmosphere that we do not have the ability to culture and go unnoticed and uncultured. More recently, however, studies using molecular microbiology techniques, microscopy, and conventional culturing have shown that bacterial cells outnumber fungal cells in the upper troposphere.

Cross-References

- [Aerosols](#)
- [Bacteria](#)
- [Desiccation](#)
- [Extreme Environment](#)
- [Mars](#)
- [Solar UV Radiation, Biological Effects](#)
- [Spore](#)
- [Survival](#)

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Aerogel

Makoto Tabata

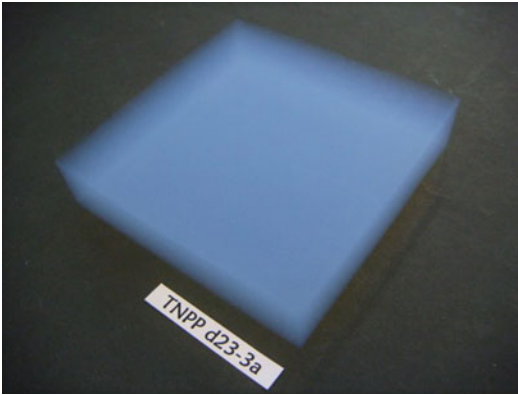
Department of Physics, Graduate School of Science, Chiba University, Chiba, Japan

Definition

An aerogel is a non-fluid colloidal system of a microporous (or mesoporous) solid in which pores are filled with a gas. It is usually used to indicate a silica aerogel. In this case, a mesoporous three-dimensional network is composed of nanoscale silicon dioxide clusters and the open pores are filled with air. Silica aerogels are optically transparent and are one of the most lightweight forms of condensed materials. The bulk density of aerogels can be controlled during the fabrication process. Low-density silica aerogels are often used to capture mostly intact cosmic dust in space.

History

Aerogels including silica-based aerogels were first created by Kistler (1931). Based on IUPAC Recommendations, an aerogel is defined as a “gel comprised of a microporous solid in which the dispersed phase is a gas” (Alemán et al. 2007). Of the aerogel family, silica aerogel (Fig. 1) is the most suitable material for capturing hypervelocity (km/s) cosmic dust grains while maintaining their chemical and structural properties due to its low-density characteristics. While decelerating, the dust particle forms impact cavities (referred to as a “track”) and is trapped inside the aerogel. The



Aerogel, Fig. 1 Hydrophobic 30 mg/cm³ silica aerogel with a dimension of 9 cm × 9 cm × 2 cm fabricated at Chiba University. Shorter wavelength visible light (blue) is strongly scattered by the aerogel structure of tens of nanometers (Rayleigh scattering)

optical transparency of the silica aerogel allows the impact track and the captured particles to be identified under optical/digital microscopes. The aerogel is stable in space, though the pore air is ejected into the vacuum. The use of silica aerogels as a cosmic dust collection media have been summarized by Tsou (1995) and reviewed by Burchell et al. (2006). In addition to silica aerogels, titanium-doped alumina–silica (Al₂O₃–SiO₂) hybrid aerogels have been suggested by Domínguez et al. (2004) to estimate the dust impact velocity using a fluorescent impact cavity imaging technique. Non-silica aerogels have also been studied by Jones (2010). Extended applications of aerogels in space exploration, including their use as thermal insulators, have been explained by Jones (2006).

To fabricate a silica aerogel, a wet silica gel is first synthesized via a sol–gel polymerization method involving the hydrolysis and condensation of a silica precursor. After aging, surface hydrophobic modification (optional) and solvent exchange are conducted. Finally, the wet gel is rendered to an aerogel by drying it using a supercritical extraction method, followed by baking at high temperature for purification (optional). More specifically, a two-step method is generally used in wet gel synthesis: a partially hydrolyzed, partially condensed silica precursor (silica oil) is produced, and then, a wet gel is synthesized

from the silica oil to obtain a highly transparent, low-density aerogel (Tillotson and Hrubesh 1992). The first step to obtain the silica oil can be omitted by using an industrial silica precursor chemical (one-pot sol–gel synthesis) as reported by Adachi et al. (1995). The aerogel density can be controlled by adjusting the volume ratio of the silica precursor and diluent solvents in the sol–gel process. Organic solvents (e.g., ethanol) or liquefied carbon dioxide are used as the supercritical fluid in the high- and low-temperature drying process, respectively. To preserve the hydrophobic groups on the surfaces of silica clusters, surface-modified aerogels cannot be baked.

The application of silica aerogels as intact cosmic dust collection media was first recognized by Tsou et al. (1988). The performance of aerogels in laboratory experiments to capture particles traveling at hypervelocity was investigated using projectile accelerators prior to space missions. Then, the aerogels were first used in two independent missions in low-Earth orbits around the same time. One was aboard a NASA space shuttle in 1992 (Tsou et al. 1993). The 9-day mission was equipped with 21 aerogel tiles with active dimensions of 9 cm × 9 cm × 1 cm and a density of 20 mg/cm³. Four hypervelocity particles captured in the aerogels were identified. The second was aboard the EURECA free-flying spacecraft of the European Space Agency (ESA) in 1992–1993 (Brownlee et al. 1994). Four 50 mg/cm³ aerogel collector modules with dimensions of 10 cm × 10 cm were exposed to space for 11 months. A total of 12 hypervelocity impact cavities were determined to have formed in the aerogels.

The first use of aerogel capture media in deep space was completed by the NASA mission Stardust, which was designed to bring the first extraterrestrial material samples back to Earth from a known planetary body (comet 81P/Wild 2) other than the Moon (Tsou et al. 2003). The Stardust spacecraft was launched in 1999, encountered the comet in 2004, and successfully returned thousands of dust particles to Earth in 2006 (Brownlee et al. 2006). For this mission, an aerogel block with a gradient density profile (ranging from 10 mg/cm³ to 50 mg/cm³) along

the 3-cm thickness direction was developed at JPL (Jones 2007). The Wild 2 sample collector was comprised of 132 gradient density, hydrophilic aerogel blocks with dimensions of 4 cm × 2 cm, which were manufactured via the two-step sol–gel method and the high-temperature supercritical drying method. The spacecraft was also equipped with an interstellar dust collector comprised of gradient density (ranging from 10 mg/cm³ to 20 mg/cm³) aerogel blocks with a thickness of 1 cm. Westphal et al. (2014) investigated seven candidate dust particles captured by the collector in the cruising phase that had an interstellar origin.

The most recent aerogel collection media was applied in a JAXA astrobiology mission, Tanpopo, which was conducted aboard the International Space Station (ISS) from 2015 to 2019. One of the primary objectives of this multifaceted experiment is to return dust possibly containing terrestrial microbes and interplanetary dust containing extraterrestrial organic compounds from low-Earth orbit to ground laboratories. For this mission, a double-layer aerogel tile with densities of 10 mg/cm³ and 30 mg/cm³ was developed at Chiba University, Chiba, Japan (Tabata et al. 2016). A total of 36 hydrophobic aerogel tiles with dimensions of 9 cm × 9 cm × ~2 cm were fabricated using the one-pot sol–gel method and the low-temperature supercritical drying method, and were launched for three annual experiments. All the aerogel tiles were annually returned to the ground by 2019, and dozens of hypervelocity impact tracks were found in the aerogels used in each year's experiment. The Tanpopo2 mission was continuously conducted aboard the ISS from 2019 to 2020.

Cross-References

- Astrobiology
- Carbon Dioxide
- Comet
- COMET (Experiment)
- Comet Wild 2
- Dust Grain
- Ethanol
- EURECA

- European Space Agency
- International Space Station
- Interstellar Dust
- IUPAC
- JAXA
- JPL
- Moon, The
- NASA
- Precursor
- Stardust Mission
- Supercritical Fluid

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Aeronautics and Space Agency of FFG

► [ASA, Austria](#)

Aerosols

François Raulin
Faculté des Sciences et Technologie, Université
Paris Est Créteil et Paris Diderot, LISA – UMR
CNRS 7583, Creteil, France

Synonyms

[Atmospheric dusts](#); [Atmospheric particles](#); [Haze particles](#)

Definition

Aerosols are small liquid or solid particles in suspension in a gas. Solid smoke particles from the burning of vegetation, dust formed by wind erosion of soil, or liquid droplets produced by the ocean waves are examples of aerosols.

Aerosols are present in many planetary environments, for example, in the atmospheres of Mars, the giant planets, and ► [Titan](#), and they were probably present in the primitive atmosphere of the Earth, much as they are presently. Atmospheric aerosols can play an important role in

climate, producing an antigreenhouse effect, like the haze in Titan's atmosphere. Atmospheric photochemistry in several extraterrestrial environments, like Titan, produces organic aerosols which are similar to laboratory-synthesized ► [tholins](#), which can produce a complex set of prebiotic chemicals when reacted with water.

Cross-References

- [Atmosphere, Structure](#)
- [Carbon](#)
- [Cassini](#)
- [Cassini-Huygens Space Mission](#)
- [Clouds](#)
- [Flux, Radiative](#)
- [Hydrocarbons](#)
- [Jupiter](#)
- [Methane](#)
- [Refractory Molecule](#)
- [Saturn](#)
- [Tholins](#)
- [Titan](#)

Affinity Chromatography

Mark Dörr
University of Southern Denmark, Odense M,
Denmark

Definition

Affinity ► [chromatography](#) is a (bio-) chemical separation method based on highly specific molecular interactions (affinity) such as between antigens and antibodies, ► [enzymes](#) and ► [substrates](#), or receptors and ligands. The stationary phase is commonly composed of beads of a gel (e.g., agarose gel) with a covalently bound ligand (e.g., an ► [antibody](#)). Affinity chromatography is one of the most powerful separation methods, as it combines the size fractionation capability of gel permeation chromatography with specific, reversible interactions of molecules.

History

The method was introduced by Cuatrecasas, Wilchek, and Anfinsen in 1968 (Cuatrecasas et al. 1968). Pedro Cuatrecasas and Meir Wilchek were jointly rewarded the Wolf Prize in Medicine 1987 for this discovery.

Cross-References

- [Antibody](#)
- [Chromatography](#)
- [Enzyme](#)
- [HPLC](#)
- [Substrate](#)

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Affinity Constant

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

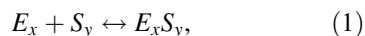
Synonyms

[Association constant](#); [Binding constant](#)

Definition

In chemistry and biochemistry, the affinity constant is the reciprocal of the dissociation constant, where both are equilibrium constants describing the strength of binding between a catalyst such as

an ► [enzyme](#) or ► [ribozyme](#) and its ► [substrate](#). A K_m value is a specific example of an affinity constant in enzymatic reactions. For example, the equilibrium for the formation of an enzyme-substrate (ES) complex between an enzyme (E) and a substrate (S),



can be represented as

$$K_m = \frac{|E_x S_y|}{[E]^x [S]^y} \quad (2)$$

where $[E]$, $[S]$, and $[ES]$ are the concentrations of enzyme, substrate, and the enzyme-substrate complex, respectively, and x and y represent their stoichiometric coefficients.

The affinity constant, also known as the Michaelis constant, has units of per molar (M^{-1}) or l/mole. Affinity constants can vary significantly with solution conditions (e.g., temperature, pH, and ionic strength).

This equilibrium is also the ratio of the rate of association (k_{ass}) and rate of dissociation (k_{diss}). Two different enzyme-substrate complexes may have the same affinity constants, but one could have a high k_{ass} and k_{diss} , while the other may have a low k_{ass} and k_{diss} .

Cross-References

- [Enzyme](#)
- [Ribozyeme](#)
- [Substrate](#)

AFGL 915, IRAS 06176-1036

- [Red Rectangle](#)

AGB

- [Asymptotic Giant Branch Star](#)

Age Measurement

► [Geochronology](#)

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Agentur für Luft-und Raumfahrt der FFG

► [ASA, Austria](#)

Agenzia Spaziale Italiana

► [ASI](#)

AIB

► [Aminoisobutyric Acid](#)

Akilia

Minik T. Rosing
Nordic Center for Earth's Evolution, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark

Definition

Akilia is the name of a small island (~2.3 km by 1.4 km) south of the town of Nuuk on the SW coast of Greenland (63.933°N, 51.667°W). The Akilia sequence of rocks has its name from this island, but they occur throughout the Eoarchean of West Greenland. The Akilia sequence consists mainly of granitic gneiss and includes some of the

oldest rocks on Earth. The largest member of this group of rocks is the ca. 3.8 Ga-old ► [Isua supracrustal belt](#) composed of metamorphosed pillow basalts, clastic, and chemical sediments that constitute the oldest known supracrustal sequence. Fractionated C, N, and S isotopic compositions of materials of probable sedimentary origin are thought to be biogenic and to provide the oldest record of life on Earth.

Cross-References

► [Earth, Formation, and Early Evolution](#)
► [Isua Supracrustal Belt](#)

Al-Andalus, Cosmological Ideas

Ahmed Ragab
Harvard Divinity School, Cambridge, MA, USA

Keywords

Islam · Islamic astronomy · Andalus · Iberia · Medieval · Ibn Tufayl · Ibn Rush · Averroes · al-Bitruji · Arzachel · al-Zarqālī · Ibn Sīnā

Overview

Ibn Tufayl's (Abubacer; d. 1185) main engagement with planetary theories was centered on his rejection of Ptolemaic eccentrics and epicycles as they contradicted the basic principles of Aristotelian physics. Ptolemy's eccentrics and epicycles implied two main violations of the classical principles of natural philosophy. On one hand, the eccentric meant that planets moved around a center different from the Earth. On the other hand, epicycles meant that planets moved west to east in their epicycles while moving east to west around the eccentric, therefore introducing double movement, which contradicted the single simple movement explained in works of natural philosophy.

While Ptolemy's model came close to solving the observational variation in movement, it violated significant principles of Aristotelian physics. Objecting to the Ptolemaic model required the production of different geometrical solutions that would allow for singular movement around the Earth and would explain the observations. Ibn Tufayl claimed to have arrived at a solution and promised to write it in a separate book but apparently never had the time to do so. Yet, Ibn Tufayl's student, al-Bitrūjī, credited his master by providing the basis for the former's solution.

Ibn Tufayl's objections had their roots in the works of Ibn Sīnā, who inspired much of Ibn Tufayl's works, including his most famous novella "Philosophus Autodidactus." Ibn Sīnā also rejected Ptolemy's model and claimed to have arrived at a solution, but after much effort he decided not to share it with any of his students and not to write it. Ibn Sīnā's student, al-Juzjānī, composed a solution for this problem in a letter addressed to his master. However, Juzjānī's solution was not sufficient.

Ibn Tufayl's more prominent student, Ibn Rushd (Averroes; d. 1198), wrote an epitome to Ptolemy's *Almagest* and acquired much of his fame because of his detailed commentaries on Aristotle. In his commentaries on Aristotle's metaphysics and *De Caelo*, Ibn Rushd criticized the Ptolemaic model and considered it to be unnatural. He explained that Aristotle and the ancients had arrived at perfect solutions for the celestial movement that escaped Ptolemy and that these solutions should be rediscovered. While he claimed to have worked on these solutions in his youth, Ibn Rushd left the task unfinished to his successors.

Ibn Tufayl's other student, al-Bitrūjī (d. 1204), who seemed to have worked entirely independently from Ibn Rushd without either of the two being aware of the other, was a more proficient astronomer and produced a model in which he attempted to address his master's objections. Bitrūjī maintained a homocentric universe in correspondence with natural philosophy, eliminating eccentrics and epicycles; he developed the notion

of rotating poles that was mentioned by Aristotle in *De Caelo*, even wondering why Ptolemy did not propose such a solution. Both Ibn Rushd and al-Bitrūjī accepted this polar movement, which was developed by Theon of Alexandria into spiral movement.

In addition to such cosmological discussions, the Toledan Tables, predicting the positions of the Sun, Moon, and planets, represented a more important contribution of Andalusian astronomers in fields of practical and computational astronomy. About a dozen astronomers in Toledo, the most prominent of whom was the astronomer and instrument-maker al-Zarqālī (Arzachel; d. 1087), and which included both Muslims and Jews, undertook different mathematical and astronomic calculations that resulted most prominently in the tables. Al-Zarqālī had an important theoretical contribution in relation to trepidation (a medieval theory related to the precession of the equinoxes), and he also improved Ptolemy's calculations of the length of the Mediterranean.

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al-Bīrūnī, Abū Rayḥān

Ahmed Ragab¹ and Allyssa Metzger²

¹Harvard Divinity School, Cambridge, MA, USA

²Harvard University, Cambridge, MA, USA

Keywords

Islam · Islamic astronomy · Avicenna ·
Medieval · India · Zij · Astrology · Calendar ·
Chronology

Overview

Abū Rayḥān al-Bīrūnī (d. 1048) was a Persian scholar of mathematics, astronomy, astrology, and geography, among other disciplines. Although he changed patrons frequently, he produced his most important works in the Ghaznavid court.

Educated in the dominant Greco-Islamic scholarship, Bīrūnī was interested in comparing different scientific traditions. His “Chronology of Ancient Nations” was a detailed exposition of calendars and chronologies used by different nations, including Arabs, Greeks, Persians, Jews, and Syriacs, among others. The *Chronology* was unprecedented in its comparative approach and its careful examination of different chronological systems. It also included detailed descriptions of these nations’ different religious feasts.

While accompanying the Ghaznavid sultan Maḥmūd (r. 998–1002) in India, Bīrūnī came in contact with Indian scholars and composed a significant volume where he addressed Indian religious beliefs and rituals, Indian sciences including astronomy and cosmology, and Indian chronology and calendars, which were missing from his *Chronology*. Bīrūnī’s work was the first to discuss “foreign” nations and histories in non-polemical fashion with the stated goal of understanding different scientific and belief traditions. His work in India included transmitting Ptolemy’s *Almagest* and other books of Greco-Islamic sciences to

Indian scholars. Bīrūnī’s comparative view was based on his stated belief that sciences are universal and they speak to universal laws of nature, only in different languages and using different models. Comparison of scientific theories, and of calendars and chronologies, was meant to explain the different approaches to a single universal truth.

Bīrūnī’s most influential text in the Islamic context was his *al-Qānūn al-Mas‘ūdī* (The Mas‘udic Canon), an 11-volume book in which he developed algebraic solutions of third-degree equations and distinguished between the motions of precession and the solar apogee. While the Canon was primarily based on Ptolemy’s *Almagest*, it was also an attempt at incorporating elements of Indian and Persian astronomy in the dominant Greco-Islamic tradition. Bīrūnī was aware of some difficulties in the Ptolemaic planetary theory. However, contrary to his contemporaries, Bīrūnī’s objections did not only stem from Ptolemaic violations of the principles of classical natural philosophy, as Avicenna’s (d. 1037) objections were, but were based on contradictions between the Ptolemaic system and Bīrūnī’s own observations. Bīrūnī’s correspondence with Avicenna showed some of Bīrūnī’s skepticism and doubts on Aristotelian natural philosophy.

While working as a court astrologer, Bīrūnī composed his *Tafhīm* on astrology, which he started with lengthy discussions of geometry and astronomy, with one quarter of the book for the actual discussion of judicial astrology. He argued that a well-trained astrologer, worthy of the name, must be proficient in all these sciences. As part of his systematic observations, Bīrūnī was interested in astronomical instruments – he wrote five books on instruments, including a lengthy one on the astrolabe. He also described a coordinated viewing of the lunar eclipse on 24 May 997 with Abu al-Wafa’ al-Buzjani (d. 998 CE) – from Khwarazm and from Baghdad – to better calculate coordinates of major Islamic cities. Some of Bīrūnī’s minor works discuss astronomical-mathematical concepts such as chords (Istikhraj al-awtār),

“shadows” or tangents (Ifrād al-maqāl), and planetary transits (Tamhīd al-mustaḡarr).

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al-Tūsī, Nasir al-Dīn

Ahmed Ragab¹ and Allyssa Metzger²

¹Harvard Divinity School, Cambridge, MA, USA

²Harvard University, Cambridge, MA, USA

Keywords

Islam · Islamic astronomy · Maragha · Medieval · Mongol · Zij · Observatory · Tusi couple · Avicenna

Overview

Nasir al-Dīn Tūsī (d. 1274) was a Persian scholar of mathematics, astronomy, philosophy, and theology; he was considered by many “the Third

Teacher” after Aristotle and al-Farabi (d. 950). Tūsī’s most renowned activities took place in the Maragha Observatory in what is now Iran, where he led a group of scholars including Chinese astronomers in different investigations and activities. It has been suggested that Tūsī’s criticisms of Ptolemaic astronomy influenced Copernicus’ rejection of equants in his *De Revolutionibus* (1543).

Tūsī studied mathematics, medicine, and Avicennan philosophy at Nishapur, then jurisprudence, mathematics, and astronomy in Iraq. In 1233, he entered the service of the Shiite Ismaili emir, Ibn Abī Maṣṣūr, for whom he dedicated his work on ethics (*Akhlaqī Naṣiri*). He spent time in the Nizari strongholds of Alamut and Maymundiz, where he had access to their libraries and produced a number of his known works. In 1255, he was sent by the lord of Alamut to negotiate with Hūlegū Khan (r. 1256–1265), who led the Mongol westward advances. He remained in Hūlegū’s service, which may have been put him in charge of Muslim endowments (*waqfs*) or other important financial institutions. Hūlegū patronized Tūsī’s works and allowed him to start the construction of the Maragha Observatory in 1259. Maragha became a destination for many scholars who benefitted from Mongol patronage and from the impressive library that was culled from conquered libraries in Mesopotamia, Baghdad, and Syria. Tūsī and his colleagues at Maragha completed a *zīj* (table of parameters for calculating the positions of the Sun, Moon, and planets; the Ilkhanid *Zīj*) around 1270 under Hūlegū’s successor, Abaqa Khan (r. 1265–1282). The *zīj* might have been one of the more practical tasks of the observatory.

Tūsī is best known for the Tusi couple – a mathematical device that transforms circular to linear motion. By rolling a circle of radius r along the inner edge of a circle of radius $2r$, such that the circles remain tangent and the smaller circle completes two rotations for every rotation of the larger, a given point on the smaller circle appears to oscillate along the diameter of the larger. The couple was produced as part of Tūsī’s

attempts to address some of the philosophical difficulties of the Ptolemaic model of planetary movements. Applied to the orbs, the couple could potentially allow for the observed variable length of the orbital radius without compromising the principle of uniform circular movement around the earth. Tūsī preferred this solution to Ptolemy's *equant*, which generated much opposition. Tūsī presented his couple not as a definitive solution but rather as "an indication of a solution," signaling perhaps that this model was only the beginning of a longer investigation to be carried out by his students and commentators. While an ostensible follower of Avicennan philosophy, Tūsī appeared to have taken a less radical approach to dealing with the Ptolemaic model than Avicenna (d. 1037) and his student al-Juzjānī (d. 1070), preferring to maintain the model for its practical values and attempting to present important modifications that would reconcile its contradictions, as opposed to rejecting the model for one that would conform better with laws of classical natural philosophy – a task that was never accomplished satisfactorily.

In his *Ethics*, Tusi presented ideas about the evolution or "perfection" of species, although his arguments had important ethical, theological, and mystical underpinnings.

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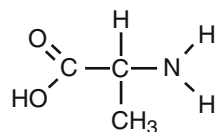
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Alanine

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

Alanine is one of the 20 α -amino acids found in coded proteins with the formula $C_3H_7NO_2$ and the structure



The α -carbon of alanine is chiral so there are two optical isomers (► [enantiomers](#)), l- and d-alanine. Alanine appears to be one of the first and is the second most common amino acids in terrestrial proteins. It was the first ► [amino acid](#) synthesized in the laboratory, by Adolph Strecker in 1850, who reacted acetaldehyde with hydrogen cyanide and ammonia in aqueous solution. It is also readily produced in ► [spark-discharge](#) experiments from a reduced gas mixture of methane, ammonia, and hydrogen and has been found in carbonaceous chondrites. Alanine is known to stabilize helical structures in proteins.

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Enantiomers](#)
- [Spark Discharge](#)
- [Strecker Synthesis](#)

Albedo

Mark S. Marley
NASA Ames Research Center, Moffett Field,
CA, USA

Keywords

Clouds · Equilibrium temperature · Planet · Spectroscopy

Synonyms

[Reflectivity](#)

Definition

Albedo is a unitless measure of the reflectivity of an object. Albedo can range between zero and one. Several different types of albedos have been defined, and it is important to appreciate their unique characteristics.

History

Albedo is derived from the Latin “albus” or “white.” The term was first applied to optics by Johann Heinrich Lambert (who gave his name to the Lambert disk) in his text *Photometria* in 1760.

Overview

From a planet-wide perspective, the albedo of most importance is the Bond albedo, A , the ratio of incident energy reflected into all angles by a planet to the total incident energy received from its star. The Bond albedo appears in the equation for the equilibrium temperature of a rapidly rotating planet T_{eq} , with radius R receiving an incident flux F ,

$$4\pi R^2 \sigma T_{\text{eq}}^4 = (1 - A)\pi R^2 F, \quad (1)$$

which equates the energy thermally radiated by the planet (left side) to the stellar (solar) energy absorbed. The Bond albedo is frequently (as in Eq. 1) computed by integrating the total reflectivity of a planet over the incident flux from the parent star and thus depends both on the reflectivity spectrum and the spectral type of the star. A planet that efficiently scatters in the blue and absorbs in the red portion of the spectrum will thus have a higher integrated Bond albedo when illuminated by a blue star than by a red star, since a greater proportion of the incident light is scattered away in the former case. However, the Bond albedo can be defined as a function of wavelength, $A(\lambda)$, e.g., Irvine et al. (1968), and is then usually termed the spherical albedo.

The geometric albedo is defined as the ratio of a planet’s reflectivity measured at zero phase angle (opposition) to that of a Lambert disk (which has the same apparent brightness at all viewing angles) of the same radius. The geometric albedo is a function of wavelength and, because it is measured at opposition (when the phase angle $\phi = 0$), does not require information on the dependence of scattering with phase. For a perfectly reflecting Lambert sphere, the geometric albedo is two-thirds and for a semi-infinite purely ► [Rayleigh scattering](#) atmosphere it is three-fourths. Both such idealized, perfectly scattering objects would have a Bond albedo of 1, but the latter atmosphere sends more light directly back to the observer at zero phase angle and thus has a higher geometric albedo. The geometric albedo is a fixed quantity for a given planet, so the computation of the geometric albedo does not depend on the type of incident flux. Other types of albedos have been defined. Great care thus must always be exercised to be certain that the correct albedo is being discussed.

Cross-References

- [Atmosphere, Structure](#)
- [Clouds](#)
- [Rayleigh Scattering](#)

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Albedo Feature

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Regio](#)

Definition

A geographic area on the surface of a [planet](#) or satellite that is distinguished from adjacent terrains by a difference in brightness or [albedo](#).

Classical albedo features have been identified with Earth-based telescopes, while no detailed morphology could be resolved. Time-varying albedo features can be due to seasonal changes, for example, due to frost covers or due to the redistribution of bright dust or dark sand sheets by aeolian activity. Thanks to high-resolution imagery on board of space probes, albedo feature nomenclatures are increasingly replaced with detailed feature descriptions.

Cross-References

- ▶ [Albedo](#)
- ▶ [Planet](#)
- ▶ [Regio](#)

Alcohol

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Definition

An alcohol is an organic compound containing a hydroxyl (-OH) group. In the IUPAC nomenclature system, the suffix “-ol” is used in the name of each alcohol. The simplest alcohol is ▶ [methanol](#) (methyl alcohol, CH₃OH), and the most commonly encountered alcohol is ▶ [ethanol](#) (ethyl alcohol, C₂H₅OH) which is contained in alcoholic beverages. Alcohols with three or more carbons have isomers: Propyl alcohol has two isomers, which are propan-1-ol (CH₃CH₂CH₂OH) and propan-2-ol (CH₃CH(OH)CH₃). Many low-molecular-weight alcohols, such as ethanol and propan-2-ol, are used as disinfectants, since they diffuse easily through cell membranes and denaturize proteins. Compounds whose hydroxyl group is connected to benzene ring are referred to as phenols.

Cross-References

- ▶ [Ethanol](#)
- ▶ [Methanol](#)

Aldehyde

John H. Chalmers
Scripps Institute of Oceanography Geosciences
Research Division, University of California, San
Diego, La Jolla, CA, USA

Definition

Aldehydes are organic compounds containing the RCHO functional group where R can be hydrogen or another carbon-containing moiety. Aldehydes are named after the corresponding carboxylic acids by dropping the -ic or -oic suffix and adding

-aldehyde or -al (e.g., acetic acid ► [acetaldehyde](#), ethanoic acid → ethanal), or if derived from acyclic aliphatic hydrocarbons, by dropping the final e and adding -al (e.g., propane → propanal). Formyl derivatives of ring compounds may be called carbaldehydes as in cyclopentanecarbaldehyde. See the IUPAC rules for more complex cases.

Aldehydes can be reduced to alcohols or oxidized to carboxylic acids and undergo a variety of addition and condensation reactions, for example, addition of cyanide in the cyanohydrin synthesis, or condensation with another aldehyde in a benzoin reaction or condensation with the carbon adjacent to an aldehyde or ketone in the aldol reaction.

History

The name may be derived from the phrase ► “[alcohol](#) dehydrogenatum.”

Cross-References

- [Acetaldehyde](#)
- [Aldose](#)
- [Amino Acid Precursors](#)
- [Carboxylic Acid](#)
- [Formaldehyde](#)
- [Formose Reaction](#)
- [Glyceraldehyde](#)
- [Propanal](#)
- [Propionaldehyde](#)

Aldose

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

An aldose is a ► [monosaccharide](#) where one end of the molecule is sp² hybridized and thus presents

as a CHO or ► [aldehyde](#) group. These are typically reactive ends of the molecules which may be involved in redox or addition reactions. Examples of biologically important aldoses include ► [ribose](#) and glucose. ► [Glycolaldehyde](#) is the simplest aldose. One of the most important aldoses is ribose, which plays key roles as part of the pentose phosphate cycle in the form of ribose 5-phosphate as well as the backbone sugar element of ribonucleic acid (RNA). Another aldose derivative of ribose, 2-deoxyribose, plays the same role in DNA.

Cross-References

- [Aldehyde](#)
- [Carbohydrate](#)
- [Glycolaldehyde \(HOCH₂CHO\)](#)
- [Monosaccharide](#)
- [Ribose](#)

Algae

Linda Amaral-Zettler
Marine Biological Laboratory, Josephine Bay
Paul Center for Comparative Molecular Biology
and Evolution, Woods Hole, MA, USA

Keywords

Brown algae · Coccolithophorids · Diatoms ·
Dinoflagellates · Euglenoids · Golden algae ·
Green algae · Phytoplankton · Red algae ·
Seaweeds

Synonyms

[Photosynthetic eukaryotes](#); [Protists with chloroplasts](#)

Definition

The algae are an eclectic grouping of photosynthetic eukaryotes that ranges from microscopic picoeukaryotes (~1 μm) (Courties et al. 1994) to

macroscopic multicellular seaweeds (50 m) (Sze 2003). Algae are phylogenetically and morphologically diverse, occur in benthic and planktonic forms, and can be free living, symbiotic, predatory, or parasitic. They inhabit diverse environments including several extreme environments of astrobiological interest, such as desert varnish, permafrost, and highly acidic Mars analog environments (Seckbach 2007). Green algae have unicellular members that share common ancestry with land plants (Charales). Eukaryotic algae along with cyanobacteria dominate global oceanic primary production.

History

The term “blue-green algae” is a colloquial term and refers to cyanobacteria that are members of the domain Bacteria. This term is seldom used in current literature but is still frequently encountered in popular articles and other media.

Overview

Algae are differentiated by various means, including phylogenetic affiliation, photosynthetic pigment type, and morphological features including: the number of flagella, external ornamentation (e.g., scales, frustules), subcellular ultrastructure, and colony-forming abilities. They are polyphyletic and possess representatives in several major lineages of the Eukarya including alveolates (e.g., dinoflagellates), chlorarachniophytes (e.g., *Chlorarachnion*), cryptomonads, euglenids, glaucophytes (e.g., *Cyanophora*), haptophytes (e.g., *Emiliania huxleyi*), red algae (Rhodophyta), stramenopiles (e.g., diatoms, brown algae), and Viridiplantae (e.g., Chlorophyta).

Newer taxonomic classifications based on molecular phylogenetic methods employing multigene approaches place representatives from these lineages into higher taxonomic level groupings called supergroups (Keeling et al. 2005). These six major supergroups are the “Plantae,”

“Chromalveolata,” “Rhizaria,” “Excavata,” “Amoebozoa,” and “Opisthokonta” – the first four of these contain algal representatives. Plantae (also referred to as the Archaeplastida (Adl et al. 2005)) include the red algae, green algae, and streptophytes; Chromalveolata include alveolates and stramenopiles; Excavata include euglenids; Rhizaria include chlorarachniophytes that group within the Cercozoa. A note of caution is that the resilience of these supergroups has been called into question (Parfrey et al. 2006; Yoon et al. 2008), so it is important to take this into consideration when using these terms. Of these six major supergroups, only the Opisthokonta appear to be strongly supported in robust phylogenetic analyses.

In addition to chlorophyll a, algae are further distinguished on the basis of other types of photosynthetic pigments they possess. Alveolates, cryptomonads, haptophytes, and stramenopiles also contain chlorophyll c, while chlorarachniophytes, euglenids, Viridiplantae, and cryptomonads contain chlorophyll b. Other accessory pigments, such as phycobilins, further distinguish cryptomonads, glaucophytes, and red algae.

A feature that all algae share is the ability to photosynthesize. There is strong evidence that this characteristic was the result of a single endosymbiotic event that occurred between a cyanobacterium and an ancestor of the glaucophytes, red algae, and green algae (including plants) (Keeling 2010). The uptake of both green and red algae by other eukaryotes has occurred multiple times in what is referred to as “secondary symbioses.” In some dinoflagellates, tertiary symbioses can occur via plastid replacement. Plastids are also sometimes stolen and used by their host for brief periods of time by sea slugs, dinoflagellates, as well as other protists, such as ciliates and foraminifera – this process is called kleptoplasty.

Cross-References

- Eukarya
- Phytoplankton

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Internet Resources

The Tree of Life Project: <http://tolweb.org/>
 AlgaeBase: <http://www.algaebase.org/>

Algin

► [Alginate](#)

Alginate

Daniel A. Petrash
 Environmental Geochemistry and
 Biogeochemistry, Czech Geological Survey,
 Prague, Czech Republic

Synonyms

3-(6-carboxy-3,4-dihydroxy-5-phosphanyloxan-2-yl)oxy-4,5-dihydroxy-6-phosphanyloxyoxane-2-carboxylic acid (IUPAC); Algin; Alginic acid; Polymannuronic acid

Chemical Formula

$C_{12}H_{20}O_{12}P_2$

Definition

Alginate is a high molecular weight ($>10^4$ Da), straight-chain hydrophilic polysaccharide comprised of polyuronic acids secreted by brown algae and mucoid bacteria, such as several strains of *Pseudomonas* and *Azotobacter*. For such model microorganisms, the physical properties of alginate are crucial for substrate colonization, osmotic and desiccation stress adaptability, and free radical resilience. Irrespectively of its origin, alginate is composed by alternating α -L-guluronate and β -D-mannuronate monomeric units linked through 1 $\rightarrow$ 4 glycosidic bonds and arranged into repeating homo- and heteropolymeric sequences. Bacterial alginate, however, is partially *O*-acetylated, which is thought as an evolutionary mechanism to alter its metal reactivity and viscosity.

History

Nelson and Cretcher (1929) provide a historical summary on early alginate research. Accordingly, the first attempt at separation of a particular carbohydrate component of algae was reportedly made by Stanford (1883), who extracted a polymerized acid fraction by means of dilute alkali and precipitated it by the addition of mineral acid, after the removal of the alkali-insoluble residue by filtration. This substance was called alginic acid or algin. As reviewed by Sutherland (1972), the compositional resemblance between the exopolysaccharides of some bacterial strains and seaweed alginate had been already noticed by a few researchers in the 1960s. Sutherland (op cit.) further defined “bacterial alginates” as group of bacterial exopolysaccharides that can be enzymatically modified.

Cross-References

- [Biofilm](#)
- [Evolution, Biological](#)
- [Polysaccharide](#)

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Alginate Acid

- [Alginate](#)

ALH 84001

Jean-Pierre de Vera
Institute of Space Operations and Astronaut
Training, Microgravity User Support Center
(MUSC), DLR, Cologne, Germany

Synonyms

[Allan Hills 84001](#)

Definition

ALH 84001 (abbreviation of Allan Hills 84001) is a 1.93 kg ► [meteorite](#) found in 1984 on the Allan Hills ice field, Antarctica (Victoria Land), by the US meteorite searchers. ALH 84001 has been classified as ► [achondrite](#) and is thought to be from ► [Mars](#). It mainly consists of coarse-grained cataclastic orthopyroxene-rich material and among the ► [SNC meteorites](#) defines the class of SNC-orthopyroxenites. In 1996, NASA scientists announced that the meteorite might contain ► [fossils](#) of Martian microorganisms, a view that has been widely criticized. Radiometric dating suggests that ALH 84001 is 4.1 billion years old. The piece of ► [rock](#) has been ejected from Mars by an impact event 15 million years ago. Thirteen thousand years ago, the meteorite landed on Earth.

Cross-References

- [Achondrite](#)
- [Bacteria](#)
- [Fossil](#)
- [Mars](#)
- [Meteorites](#)
- [Rock](#)
- [SNC Meteorites](#)

Alignment of Dust Grains

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

► [Interstellar dust](#) produces not only extinction of transmitted starlight but also introduces polarization of that light, with a positive correlation between the amount of reddening and the linear polarization. This effect is normally ascribed to the alignment of asymmetric grains in the galactic magnetic field. When the direction of alignment

changes along the line of sight, a circularly polarized component is produced. Consequently, observations of this polarization provide (model-dependent) information on both dust grain properties and on the galactic magnetic field. Various mechanisms have been proposed to produce the grain alignment. Since circularly polarized light could conceivably affect the chiral symmetry of irradiated molecules such as amino acids, it could possibly play a role in producing the observed ► [enantiomeric excess](#) in some meteoritic organics, although this is far from being demonstrated.

Cross-References

- [Chirality](#)
- [Enantiomeric Excess](#)
- [Interstellar Dust](#)
- [Reddening, Interstellar](#)

Aliphatic Carboxylic Acids

- [Fatty Acids, Geological Record of](#)

Aliphatic Hydrocarbon

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

An aliphatic hydrocarbon is an organic compound composed of carbon and hydrogen which does not contain aromatic rings. It may be linear or cyclic and may contain unsaturated double or triple bonds; thus, alkanes, alkenes, and alkynes are all

aliphatic compounds. Some illustrative examples are ► [methane](#), ethylene, ► [acetylene](#), and cyclopentane.

Cross-References

- [Acetylene \(C₂H₂\)](#)
- [Aromatic Hydrocarbon](#)
- [Methane](#)

Alkaline Lake

- [Soda Lake](#)

Alkaliphile

Antonio Ventosa and Rafael R. de la Haba
Department of Microbiology and Parasitology,
Faculty of Pharmacy, University of Sevilla,
Sevilla, Spain

Keywords

Alkaline · Extreme habitat · Extremophile ·
pH · Soda lake

Definition

Alkaliphiles are microorganisms that grow optimally or very well at pH values above 9, often between 10 and 12, but cannot grow or grow slowly at the near-neutral pH value of 6.5 (Horikoshi [1999](#)).

Overview

There is no precise definition of what characterizes an alkaliphilic organism. Several microorganisms exhibit more than one optimum pH for growth depending on growth conditions, particularly nutrients, metal ions, and temperature. However, the definition given above is the most extended one.

Many different taxa are represented among the alkaliphiles, including ► [prokaryotes](#) (aerobic ► [bacteria](#) belonging to the genera *Bacillus*, *Micrococcus*, *Pseudomonas*, and *Streptomyces*; anaerobic bacteria from the genera *Amphibacillus*, *Anaerobranca*, and *Clostridium*; halophilic ► [archaea](#) belonging to the genera *Halorubrum*, *Natrialba*, *Natronomonas*, and *Natronorubrum*; methanogenic archaea from the genus *Methanohalophilus*; anaerobic archaea from the genus *Thermococcus*; cyanobacteria; spirochetes; actinomycetes; sulfur-oxidizing and sulfate-reducing bacteria), eukaryotes (► [yeasts](#) and filamentous ► [fungi](#)), and even phages (Horikoshi 1998, 1999).

Alkaliphiles require alkaline environments and, in most cases, sodium ions for their growth, germination, and sporulation (Kudo and Horikoshi 1983). Isolation of alkaliphilic microorganisms in laboratory conditions must be carried out in alkaline media containing sodium carbonate, sodium bicarbonate, or sodium hydroxide, following conventional means. Alkaliphiles are widely distributed in different habitats and isolated from soils, feces, and alkaline and/or saline lakes. The frequency of alkaliphilic microorganisms in neutral “ordinary” soil samples is 10^2 – 10^5 /g of soil, which corresponds to 1/10 to 1/100 of the population of the neutrophilic microorganisms (Horikoshi 1991). Some studies show that alkaliphilic bacteria have also been found in deep-sea sediments collected from depths of up to 10,898 m in the Mariana Trench (Takami et al. 1997).

Most alkaliphiles have an optimal growth at around pH 10, which is the most significant difference from well-investigated neutrophilic microorganisms. These alkaliphilic microorganisms can grow in such extreme environments because their internal pH is maintained at 7.5–8.5, despite a high external pH of 8–13 (Aono et al. 1997). Therefore, one of the key features in alkaliphily is associated with the cell surface, which discriminates and maintains the intracellular neutral environment separate

from the extracellular alkaline environment. Alkaliphiles have two mechanisms of cytoplasmic pH regulation. The first one involves the cell wall structure, which contains acidic polymers that function as a negatively charged matrix and may reduce the pH value at the cell surface (Aono and Horikoshi 1983). The surface of the cytoplasmic membrane must presumably be kept below pH 9, because the cytoplasmic membrane is very unstable at alkaline pH values (pH 8.5–9.0) much below the pH optimum for growth (Aono et al. 1992). The second strategy to maintain pH ► [homeostasis](#) consists of the use of the Na^+/H^+ membrane antiporter system ($\Delta\psi$ dependent and ΔpH dependent), the K^+/H^+ antiporter, and ATPase-driven H^+ expulsion (Krulwich et al. 1998).

The flagella motility of alkaliphiles is considered to be driven by a sodium-motive force instead of a proton-motive force, as shown by neutrophiles. These alkaliphiles are most motile at pH 9.0–10.5, whereas no motility is observed at pH 8; in addition, they require Na^+ for motility (Horikoshi 1998).

Studies of alkaliphiles have led to the discovery of many types of enzymes that exhibit interesting properties. Alkaliphilic microorganisms produce some enzymes such as proteases, amylases, cyclomaltodextrin glucanotransferases, pullulanases, cellulases, lipases, xylanases, pectinases, chitinases, and alginate lyases that are of great interest (Horikoshi 1999; Kobayashi et al. 2009).

Cross-References

- [Anaerobe](#)
- [Archaea](#)
- [Bacteria](#)
- [Cyanobacteria](#)
- [Eukaryote](#)
- [Fungi](#)
- [Homeostasis](#)
- [Methanogens](#)
- [Prokaryote](#)

- Soda Lake
- Yeast

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Alkanoic Acids

- Fatty Acids, Geological Record of

Allan Hills 84001

- ALH 84001

ALMA

Stuart A. Corder

Joint ALMA Observatory, National Radio Astronomy Observatory, Santiago, Chile

Keywords

Array · Atacama · Interferometer · High frequency · Millimeter/Submillimeter wavelength · Radioastronomy

Acronyms

Atacama Large Millimeter/Submillimeter Array

Definition

ALMA, an international astronomy facility, is an interferometric array of 66 antennas of 12-m (54) and 7-m (12) diameters. ALMA collects and delivers high-quality datasets to the scientific community while further developing the observatory to explore the universe in the millimeter/submillimeter wavelength range. Each antenna is (or will soon be) equipped with receivers covering the transparent atmospheric windows between 35 and 950 GHz and the signals are processed by one of two correlators. ALMA is located at 5000 m elevation in Northern Chile near San Pedro de Atacama on the Chajnantor, a place sacred to the local Likan Antai people.

History

The construction of the observatory dates back to 2004. However, in the 1980s, the global scientific community had already identified the need for a radiotelescope with the characteristics of the Atacama Large Millimeter/Submillimeter Array (ALMA). Independent projects began with Europe, North America, and East Asia each proposing to build a telescope that would receive

radiation in millimeter and submillimeter wavelengths. In 1995, the three partners represented by the National Radio Astronomy Observatory (NRAO), the European Organization for Astronomical Research in the Southern Hemisphere (ESO), and the National Astronomical Observatory of Japan (NAOJ) ran site tests in the Chilean plains, with positive results. Consequently, in 1999, Europe and North America signed a Memorandum of Understanding, and 2 years later in Tokyo a resolution was signed to support the joint intent to construct ALMA between Europe, North America, and Japan.

At the end of 2003, the first stone was placed in what was to become the most ambitious radio observatory on Earth. ALMA construction was completed officially in 2013 with the inauguration of the telescope array. The operations phase for ALMA started in January 2008, in parallel with late construction, marked by the milestone of “operations” taking the responsibility of the ALMA site. Today, this international astronomy facility is a partnership of ESO, the United States National Science Foundation (NSF) and the National Institutes of Natural Sciences of Japan (NINS), and is funded by ESO on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC), and by NINS in cooperation with the Academia Sinica of Taiwan (AS) and the Korea Astronomy and Space Science Institute (KASI). ALMA operations are led by ESO on behalf of its Member States; by the NRAO, managed by the Associated Universities, Inc. (AUI), on behalf of North America; and by the NAOJ on behalf of East Asia. The Joint ALMA Observatory (JAO), staffed by the executives and headed by the ALMA Director, provides the unified leadership and management of ALMA operations.

Overview

The ALMA operations are concentrated in the Chilean Andes at an elevation of 5000 m, on a

flat plain known as Chajnantor, or “the launching place” in the dialect of the Likan Antai people who have called the surrounding area home for 12,000 years. The high altitude and geography yield dry skies, which limit the attenuation of astronomical submillimeter signals, and the ability to spread the antennas over a large, flat area. Technical operations support is located, locally, at 3000 m near the towns of Toconao and San Pedro de Atacama. Operations are also supported in Santiago, Chile, and in the ALMA Support Centers (ASCs). The ASCs, operated and managed by the respective executives, provide the support and necessary scientific and technical interactions between the respective regional user communities and ALMA. ALMA aims to be accessible to users with no previous submillimeter or interferometric experience. The ACSs provided end-to-end support from proposal preparation through data imaging and analysis.

ALMA has already transformed our understanding of the cold universe, with over 2600 refereed papers with over 82,000 citations as of January 2022. ALMA science spans from the formation of planets to the origins of galaxies. In 2014, ALMA imaged the disk of gas and dust surrounding the forming star HL Tau with unprecedented resolution and quality, revealing a network of gaps and rings in the disk resulting from the planet formation process (ALMA Partnership et al. 2015). A subsequent large program found these structures, and others, to be common place (Andrews et al. 2018), revolutionizing the study of protoplanetary systems. More recently, ALMA participated as a critical element in the first image of a black hole shadow (e.g., Event Horizon Telescope Collaboration 2019), pulling back the veil on the most extreme type of object in the universe. Contributions to star formation studies and cosmology have also been profound (e.g., Dunlop et al. 2017). ALMA is capable of detecting some of the most distant objects in the universe as well (e.g., Hashimoto et al. 2018), with more distant detections coming steadily with time. Currently ALMA is embarking on a ten-year plan to upgrade the system from receivers through the correlator, providing

broader bandwidths and finer spectral resolutions, as well as increasing sensitivity and spectral reach, in order to better understand the origins of galaxies, chemical complexity, and planets.

ALMA is composed of 66 high-precision antennas, 54 of 12-m diameter and 12 of 7-m diameter. The antennas operate in various combinations as an interferometer. The array of 12-m antennas is reconfigured over a biennial cycle with maximum extents ranging up to 16.2 km (giving angular resolutions as fine as $0.012''$). Typically, four 12-m antennas conduct single dish observations and the 7-m diameter antennas operate in a compact, fixed array. Collectively these four 12-m antennas and 7-m antennas are referred to as the Atacama Compact Array (ACA) or the Morita Array. ALMA is currently equipped with eight receivers, with an additional receiver currently being outfitted and a tenth, and final, receiver in development. These ten receiver bands cover all atmospheric windows between 35 and 950 GHz. ALMA's two correlators are capable of generating four tuneable blocks of up to 3840 channels each with bandwidths from 1875–58.6 MHz, for a finest effective channel width of 15 kHz ($\sim$ a few km/s depending on band). The maximum bandwidth in continuum mode is 8 GHz per polarization. This combination allows for detection of thermal emission from dust grains with high sensitivity over a broad frequency range. It also provides the ability to spatially and kinematically resolve spectral emission from a variety of chemical species. For more information, see the ALMA science portal.

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Alpha Centauri Bb

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Definition

Alpha Centauri Bb is a putative planet orbiting the star Alpha Centauri B. Alpha Centauri is a triple stellar system consisting of a moderately close binary α Cen AB, and a distant M dwarf companion known as Proxima Centauri at approximately 15,000 AU away from the binary. At a distance of 4.37 light years from the Sun, α Centauri is the closest stellar system to the solar system and is located in the southern constellation of Centaurus. The binary system has a semi-major axis of 23.5 AU and an eccentricity of 0.518. The component A of this system is a G2V star (see ► [Spectral Type](#)) with a mass of 1.1 solar-masses, a luminosity of 1.519 times solar, and an effective temperature of 5790 K. Its component B has a spectral type of K1V and its mass, luminosity, and effective temperature are equal to 0.934 solar-mass, 0.5 solar luminosity, and 5214 K, respectively.

In 2012, a team of scientists lead by Xavier Dumusque announced the detection of a 1.13 Earth-mass planet around α Cen B. One year later, the existence of this planet, known as α Cen Bb, was questioned in an article by Artie Hatzes (2013).

The probable existence of α Cen Bb would indicate that, unlike the region around α Cen A where terrestrial planet formation encounters complications, as predicted by several researchers, planet formation around α Cen B may be efficient.

Note that a planet has been detected around the M dwarf companion Proxima Centauri. This planet is called Proxima-b, has a minimal mass of 1.3 Earth mass and orbits in the habitable zone of Proxima Centauri.

Cross-References

► [Proxima-b](#)

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Alpha Helix

John H. Chalmers

Scripps Institute of Oceanography Geosciences
Research Division, University of California, San
Diego, La Jolla, CA, USA

Definition

The alpha (or α -) helix is one of the two most common ► [polypeptide](#) secondary structural motifs and consists of a right-handed helix with 3.6 amino acid residues per turn. The helix has a pitch of 0.54 nm and a width of 1.2 nm and is stabilized by ► [hydrogen bonds](#) between the peptide -C=O- and -NH- moieties of every

fourth bond. The amino acids proline and glycine tend to kink or break alpha helices, whereas alanine, leucine, methionine, lysine, and glutamate stabilize them. Protein alpha-helical regions often fold into coil-coiled configurations that can span membranes, bind DNA, or serve structural roles.

History

The term alpha helix was coined by William Astbury in the 1930s. Linus Pauling worked out the structure accurately in 1948.

Cross-References

- [Amino Acid](#)
- [Oligopeptide](#)
- [Peptide](#)
- [Polypeptide](#)
- [Protein](#)
- [Proteins, Secondary Structure](#)

Alpha Particles

► [Alpha Rays](#)

Alpha Rays

Jun-ichi Takahashi

Faculty of Engineering, Yokohama National
University, Yokohama, Japan

Synonyms

[Alpha particles](#); [Helium nuclei](#)

Definition

An alpha ray is a stream of alpha particles. An alpha particle consists of two protons and two

neutrons bound together into a particle identical to a helium nucleus; it is produced in the radioactive process called alpha decay. Alpha particles, like helium nuclei, have a net spin of zero. The energy of alpha particles varies, depending upon the specific decay reaction, with higher-energy alpha particles being emitted from larger nuclei, but most alpha particles have energies of between 3 and 7 MeV, corresponding to extremely long to extremely short half-lives of alpha-emitting nuclides. They are a highly ionizing form of particle radiation that when resulting from radioactive alpha decay have low penetration depth. Helium nuclei, which form 10–12% of cosmic rays, are usually of much higher energy than those produced by radioactive decay.

Cross-References

- [Beta Rays](#)
- [Gamma Rays](#)
- [Radiochemistry](#)

Alteration

Nicholas Arndt
ISTerre, Université Grenoble Alpes, Grenoble,
France

Definition

Alteration in geochemistry refers to processes by which the mineralogy, composition, and texture of a rock are changed as a result of re-equilibration under conditions of lower temperature and pressure or through interaction with aqueous or CO₂-rich fluids. The minerals of the original rock, which may be magmatic, sedimentary, or metamorphic, are transformed into an assemblage of low-temperature, usually finer-grained minerals. A typical example is the replacement of magmatic minerals such as olivine, pyroxene, and feldspar by chlorite, clay minerals, or carbonates. ► [Weathering](#) is a type

of alteration that takes place close to the surface through interaction of rock with the atmosphere and with ground- or surface waters. *Alteration* is also used in chemistry and biology (e.g., DNA alterations).

Cross-References

- [DNA Damage](#)
- [Weathering](#)

Alteration Profile

- [Weathering Profile](#)

Aluminilite (older name)

- [Alunite](#)

Alunite

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the
Earth System, Montréal, QC, Canada

Synonyms

[Aluminilite \(older name\)](#)

Chemical Formula (Optional)

KAl₃(SO₄)₂(OH)₆

Definition

Alunite is a clay mineral forming solid solutions with jarosite. It is the product of medium-

temperature (80–150 °C) hydrothermal alteration of feldspar-rich volcanic rocks. On Earth, alunite can be found together with kaolinite and quartz in deposits formed by the alteration of rocks by acidic waters from acid sulfate hot springs. These deposits are recognized as candidates for preserving biosignatures. Detection of alunite at *Terra Sirenum*, Mars, could be an indicator of basalt alteration in contact with H₂SO₄-rich water. Alunite and kaolinite layered deposits detected at *Cross Crater*, Mars, are another indication of weathering at the surface of Mars.

Cross-References

- [Hydrothermal alteration](#)
- [Hydrothermal Environments](#)
- [Jarosite](#)
- [Mars](#)
- [Weathering](#)

References and Further Reading

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Amazonian

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Definition

It is the youngest of the three systems (of time-stratigraphic units) or periods (the chronologic equivalents to systems) in the Martian stratigraphic scheme, named after the region of Amazonis Planitia (*Amazonis*: from the classical land of the Amazons on the island Hesperia; see US Geological Survey Gazetteer of

Planetary Nomenclature). Depending on the different models to determine absolute ages on planetary surfaces by crater statistics, the Amazonian began at some point in time between 3.55 and 1.8 billion years ago and lasts until the present.

Cross-References

- [Chronostratigraphy](#)
- [Hesperian](#)
- [Mars](#)
- [Mars Stratigraphy](#)
- [Noachian](#)

Ambipolar Diffusion

Steven W. Stahler
Department of Astronomy, University of California, Berkeley, CA, USA

Definition

Ambipolar diffusion is the slippage of neutral matter in a plasma with respect to an internal magnetic field. This slippage occurs when the ionization fraction is so low that collisions between neutral species and ions become relatively rare. At this point, the neutral atoms can move relative to the ions, which are effectively tied to the magnetic field. Ambipolar diffusion is thought to occur in ► [molecular clouds](#), which are dense enough to shield much of the external, ionizing radiation. The cloud's self-gravity can then cause the gas to condense, in spite of its internal magnetic field. This condensation ultimately leads to star formation.

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Gravitational Collapse, Stellar](#)
- [Molecular Cloud](#)
- [Star Formation, Theory](#)

Amide

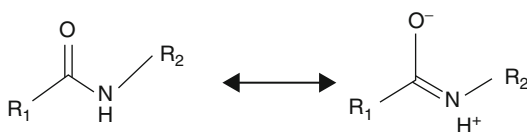
Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Georgia Institute of Technology, Center for
 Chemical Evolution, Atlanta, GA, USA

Definition

In chemistry, an amide is an organic compound which contains the functional group or the name given to a type of bond formed from the condensation of a carboxylic acid and an [amine](#). Mono-substituted amides may exhibit the resonance shown in Fig. 1. Some important amides include peptides, urea, and formamide. Amides are also important intermediates in the Strecker amino acid synthesis. Hydrogen bonding between amide functional groups in polypeptide allows the formation of secondary structural motifs such as α -helices and β -sheets. Amides can be hydrolyzed back to the constituent amine and carboxylic acid. Cyclic amides are known as lactams.

Cross-References

- [Amine](#)
- [Carboxylic Acid](#)
- [Polypeptide](#)
- [Strecker Synthesis](#)



Amide, Fig. 1 Two states of amide

Amidocyanogen

- [Cyanamide](#)

Amidogen

- [Amino Radical](#)

Amine

Kensei Kobayashi
 Yokohama National University, Yokohama, Japan

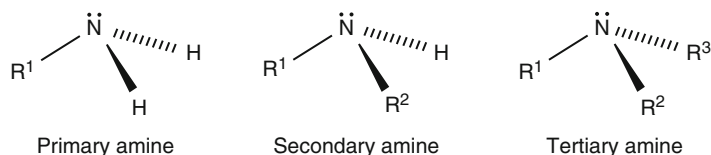
Definition

An amine is an organic compound containing an amino group ($-NR_3$). Since the nitrogen atom in an amino group has a lone electron pair, amines are Lewis bases. Amines are classified as primary amines, secondary amines, or tertiary amines depending on the number of alkyl substituents (primary amines having a single alkyl substituent) (Fig. 1). The simplest amine is methylamine (CH_3NH_2). Methylamine was found as an interstellar molecule in 1974. Amines have also been detected among organic compounds extracted from carbonaceous [chondrites](#).

Cross-References

- [Amino Acid](#)
- [Chondrite](#)
- [Molecular Cloud](#)

Amine, Fig. 1 Amine



Amino Acid

Jeffrey Bada

Scripps Institution of Oceanography, La Jolla,
CA, USA

Keywords

Amino group · Carboxyl group

Synonyms

Amino alkanolic acid

Definition

Amino acids are organic molecules that contain at least one primary amino group (NH_2) and one carboxyl group (COOH). The general formula for amino acids with alkyl side chains that have one amino and one carboxyl group, known as amino alkanolic acids, is $\text{C}_n\text{H}_{2n}\text{NH}_2\text{COOH}$.

History

Most of the biologically important amino acids were isolated and characterized in Europe in the early nineteenth century (Vickery and Schmidt 1931). For example, asparagine, the first amino acid discovered, was isolated from asparagus by Vauquelin and Robiquet in 1806. Glycine was isolated by Braconnot in 1820. Laboratory syntheses were developed shortly thereafter.

Overview

The structural isomers with the amino group on the sequential carbon atoms adjacent to the carboxyl group are called α , β , γ , etc. -amino acids. Thus, α -amino acids are 2-amino alkanolic acids, β -amino acids are 3-amino alkanolic acids, etc. General structural formulae for α , β , and γ amino acids are shown in Fig. 1 and Table 1.

The common names of the amino acid isomers with up to five carbon atoms are given in Table 2.

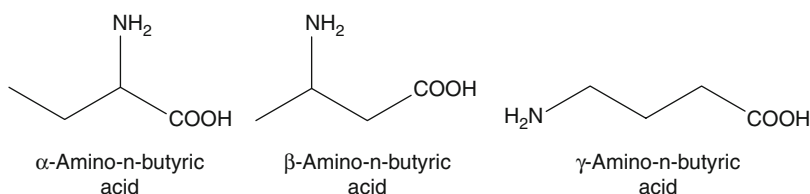
Some amino acids have aromatic side chains: examples are phenylglycine (α -aminophenylacetic acid), phenylalanine (α -amino- β -phenylpropanoic acid), and tyrosine (α -amino- β -(4-hydroxyphenyl)propanoic acid). Amino acids can also have side chains consisting of an indole (a benzene ring linked to a five-membered nitrogen-containing pyrrole ring) or an imidazole (five-membered diunsaturated ring composed of three carbon atoms and two nitrogen atoms at non-adjacent positions): two examples of this type of amino acid found in biochemistry are tryptophan and histidine, respectively.

There are also amino acids with hydroxyl- and sulfur-containing side chains. The common names of some examples of these amino acids are serine (α -amino- β -hydroxypropanoic acid), threonine (α -amino- β -hydroxybutanoic acid), cysteine (α -amino- β -mercaptopropionic acid), and methionine (α -amino- γ -(methylthio)butyric acid). Selenium can also substitute for sulfur in the sulfur-containing amino acids in some organisms.

Some amino acids have more than one amino group (e.g., lysine or α , ϵ -diaminohexanoic acid) and/or more than one carboxyl group: for example, α -aminomalonic acid, aspartic acid

Amino Acid,

Fig. 1 Generalized structural formulas for α -, β -, and γ -amino acids



Amino Acid, Table 1 The numbers of possible structural isomers for amino alkanolic acids (with the formula $C_nH_{2n}NH_2COOH$) (Henze and Blair 1934)

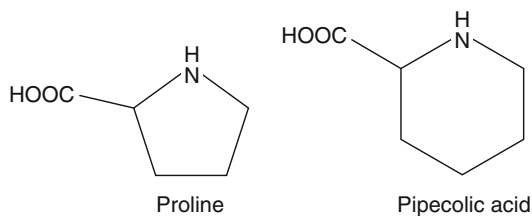
Number of carbon atoms	Number of possible isomers
2	1
3	2
4	5
5	12
6	31
10	1479

Amino Acid, Table 2 The names of the structural isomers for 2, 3, 4, and 5 carbon amino alkanolic acids

Number of carbon atoms	Common names
2	Glycine
3	Alanine, β -alanine
4	α -Amino- <i>n</i> -butyric acid, β -amino- <i>n</i> -butyric acid, α -aminoisobutyric acid, β -aminoisobutyric acid, γ -amino- <i>n</i> -butyric acid
5	Valine, isovaline, β -aminopentanoic acid, γ -aminopentanoic acid, δ -aminopentanoic acid, α -methyl- β -aminobutyric acid, allo- α -methyl- β -aminobutyric acid, α -methyl- γ -aminobutyric acid, β -methyl- β -aminobutyric acid, β -methyl- γ -aminobutyric acid, α -ethyl- β -aminoproponic acid, α -dimethyl- β -aminoproponic acid

(α -aminobutanedioic acid), and glutamic acid (α -aminopentanedioic acid). Asparagine (α -amino- β -carbamoylpropanoic acid) and glutamine (α -amino- δ -carbamoylbutyric acid) are the side group carboxamides of aspartic and glutamic acids, respectively. Interestingly, asparagine was the first amino acid discovered in 1806 when it was crystallized from the “juice” squeezed from asparagus shoots. The amino acid arginine (α -amino- ϵ -guanidinopentanoic acid) has a guanidinium group attached to the end of its alkyl side chain.

Some amino acids have a cyclic secondary amine rather than a primary amino group.

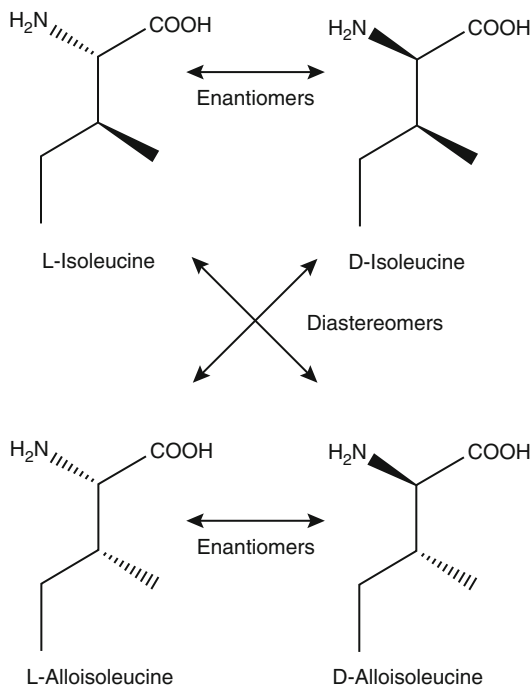


Amino Acid, Fig. 2 Some cyclic amino acids, proline, and pipecolic acid

Examples include proline (pyrrolidine-2-carboxylic acid, $C_5H_9NO_2$) where the primary amino group is replaced with a five-membered pyrrolidine ring or tetrahydropyrrole and pipecolic acid (piperidine-2-carboxylic acid, $C_6H_{11}NO_2$) where the amino group is replaced by six-membered piperidine ring (Fig. 2).

The ionization constants (pK_a) at 25 °C of the amino and carboxyl groups of amino alkanolic acids are in the range 8–10 and 2–4, respectively. Thus, at neutral pH, the amino group is protonated, while the carboxyl group is deprotonated, producing a doubly charged ► **zwitterion** with no net charge. Amino acids with other amino or carboxyl groups have additional ionization constants characteristic of the particular group. The pK_a of the β -carboxyl group of aspartic acid is 3.9 at 25 °C; thus at neutral pH aspartic acid has a net negative charge. The pK_a of the guanidinium group of arginine is 12.5, and arginine is thus positively charged at neutral pH.

When a carbon atom in an amino acid has four different groups attached to it, referred to as an asymmetric or ► **chiral** carbon, it is optically active. For those amino acids with one chiral carbon, there are two possible optically active isomers designated, the L- and D-enantiomers. Some amino acids have more than one chiral carbon so several stereoisomers are possible. An amino acid with two chiral carbons is said to be diastereomeric, and there are thus two diastereomers, each of which has two enantiomers, for a total of four possible optical isomers. For the diastereomeric pair L-isoleucine/D-alloisoleucine (α -amino- β -methylpentanoic acid), the two sets

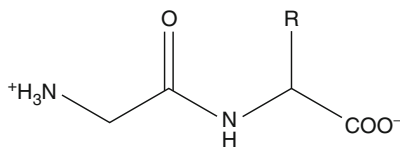


Amino Acid, Fig. 3 Enantiomers and diastereomers of iso- and alloisoleucine

of enantiomers are L- and D-isoleucine and L- and D-alloisoleucine, respectively (Fig. 3).

Amino acids can be linked together by the formation of a ► [peptide](#) bond that involves the amino group of one amino acid and the carboxyl group of another. Two amino acids connected in this fashion are called a dipeptide which has the structure given below (in this case, one amino acid is glycine and the other has a generic R-group side chain) (Fig. 4).

Polypeptides and proteins consist of a large number of amino acids connected in peptide linkages. A total of 20 different amino acids (for this discussion, the amino acids selenocysteine and pyrrolysine are not included because they are relatively rare coded amino acids) are decoded from DNA sequences and encoded into RNA for incorporation into proteins. A list of the “canonical” 20 protein amino acids and their abbreviations are given in Table 3. There are peptides that contain additional amino acids other than the standard protein amino acids, but these are incorporated by posttranslational modifications or the



Amino Acid, Fig. 4 A generic dipeptide

Amino Acid, Table 3 The 20 amino acids commonly found in proteins and their commonly used abbreviations

Amino acid common name	Three-letter abbreviation	One-letter abbreviation
Aspartic acid	Asp	D
Glutamic acid	Glu	E
Asparagine	Asn	N
Glutamine	Gln	Q
Glycine	Gly	G
Alanine	Ala	A
Valine	Val	V
Isoleucine	Iso	I
Leucine	Leu	L
Phenylalanine	Phe	F
Tyrosine	Tyr	Y
Serine	Ser	S
Threonine	Thr	T
Cysteine	Cys	C
Methionine	Met	M
Lysine	Lys	K
Histidine	His	H
Arginine	Arg	R
Tryptophan	Trp	W
Proline	Pro	P

peptides themselves are synthesized by non-ribosomal peptide synthetases (NRPSs). For example, α -aminoisobutyric acid and isovaline are found in some fungal peptides synthesized by NRPSs.

With the exception of achiral glycine, only the L-enantiomers of the proteinogenic amino acids are incorporated into proteins. The discrimination against the incorporation of D-amino acids during the protein synthesis process is estimated to be greater than 10⁴. However, there are D-amino acids present in some peptides, but these are introduced either by the conversion of L-amino acids by posttranslational isomerization enzymes or are

introduced by NRPSs. Some D-amino acid-containing peptides have potent antimicrobial activity.

The total number of amino acids theoretically possible is huge, and several hundred different amino acids have been isolated from organisms, and an even larger number have been made in the laboratory by a variety of synthetic methods. Moreover, the synthesis of amino acids is not confined to terrestrial biology or laboratory synthesis: amino acids have been detected in meteorites, and there are hints that at least the simplest amino acid glycine is present in interstellar clouds and comets (see ► [Molecules in Space](#)). One of the meteorites most extensively studied is the ► [Murchison](#) carbonaceous chondrite that fell in southeastern Australia in 1969. Over 75 different amino acids have been detected in Murchison (Sephton 2002), with only 8 of these also being found in biological proteins. These amino acids are clearly of extraterrestrial origin: many are unique to the meteorite and do not occur naturally on Earth and those with a chiral carbon are racemic (or close to racemic). The Murchison amino acids are thought to have been synthesized by natural reactions, such as the ► [Strecker synthesis](#), directly on the juvenile meteorite parent body or in the early solar nebula before incorporation into planetesimals. Amino acids have been detected in even larger quantities in other carbonaceous chondrites (Pizzarello and Shock 2010).

Amino acids may also have been synthesized by natural processes on the early Earth as demonstrated by the classic Miller spark discharge experiment carried out in 1953 (Miller 1953; Johnson et al. 2008). These amino acids could have accumulated on the Earth and been available for incorporation into the first living entities. To date, 12 of the amino acids found in the proteins of terrestrial organisms have been synthesized in spark discharge experiments with various reduced gas mixtures.

The striking overlap between amino acids generated in experiments simulating prebiotic chemistry and found in meteorites represents evidence for the abiotic plausibility of approximately half of the canonical amino acid set. This is also supported by the thermodynamics of their

formation (Higgs and Pudritz 2009). Debate continues, however, as to whether these amino acids would have been sufficient to comprise the first functional proteins. It is also unclear how these amino acids came to be used by life when many others might have been also available (Weber and Miller 1981; Cleaves 2010).

The amino acids absent from abiotic simulations and meteorites are not only difficult to make but are also either thermally unstable (Gln, Asn) or are unstable under UV conditions (Cys, Met, Trp, His, Tyr, Phe). This strongly suggests that these amino acids are biological “inventions” and their multi enzymatic synthesis pathways appeared only after the onset of Darwinian evolution. The order of biologically invented amino acid entering the code has been hypothesized based on thermodynamics (Higgs and Pudritz 2009); however, the entry and retention of amino acids is likely to be complex, with such factors as accessibility, compatibility, complementarity with existing code members, and stability on transfer RNA all playing a role (Weber and Miller 1981; Cleaves 2010). The culmination of this selection is a set of amino acids unchanged since the last universal common ancestor (LUCA), which is exceptional in breadth and evenness in terms of size, hydrophobicity, and charge (Philip and Freeland 2011).

Cross-References

- [Diastereomers](#)
- [Enantiomers](#)
- [L-Amino Acids](#)
- [Molecules in Space](#)
- [Peptide](#)
- [Protein](#)
- [Strecker Synthesis](#)

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Amino Acid *N*-Carboxy Anhydride

Laurent Boiteau
Institut des Biomolécules Max Mousseron,
UMR5247 CNRS, University Montpellier-2,
Montpellier, Cedex, France

Synonyms

1,3-Oxazolidine-2,5-dione; Leuchs' Anhydride; NCA

Definition

An amino acid *N*-carboxy anhydride (or NCA) is a cyclic organic compound structurally related to an ► [amino acid](#), which is an intramolecular mixed anhydride of a carboxylic and carbamic acid (structure -CO-O-CO-NH-), making it both an *N*-protected and a *CO*-activated amino acid. NCAs are structurally related to hydantoins but have very different chemical reactivity. They are rather unstable in water and physiological media. The term NCA is usually used to refer to the

NCAs of α -amino acids (although NCAs of β -amino acids etc. are also possible). NCAs can condense to give oligo- or polypeptides, with the release of CO₂. NCAs are postulated or observed intermediates in many prebiotically relevant reactions leading to ► [peptides](#) from amino acid derivatives, especially in aqueous media in the presence of carbonate. NCAs are also considered to be potentially prebiotic reagents, as they are versatile free energy carriers which can potentially activate other biologically relevant chemical species, such as nucleotides.

History

Although speculations that NCAs might have played a role in prebiotic chemical evolution arose in the mid-1970s, notwithstanding their use since the late 1970s in “model” prebiotic reactions, studies in the early 2000s improved the status of NCAs as prebiotically relevant compounds.

Overview

Discovered by Hermann Leuchs in 1906, NCAs are well-known reactants in both organic and polymer synthesis (Kricheldorf 2006). Since their most popular preparative method involving the reaction of free amino acids with phosgene is *not* prebiotically relevant, NCAs themselves were long considered as prebiotically irrelevant (Pascal et al. 2005). Nevertheless, NCAs have been continuously used from the 1970s in model reactions of prebiotic peptide formation, especially to assess stereoselection hypotheses in relation with the emergence of *homochirality* of the natural amino acid pool, e.g., enantiomeric excess amplification processes (Kricheldorf 2006; Pascal et al. 2005; Illos et al. 2008). NCAs have long been postulated as likely intermediates in the reaction of activated amino acid esters (e.g., adenylates, thioesters) based on the observation that the formation of peptides is accelerated by the presence of CO₂ or bicarbonate. Since the late 1990s, several prebiotically relevant pathways for NCA

formation have been identified, thus confirming the prebiotic status of NCAs (Kricheldorf 2006; Pascal et al. 2005):

- The nitrosation of *N*-carbamoyl amino acids (CAA) promoted by nitrogen oxides (Kricheldorf 2006; Pascal et al. 2005).
- The decomposition of diacyldisulfides
- The reaction of amino acids with carbonyl sulfide in the presence of oxidizing or alkylating agents (Leman et al. 2004).
- The spontaneous decomposition of CAA in water (Danger et al. 2006).

NCAs represent both (1) the structurally simplest activated amino acids (formally resulting from condensation with CO₂), (2) an unavoidable intermediate from any form of CO-activated amino acid in a bicarbonate/CO₂-rich environment, and (3) the most activated amino acid species achievable in water in a prebiotic environment. Thermodynamic calculations show NCAs to be quite stable (because of the cyclic structure) compared to other anhydrides, although kinetically they are as reactive as the latter. Furthermore, NCAs may be kinetically competent intermediates from almost any inactivated amino acid derivatives, provided their spontaneous hydrolysis is slower than NCA formation (Pascal et al. 2005).

Such thermodynamic and kinetic features make NCAs potential *energy carriers* in an amino acid-based protometabolism, as exemplified by their ability to activate inorganic phosphate (Pascal et al. 2005) or nucleotides (Biron et al. 2005; Leman et al. 2006), which could be coupled to a peptide/nucleic acid coevolution scenario supporting speculations on the emergence of the translation apparatus (Pascal et al. 2005).

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Metabolism, Prebiotic](#)
- [N-Carbamoyl Amino Acid](#)
- [Peptide](#)
- [Prebiotic Chemistry](#)

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Amino Acid Precursors

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Definition

► **Amino acid** precursors are compounds that give amino acids after some reactions (usually hydrolysis). One of the typical amino acid precursors is ► **aminoacetonitrile**, which is converted to glycine by hydrolysis via glycine ► **amide**:

$$\text{NH}_2\text{CH}_2\text{CN} + 2\text{H}_2\text{O} \rightarrow \text{NH}_2\text{CH}_2\text{CONH}_2 + \text{H}_2\text{O} \rightarrow \text{NH}_2\text{CH}_2\text{COOH} + \text{NH}_3.$$
 Hydantoins (substituted glycolylurea) are also typical amino acid precursors and have been found in carbonaceous chondrites. Complex organic polymers with large molecular weights are also possible precursors. ► **Tholins**, which are formed by reactions of

mixtures of nitrogen and methane, are large complex molecules which give amino acids after hydrolysis. Amino acids are frequently detected in carbonaceous ► [chondrites](#) (meteorites), but the amount of amino acids recovered usually increases after hydrolysis, suggesting that some amino acids are present in the form of amino acid precursors.

Cross-References

- [Amide](#)
- [Amino Acid](#)
- [Aminoacetonitrile \(NH₂CH₂CN\)](#)
- [Chondrite](#)
- [Complex Organic Molecules](#)
- [Hydantoin](#)
- [Hydrolysis](#)
- [Tholins](#)

Amino Alkanoic Acid

- [Amino Acid](#)

Amino Radical

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Amidogen](#); [Aminyl radical](#); [NH₂](#)

Definition

This triatomic radical is an important intermediary in the interstellar chemistry of ► [ammonia](#), NH₃. Like many light hydrides, its pure rotational transitions occur at far infrared/submillimeter wavelengths, making its observation from ground-based observatories difficult because of the opacity of the terrestrial atmosphere.

History

The NH₂ radical was first detected in the ► [interstellar medium](#) in 1993 (van Dishoeck et al.), at submillimeter wavelengths, and has been extensively observed toward different molecular clouds using the HIFI instrument on board the Herschel satellite (Persson et al. [2010](#), [2012](#)).

Cross-References

- [Ammonia](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

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Aminoacetic Acid

- [Glycine](#)

Aminoacetonitrile (NH₂CH₂CN)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[AAN](#); [Cyanomethylamine](#); [Glycinonitrile](#);
[NH₂CH₂CN](#)

Definition

Aminoacetonitrile (IUPAC name 2-Aminoacetonitrile) is a (toxic) liquid at room temperature and standard pressure. It is a precursor of the simplest amino acid, ► [glycine](#), which it forms by reaction with liquid water. It is also an intermediary in the ► [Strecker synthesis](#) of glycine. It was identified in the interstellar medium in 2008.

History

Although its rotational spectrum has been studied since the 1970s, and modeled explicitly for a search in the interstellar medium in 1990, aminoacetonitrile has only been detected recently in space, in a large molecular cloud Sagittarius B2 (Sgr B2) at the center of the Galaxy (Belloche et al. [2008](#)).

Cross-References

- [Glycine](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Strecker Synthesis](#)

References and Further Reading

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Aminobutyric Acid

Mark Dörr
University of Southern Denmark, Odense M,
Denmark

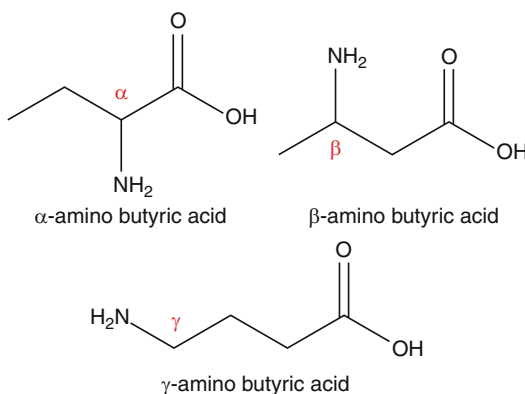
Synonyms

[Butyrine](#); [Ethyl-glycine](#)

Definition

Aminobutyric acid is the term for a variety of structural isomers of amino acids derived from *n*- or isobutyric acid with the chemical formula $C_4H_9NO_2$. They belong to the substance class of amino acids, since they contain an amino functional group and a carboxylic acid functional group. In nature, several different isomers of aminobutyric acid are found: (1) α -aminobutyric acid (α ABA), a key intermediate in the biosynthesis of ophthalmic acid, (2) β -aminobutyric acid (β ABA), (3) γ -aminobutyric acid (GABA), which modulates the excitability of neurons of vertebrates and muscle tone, and (4) α -aminoisobutyric acid (α AIB), which is found in some fungal membrane peptides. Several aminobutyric acid isomers have been found in carbonaceous chondrite meteorites.

α , β , and γ denote the position of the amino group relative to the carboxyl group in the ► [amino acid](#) molecule: α refers to the first, β the second, and γ the third position.



Cross-References

- [Amino Acid](#)

Aminocyanocarbene

- [Aminomaleonitrile](#)

Aminoethanoic Acid

► Glycine

Aminoisobutyric Acid

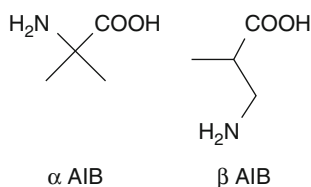
Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

AIB

Definition

Amino isobutyric acid (AIB) is an amino acid derived from isobutyric acid. There are two structural isomers of amino isobutyric acid (Fig. 1), α -aminoisobutyric acid (α AIB), which is achiral, and β -aminoisobutyric acid (β AIB), which has two ► [stereoisomers](#), a D and L form. Both isomers have been found in carbonaceous chondrites, with α AIB often being one of the most abundant amino acids. This is thought to be significant as α AIB is not found in proteins, suggesting an extraterrestrial origin of this compound. However, several fungi are now known to



Aminoisobutyric Acid, Fig. 1 The two structural isomers of aminoisobutyric acid

synthesize this compound for incorporation in non-ribosomally encoded peptide antibiotics.

Cross-References

- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Stereoisomers](#)

Aminomaleonitrile

Martin Ferus
J. Heyrovsky Institute of Physical Chemistry,
Czech Academy of Sciences, Prague, Czech
Republic

Synonyms

[2-aminopropanedinitrile](#); [Aminocyanocarbene](#)

Chemical Formula

$\text{NCCH}(\text{NH}_2)\text{CN}$

Acronyms

AMN

Definition

Aminomaleonitrile is a likely prebiotic molecule. It is a reactive intermediate in formamide- and hydrogen cyanide-based prebiotic syntheses of nucleic acid bases (Ruiz-Bermejo et al. [2013](#); Hudson et al. [2012](#)) and HCN oligomers (Moser et al. [1967](#)). AMN is synthesized from iminoacetoneitrile, in basic (1–11 M) HCN solutions (Oró and Kimball [1962](#)). Further condensation affords 2, 3-diaminomaleonitrile (DAMN). Reaction with formamidine results in the synthesis of 5-aminoimidazolecarbonitrile (AICN). This

reaction pathway is involved in prebiotic syntheses initiated by heat (Saladino et al. 2005), electric discharges (Hoerst et al. 2012), or impact event (Ferus et al. 2020).

History

According to Miller (1953), the synthesis of purines and pyrimidines remains a hurdle for understanding of the origin of life. In 1960, Oró demonstrated the synthesis of adenine from ammonium cyanide (Oró 1960). AMN has been identified as an intermediate of basic HCN-based synthesis in 1962 (Oró and Kimball 1962); however, it also participates in one-pot prebiotic synthesis of nucleobases as suggested by Saladino and Di Mauro (Saladino et al. 2006), as well as by meteoric impact-like processes (Ferus et al. 2017).

Cross-References

- [Aminoacetonitrile \(NH₂CH₂CN\)](#)
- [Diaminomaleonitrile](#)
- [Formamide \(NH₂CHO\)](#)
- [Hydrogen cyanide](#)

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Aminomethane

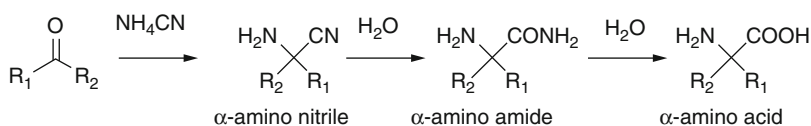
- [Methylamine \(CH₃NH₂\)](#)

Aminonitrile

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

An aminonitrile is a compound containing both an amino and a nitrile functional group. The simplest aminonitrile is ► [cyanamide](#). α -Aminonitriles, such as α -aminoacetonitrile, are important

Aminonitrile,**Fig. 1** Strecker amino acid synthesis via aminonitrile

intermediates in the ► [Strecker synthesis](#) of amino acids, as they are hydrolyzed consecutively to α -amino amides and finally to α -amino acids (Fig. 1). α -Aminoacetonitrile was detected in interstellar space in 2008.

Cross-References

- [Amino Acid](#)
- [Amino Acid Precursors](#)
- [Cyanamide](#)
- [Strecker Synthesis](#)

2-Aminopropanedinitrile

- [Aminomaleonitrile](#)

Aminyl Radical

- [Amino Radical](#)

Amitsoq Gneisses

Hervé Martin
Laboratoire Magmas et Volcans, Université
Clermont Auvergne, Aubière Cedex, France

Keywords

Greenland · Isua Supracrustal Belt · Archaean ·
TTG · Gneiss · Metamorphic rocks

Synonyms

[Itsaq Gneiss Complex](#)

Definition

The Amitsoq gneisses are among the older metamorphic rock complexes yet discovered on Earth. These rocks outcrop on the southwestern coast of Greenland, where they extend over more than 50 km northeast of Nûk (Godthåb). The oldest age obtained on a zircon crystal extracted from a tonalitic gneiss sample is of 3.872 ± 0.010 Ga.

Overview

The Amitsoq gneisses outcrop on the southwestern coast of Greenland, where they extend over more than 50 km northeast of Greenland's capital Nûk (Godthåb), along the southern coast of the Godthåbsfjord. After long and detailed field work, Mc Gregor (1968, 1973) was the first who recognized these Archaean terrains as among the oldest in the world. He distinguished two groups of gneisses: (1) very old ones cut by mafic dykes (Ameralik dykes) that he called the Amitsoq gneisses, (2) younger ones emplaced after the Ameralik dykes and that are referred as the Nûk gneisses. Both groups are crosscut by the late Qôrqt granite. The first dating of the Amitsoq gneisses was conducted by Black et al. (1971), who obtained a Rb-Sr isochron age of 3.98 ± 0.17 Ga, and Moorbath et al. (1972), who measured a slightly younger age (3.74 ± 0.1 Ga) using the same method. Newer researches showed that the so-called Amitsoq gneisses were heterogeneous and made up of several intrusive bodies. In order to account for this diversity, Nutman et al. (1996) proposed to refer to these formations as the Itsaq Gneiss Complex. In fact, both terms are equivalently used in geological literature.

This view has been subsequently corroborated by intensive zircon dating. Nutman et al. (1996) and Nutman and Hiess (2009) determined that the emplacement of Amitsoq gneiss protolith (protolith

Amitsoq Gneisses,

Fig. 1 General view of the ~3.8 Ga Amitsoq gneisses. They consist in grey gneiss, TTG in composition. (On this photo, they are crosscut by a black Ameralik dyke (Photo G. Gruau))



is the original, unmetamorphosed rock from which a metamorphic rock is formed) occurred between 3.88 and 3.60 Ga, during at least three main petrogenetic episodes at ~3.80 Ga, ~3.7 Ga, and ~3.65 Ga. It must be noted that some ages older than 3.85 Ga were also measured (Horie et al. 2010; Nutman et al. 2013). Indeed, a zircon crystal extracted from a tonalitic gneiss sample gave an age of 3.872 ± 0.010 Ga, which is the oldest reliable age so far measured in Amitsoq gneisses. The same authors reported an age of 3.883 ± 0.009 Ga measured in a zircon core, while the rim provided a slightly younger age of 3.861 ± 0.022 Ga; these dates are assumed as those of parental magma crystallization.

The Amitsoq gneisses outcrop over vast areas, over about 3,000 km². Their protolith was a felsic plutonic rock, having a tonalitic, trondhjemitic, and granodioritic (TTG) composition (O’Nions and Pankhurst 1978; Nutman and Bridgwater 1986; Nutman et al. 2000, 2007, 2013; Steenfelt et al. 2005; Hiess et al. 2009). In Archaean terrains, TTGs are very abundant; these are by far the most abundant rocks of the Archaean continental crust (Moyen and Martin 2012). They are generated by partial melting of hydrous basalt, possibly in a subduction-like environment (Martin 1986; Martin et al. 2005, 2014). Subsequently, they underwent granulite facies metamorphism at about 3.6 Ga (Friend and Nutman 2005).

Before the Cretaceous, and the development of the Labrador ridge and the Baffin Bay basin, west

Greenland and Labrador were closer to each other. At that time, Archaean terrains on both sides should have been connected. Indeed, along the northern coast of Labrador outcrop the Uivak gneisses, which are metamorphic rocks, mostly TTG in composition and very similar to the Amitsoq gneisses. The Uivak gneisses contain zircon crystals dated at 3.733 ± 0.009 Ga; however, they also contain rounded cores dated at 3.863 ± 0.012 Ga (Bridgwater and Collerson 1976; Bridgwater and Schiøtte 1991). Contrarily to Greenland, in Labrador these rocks suffered a Neoarchaean granulite facies metamorphism (Collerson and Bridgwater 1979) (Fig. 1).

Cross-References

- [Archean Eon](#)
- [Chronological History of Life on Earth](#)
- [Isua Supracrustal Belt](#)
- [Metamorphic Rock](#)
- [Tonalite-Trondhjemitic-Granodiorite](#)

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Ammonia

Alexander Smirnov

Department of Earth and Marine Science,
Dowling College, Oakdale, NY, USA

Keywords

Prebiotic synthesis · Nitrogen · Abiotic reduction

Synonyms

Azane; Nitro-sil; Trihydrogen nitride

Definition

Ammonia (NH₃) is a chemical compound composed of ► **nitrogen** and hydrogen which exists as a gas at standard conditions of temperature and pressure. In the trigonal pyramidal ammonia molecule, the lone electron pair of the nitrogen atom is responsible for its dipole moment (polarity) and its behavior as a base (proton acceptor). It dissolves readily in water and its protonation results in the formation of the conjugate acid ammonium ion (NH₄⁺) with both species coexisting in a pH-dependent equilibrium (pK_a NH₄⁺ = 9.25 at 25 °C). Liquid ammonia (boiling point –33.35 °C at atmospheric pressure) is an ionizing solvent

with physical properties and behavior similar to water (Lagowski 2007).

History

Ammonia has been known since ancient times, although it was first isolated by Priestly in 1774. In 1785, Berthollet determined its composition. The Haber-Bosch process to synthesize ammonia from nitrogen and hydrogen was developed by Fritz Haber and Carl Bosch in 1909. It was found in space by Cheung et al. (1968) and in comets by Altenhoff et al. (1983) using radio-astronomical techniques.

Overview

Ammonia has been detected throughout our solar system as well as in interstellar space (see ► [Molecules in Space](#)). The deuterated ammonium ion NH_3D^+ has recently been detected in the interstellar medium (Cernicharo et al. 2013; note that the symmetry of the principle isotopic form, NH_4^+ , leads to a zero electric dipole moment and hence no pure rotational transitions that might be observed astronomically). Ammonia is found as a gas in planetary atmospheres and in the solid form (ice) in cometary nuclei and planetary surfaces. Ammonia is hypothesized to be present in liquid form in a subsurface ocean on some outer planet satellites (e.g., ► [Titan](#)) where it would effectively lower the freezing point of water (Raulin 2008).

On the early Earth, ammonia was likely a necessary precursor for prebiotic organic synthesis, such as the ► [Strecker synthesis](#) of amino acids. It was used as the nitrogen source in the Miller-Urey experiment, which produced a suite of organic compounds such as amino acids from a mixture of reduced gases simulating the primordial atmosphere (Miller 1953). However, most current models suggest the early atmosphere was only mildly reducing, with the redox state linked to the evolution and oxidation state of the Hadean and early Archaean mantle, with ► [dinitrogen](#) (N_2) as the dominant nitrogen species (Kasting and Catling 2003).

It has been experimentally shown that ammonia-containing environments are more

efficient in organic synthesis than those dominated by dinitrogen in both aqueous and gaseous environments. This notion is not unexpected, considering that the strong triple bond (948 kJ.mol^{-1}) of the N_2 molecule results in large reaction activation energy barriers even if the overall reaction is thermodynamically favored. The process of conversion (e.g., reduction) of unreactive dinitrogen to reactive and prebiologically useful ammonia is referred to as ► [nitrogen fixation](#).

Mechanisms suggested for abiotic ammonia production on the early Earth include reduction of atmospherically derived nitrite (NO_2^-) by ferrous iron or iron-bearing minerals (Summers and Chang 1993); hydrolysis of atmospherically produced HCN (Zahnle 1986); reduction of dinitrogen on mineral surfaces (sulfides, metals, alloys) in hydrothermal systems (Brandes et al. 2008; Smirnov et al. 2008; Singireddy et al. 2012); or delivery of reduced nitrogen (nitride, N^{3-}) in iron meteorites followed by dissolution and reaction with H^+ (Smirnov et al. 2008). The concentrations of ammonia and/or ammonium ion in the prebiotic atmosphere and hydrosphere were likely controlled by mechanisms such as photolytic destruction, sequestration in clay minerals by substitution for K^+ and formation of N-bearing organic molecules.

Cross-References

- [Amino Acid](#)
- [Dinitrogen](#)
- [Hydrogen Cyanide](#)
- [Mildly Reducing Atmosphere](#)
- [Nitrogen](#)
- [Nitrogen Fixation](#)
- [Prebiotic Chemistry](#)
- [Strecker Synthesis](#)
- [Titan](#)

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Ammonium (NH_3D^+)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Deuterated ammonium ion](#)

Definition

The deuterated ammonium ion, NH_3D^+ , has been detected by radio astronomers toward a cold, dense [molecular cloud](#) core in the [Milky Way](#) galaxy (Cernicharo et al. 2013; cf. [Ammonia](#)). Note that the symmetry of the corresponding principal [isotopolog](#), NH_4^+ ,

leads to a zero electric dipole moment and hence no pure rotational transitions, making its interstellar detection very difficult. Large isotopic fractionation for deuterium/hydrogen isotopologs is expected, and indeed observed for many molecules, in cold molecular clouds.

Cross-References

- [Ammonia](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)

References and Further Reading

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Amoebae

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

Amoebae are microscopic unicellular eukaryotes (► [Protists](#)) able to deform their cytoplasm to move (amoeboid or crawling-like movement). They represent a large diversity of unrelated groups of eukaryotes. Some are surrounded by a cell coat (glycocalyx); others are naked. Some are pathogens. Others produce a mineral test made of siliceous plates, an organic test, or an agglutinated test made of external organic or mineral particles (thecamoebae or testate amoebae). Some amoebae demonstrate a social behavior when several individuals join to form

complex multicellular structures such as slugs or fruiting bodies. The oldest fossil amoeba reported so far is 750 Ma old.

Cross-References

- [Eukaryote](#)
- [Protists](#)

Amorphous Carbon

Akira Kouchi

Institute of Low Temperature Science, Hokkaido University, Kita-ku, Sapporo, Hokkaido, Japan

Keywords

Amorphous carbon · Carbon star · Carbonaceous chondrites · Cometary particles · Hydrogenated amorphous carbon · Interplanetary dust particles

Synonyms

[Glassy carbon](#); [Vitreous carbon](#)

Definition

Amorphous carbon is a noncrystalline solid allotropic form of carbon. There is no long-range order in the positions of the carbon atoms, but some short-range order is observed. Chemical bonds among atoms are a mixture of sp^2 - and sp^3 -hybridized bonds with a high concentration of dangling bonds. Because amorphous carbon is thermodynamically in a metastable state and the ratio of sp^2 - and sp^3 -hybridized bonds is variable, the properties of amorphous carbon vary greatly depending on the formation methods and conditions (Silva and Ravi 2003). Amorphous carbon is often abbreviated as “*a-C*.”

Overview

In the laboratory, amorphous carbon can be produced by physical vapor deposition, chemical vapor deposition, sputtering, and ion irradiation of diamond or graphite. The structure of amorphous carbon has been analyzed by X-ray and electron diffraction methods. The ratio of sp^2 - and sp^3 -hybridized bonds can be determined by electron energy loss spectroscopy, X-ray photoelectron spectroscopy, and Raman spectroscopy. Amorphous carbon whose dangling bonds are terminated with hydrogen is called hydrogenated amorphous carbon (*a-C:H*). Depending on the sp^2 and sp^3 ratios, the properties of amorphous carbon differ greatly. When a significant fraction of sp^3 bonds is present in amorphous carbon, this is called tetrahedral amorphous carbon (*ta-C*) or diamond-like carbon. Tetrahedral amorphous carbon is hard, transparent, and electrically insulating and has higher density than *a-C* and *a-C:H*.

In space, the occurrence of amorphous carbon is observed in circumstellar envelopes around carbon stars. When carbon stars lose mass to stellar winds, carbonaceous materials, such as polycyclic aromatic hydrocarbons (PAH), SiC, and amorphous carbon (*a-C/a-C:H*), that condense in their extended atmospheres are released to the interstellar medium. The conditions for the formation of amorphous carbon (*a-C*) grain have been investigated theoretically (Gail and Sedlmayr 1984), and the occurrence of amorphous carbon (*a-C*) and SiC has been deduced by observing the spectra of carbon stars (Blanco et al. 1990).

Very recently, amorphous carbon has been found in various extraterrestrial materials. Cometary particles from comet 81P/Wild 2, captured by NASA's Stardust mission, were analyzed by transmission electron microscopy, and a small amount of amorphous carbon grains less than 200 nm in size was found (Matrajt et al. 2008). In interplanetary dust particles (IDPs), investigated with Raman and infrared spectroscopy, the dominant type of carbon is found to be either a form of amorphous carbon (*a-C*) or of hydrogenated amorphous carbon (*a-C*:

H), depending on the type of IDP (Muñoz Caro et al. 2006). It has been proposed that amorphous carbon in cometary particles and IDPs was formed by energetic processing (UV photons and cosmic rays) of icy grains in interstellar molecular clouds (Greenberg 1998; Kouchi et al. 2005). Amorphous carbon grains have also been found in the matrix of carbonaceous chondrites (Brearley 2008). These grains are essentially made of pure carbon embedded in an amorphous silicate matrix. It has been proposed that these grains were originally primitive macromolecular organic material that has undergone mild thermal metamorphism in the parent bodies of carbonaceous chondrites.

Cross-References

- [Insoluble Organic Matter](#)
- [Kerogen](#)
- [Molecular Cloud](#)
- [Organic Refractory Matter](#)
- [Polycyclic Aromatic Hydrocarbon](#)

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Amorphous Solid

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

An amorphous solid lacks long-range order in the positioning of its constituent atoms; glass is an example. This contrasts with a crystalline solid, where such order is present, e.g., quartz. Both the ices and the silicates in ► [interstellar dust](#) grains are typically amorphous, although crystalline silicates are present in some circumstellar and cometary dust. The conversion of amorphous to crystalline water ice has often been invoked as an energy source in cometary outbursts at large heliocentric distances. The presence of crystalline silicates (presumably formed in the hot and dense inner solar system, possibly under the action of energetic particles from the young Sun) in ► [comets](#), which are formed in the cold outer part of the solar system, suggests that mixing of material was important in the ► [solar nebula](#).

Cross-References

- [Comet](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Solar Nebula](#)

Amphibolite Facies

Nicholas Arndt

ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Amphibolite facies refers to one of the divisions of the mineral-facies classification of the ► [metamorphic rocks](#). It corresponds to rocks

formed under moderate to high temperatures (400–600 °C) and pressures (200–900 MPa) conditions. Rocks in most Archean granulite-gneiss belts are metamorphosed to the amphibolite facies or higher. The name-giving rock is amphibolite, a dense and dark green to black rock generated by metamorphism under moderate temperature (ca. 500 °C) and pressure (1 GPa) from a mafic (basaltic) protolith or, more rarely, from impure dolostone (carbonate rock). It contains mainly hornblende, a type of amphibole (a chain silicate mineral group), with lesser proportions of plagioclase (a framework silicate mineral), and in some cases biotite, epidote, titanite, and iron oxides. Amphibolite is a common constituent of metamorphosed ► [oceanic crust](#) or of mafic intrusions in orogenic belts.

Cross-References

- [Mafic and Felsic](#)
- [Metamorphic Rock](#)
- [Oceanic Crust](#)

Amphiphile

David Deamer
Department of Chemistry, University of
California, Santa Cruz, Santa Cruz, CA, USA

Synonyms

[Detergent](#); [Lipid](#); [Surfactant](#)

Definition

An amphiphile is a molecule having both a hydrophobic nonpolar group and a hydrophilic polar group. The nonpolar hydrophobic portion of the molecule is typically a hydrocarbon chain ranging from 10 to 20 or more carbon atoms in length, and the polar moiety can be a carboxylic acid, phosphate, sulfate, amine, or alcohol group, among

other possibilities. Examples of amphiphiles are fatty acids, detergents, and all lipids including phospholipids and sterols. All amphiphiles are surface active and form monolayers at air-water interfaces. Some amphiphiles, particularly those with a single hydrocarbon chain, assemble into ► [micelles](#) in aqueous solutions. Other amphiphiles with two hydrocarbon chains, for instance, phospholipids, typically self-assemble into bilayer membranes that are the permeability barriers defining most forms of cellular life. Amphiphilic molecules resembling fatty acids are present in carbonaceous meteorites and are plausible membrane-forming components of the first living cells.

Cross-References

- [Lipid Bilayer](#)
- [Self-Assembly](#)

Amphiphilicity

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Amphiphilicity refers to the property of some molecules to have an affinity to two phases and most notably in biochemical systems the affinity to both a polar solvent phase (in this case water) and hydrophobic phase (such as the interior of cell membranes or proteins). Amphiphilic molecules usually contain both hydrophobic (e.g., benzyl or alkyl) and hydrophilic groups (e.g., -OH, -NH₂ and -COOH). Amphiphilic molecules are often useful as surfactants. Sodium dodecylbenzene sulfonate is a typical amphiphilic molecule used as a laundry detergent or shampoo and complexes hydrophobic substances such as dirt and oil with its hydrophobic dodecylbenzene moiety (C₁₂H₂₅-C₆H₄-) and is dispersed by affinity of the sulfonate moiety (-SO₃H⁻) to water.

Amphiphilic molecules can assemble in various solvents. Phospholipids are typical amphiphilic biomolecules, having hydrophilic heads including phosphate ions or charged tertiary or quaternary amines and hydrophobic tails including fatty acids. Many phospholipids form lipid bilayer membranes in water, where the polar heads face toward the solvent and hydrophobic tails which aggregate to form the inner part of the vesicle.

Cross-References

- [Hydrophobicity](#)
- [Membrane](#)
- [Self-Assembly](#)
- [Self-Assembly, Biological](#)

Ampholytes

- [Amphoteric Compounds](#)

Amphoteric Compounds

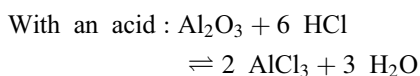
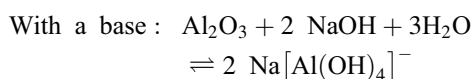
Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

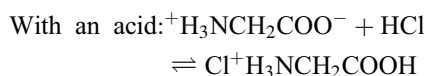
[Ampholytes](#)

Definition

An amphoteric compound is a compound that can act both as an acid and as a base. Some metal oxides or metal hydroxides, such as aluminum oxide (Al_2O_3), show amphotericity:



Some organic compounds also show amphotericity. These include amino acids, compounds having both carboxylic group(s) and amino group(s). For instance, glycine is predominantly present as a zwitterion ($^+\text{NH}_3\text{-CH}_2\text{-COO}^-$) in circumneutral aqueous solution, and it can neutralize either an acid or a base as follows:



Amino acids and their polymers (proteins) dissolved in aqueous solution possess both positively and negatively charged groups. In acidic solution, there are typically more positively charged groups, while there are typically more negatively charged groups in basic solution, though this depends somewhat on the sequence of the protein. At a defined pH called the isoelectric point (pI), amino acids or proteins have balanced positive and negative charges. At the isoelectric point of a protein, its hydrophobicity becomes maximum, and its solubility to water becomes minimum.

Cross-References

- [Amino acid](#)
- [Zwitterion](#)

Amplification (Genetics)

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

In molecular biology, amplification is a process by which a ► [nucleic acid](#) molecule is enzymatically

copied to generate a progeny population with the same sequence as the parental one. The most widely used amplification method is the ► [polymerase chain reaction](#) (PCR). The result of a PCR amplification of a segment of ► [DNA](#) is called an “amplicon.” Nucleic acids can also be amplified in an isothermal reaction involving a reverse transcriptase, which copies ► [RNA](#)→DNA, and a DNA-dependent RNA polymerase, which transcribes DNA→RNA. Isothermal amplification does not generate double-stranded DNA, and it is mainly used for copying RNA. Ligase-based methods, including the so-called ligase chain reaction (LCR), can be also used for specific DNA or RNA amplification. A fourth general method for nucleic acid amplification involves ► [cloning](#) the selected DNA molecule into bacterial or eukaryotic cells, allowing them to reproduce, and collecting the amplified DNA.

Cross-References

- [Cloning](#)
- [DNA](#)
- [Nucleic Acids](#)
- [Plasmid](#)
- [Polymerase Chain Reaction](#)
- [Replication \(Genetics\)](#)
- [RNA](#)

Anabolism

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Biosynthesis](#)

Definition

Anabolism is the subset of metabolic networks by which cell components are derived from organic

or inorganic precursors. Anabolism requires a source of energy – usually in the form of ATP – and reducing power, usually as NADPH.

Cross-References

- [Assimilative Metabolism](#)
- [Catabolism](#)
- [Metabolism](#)

Anaerobe

José Luis Sanz
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Non-aerobic](#)

Definition

Anaerobes are organisms that do not require oxygen to obtain energy or to grow. Anaerobic metabolism is restricted to microorganisms, both prokaryotic (► [Bacteria](#) and ► [Archaea](#)) and eukaryotic (yeast, microsporidia), although an anaerobic multicellular organism (phylum *Loricifera*) has been recently discovered in marine sediments.

Overview

There are two main categories of anaerobic microorganisms: (1) facultative anaerobes that can use oxygen for ► [respiration](#) if it is present but in its absence obtain energy from ► [fermentation](#) (such as enterobacteria or yeasts), ► [anaerobic respiration](#) (some *Pseudomonas*, *Thiobacillus*, *Bacillus*, and many others), and anoxygenic photosynthesis (some *Proteobacteria*) and (2) obligate anaerobes, which never use oxygen. These can, in turn,

be divided into two subcategories: (a) strict or obligate anaerobes, for whom oxygen is poisonous (i.e., oxygen is extremely toxic to ► [methanogens](#)), and (b) aeroduric or aerotolerant anaerobes that can grow in the presence of oxygen, although they never use it (i.e., bacteria involved in lactic acid fermentations). Cultivating strict anaerobes in the laboratory is an arduous task due to their extreme sensitivity to oxygen. Anaerobic jars or chambers are necessary for the isolation and growth of methanogenic archaea, sulfur-reducing bacteria, or bacteroides.

Some anaerobes are etiological agents of important diseases, such as tetanus (*Clostridium tetani*), botulism (*Clostridium botulinum*), cholera (*Vibrio cholera*), salmonellosis and typhoid fever (*Salmonella enterica*), or peptic ulcers (*Helicobacter pylori*). Others, such as the lactic acid fermenters *Lactobacillus* and *Lactococcus*, are involved in the production of food from dairy (yogurt, cheese, kefir, sour cream), vegetables (sauerkraut, olives, pickles), or meat (sausages). Some yeast (*Saccharomyces*) are responsible for bread, beer, and wine production. Finally, the methanogenic archaea carry out the last step of anaerobic degradation of organic matter in the absence of oxygen and, therefore, play a key role in anaerobic wastewater treatment and biomethanization of municipal solid waste processes. It is important to underline that Earth's atmospheric O₂ is of biological origin, and for an extended period of biological evolution, including the period in which the ► [origin of life](#) is suggested, the Earth remained strictly anaerobic. Anaerobes are of astrobiological interest because anaerobic conditions prevail on many planets, for instance, ► [Mars](#).

Cross-References

- [Anaerobic Respiration](#)
- [Anoxygenic Photosynthesis](#)
- [Archaea](#)
- [Bacteria](#)
- [Fermentation](#)
- [Mars](#)
- [Methanogens](#)

- [Origin of life](#)
- [Respiration](#)

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Anaerobic Photosynthesis

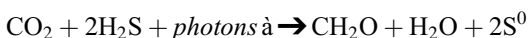
Casey Bryce and Andreas Kappler
Geomicrobiology, Center for Applied
Geoscience, University of Tübingen, Tübingen,
Germany

Keywords

Photosynthesis · Anoxygenic · Light energy · Bacteriochlorophyll · Pigments · Sulfide oxidation · Green sulfur bacteria · Purple sulfur bacteria · Purple non-sulfur bacteria

Chemical Formula

Numerous organic and inorganic electron donors can be utilized by anaerobic phototrophs to fix CO₂, with sulfide being one of the most common electron donors. The chemical formula for anaerobic photosynthesis coupled to hydrogen sulfide oxidation and elemental sulfur formation, one of the most common electron donors for anaerobic phototrophs, is expressed as:



As shown here, oxygen is not produced in this reaction leading to this process being referred to synonymously as “anoxygenic photosynthesis”.

Definition

The process by which anaerobic phototrophic bacteria harvest light energy coupled to fixation of CO₂, without the use of water as an electron donor or the production of oxygen as a by-product.

History

The study of anaerobic photosynthesis stems back to the dawn of microbiology itself with the first documented observation made in 1876 by E. Ray Lankester who noted the formation of red-colored “crusts” in a bacterial enrichment culture from decaying organic matter. The first isolate of a purple anaerobic phototroph, *Rhodospirillum rubrum*, was obtained in 1887 from a Berlin tap water sample in which a mouse had died. In 1907, it was finally demonstrated conclusively that these purple phototrophic bacteria did not produce O₂ (Molisch 1907). The first green anaerobic phototroph, *Chlorobium limicola*, was described in 1906 by Georgii Nadson (1906), which was isolated and characterized by Cornelis van Niel (1932). Since then, huge advances have been made in our understanding of the metabolisms, physiology, lifestyle, and environmental importance of anaerobic phototrophs which is summarized below. A complete timeline of major advances in the study of anoxygenic photosynthesis can be found in Gest and Blankenship (2004)

Overview

Anaerobic photosynthesis is a process by which anaerobic phototrophic bacteria use energy from sunlight to drive the fixation of CO₂. In contrast to oxygenic photosynthesis, which is conducted by organisms such as cyanobacteria and plants, anaerobic photosynthesis does not couple CO₂ fixation to the oxidation of water and therefore does not produce oxygen as a by-product. Instead of using water as an electron donor, these phototrophs utilize numerous inorganic compounds including sulfide, ferrous

iron, hydrogen, or even arsenite (Kulp et al. 2008) and nitrite (Griffin et al. 2007), as well as organic compounds. Several groups of bacteria are capable of conducting anaerobic photosynthesis including green sulfur bacteria (GSB), purple sulfur bacteria (PSB), purple non-sulfur bacteria (PNSB), *Acidobacteria*, *Heliobacteria*, and both red and green filamentous phototrophs such as *Chloroflexi* (Overmann and Garcia-Pichel 2013).

Anaerobic photosynthesis evolved before aerobic photosynthesis and was likely the dominant means of primary production in the Earth's ancient oceans, taking advantage of the anoxic, ferruginous, and sulfidic conditions that dominated for much of Earth's history (reviewed in Camacho et al. 2017). Anaerobic photosynthesis contributed significantly to early biogeochemical cycling, in particular by catalyzing oxidation of Fe (II) which led to the formation of vast deposits of Fe-rich rocks in the ancient oceans (see ► [Photoferrotrophy](#)). Distribution of anaerobic phototrophs became limited as high oxygen concentrations forced them to retreat into anoxic, sunlit niches. They are commonly found today in redox-stratified lakes, waterlogged sands and soils, sulfidic springs, and salt marshes. They are also found in extreme environments such as acidic and alkaline hot springs, salt marshes, soda lakes, and polar environments such as the high Arctic (Madigan 2003).

It is likely that the molecular pathways involved in anaerobic photosynthesis gave rise to aerobic photosynthesis (Blankenship 2010). Aerobic photosynthesis is a more complex molecular process than anaerobic photosynthesis, requiring two connected photosystems (Photosystem I and Photosystem II) to work in tandem. In order to harvest light energy, the chlorophyll-containing reaction center in Photosystem II is excited by light and readily passes an electron down the electron transport chain to a second chlorophyll-containing reaction center in Photosystem I. This second reaction center is excited by light and an electron passed down the second electron transfer chain, ultimately oxidizing NADP⁺ to NADPH. Anaerobic photosynthesis, on the other hand,

requires only one photosynthetic reaction center, where the electron can either end up oxidizing NAD⁺ to create reducing equivalents or return to the reaction center in a process known as “cyclic photophosphorylation.” The Type I reaction center found in the GSB and *Heliobacteria* is structurally similar to Photosystem I found in aerobic phototrophs, whereas the Type II reaction center found mainly in the purple bacteria and filamentous anaerobic phototrophs is similar to Photosystem II. It is therefore considered that the reaction centers in anaerobic phototrophs are the ancestors of Photosystems I and II. It is still debated, however, whether the photosystems were merged in one anaerobic phototroph shortly before the evolution of aerobic photosynthesis or whether ancient anaerobic phototrophs had both photosystems and later specialized to use just one (Allen 2005).

In addition to utilizing different electron transport chains from aerobic phototrophs, anaerobic phototrophs also employ different pigments for harvesting light. Anoxygenic phototrophs use bacteriochlorophylls for this purpose, which are similar to chlorophyll in aerobic photosynthesis. Chlorophyll has peak absorption of light in the red range of the spectrum, whereas bacteriochlorophylls have a maximum absorption in the near infrared. Anaerobic phototrophs, particularly the GSB, also utilize bacteriochlorophylls that are specifically adapted to harvest light at low intensities. This difference in both the wavelength and intensity of light utilized by anaerobic phototrophs can enable them to coexist alongside oxygenic phototrophs in the same environment where they can carve out independent niches based on the wavelength and intensity of light (e.g., de Beer et al. 2017).

To summarize, anaerobic photosynthesis is an ancient metabolism that helped significantly shape the biogeochemical evolution of the Earth, and it provided much of the genetic machinery later adapted for aerobic photosynthesis. Despite being relegated to more specialized environments following the evolution of aerobic photosynthesis, these organisms are still prevalent in many sunlit environments today where they contribute as primary producers and actively

shape the biogeochemical cycling of elements such as sulfur and iron.

Cross-References

- ▶ [Anoxygenic Photosynthesis](#)
- ▶ [Cyanobacteria, Diversity and Evolution of](#)
- ▶ [Oxygenation of the Earth's Atmosphere](#)
- ▶ [Photoferrotrophy](#)
- ▶ [Sulfide Oxidation](#)
- ▶ [Sulfidic Oceans](#)

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Anaerobic Respiration

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Anaerobic ► [respiration](#) is a metabolic process in which oxidized organic compounds, such as fumarate, or inorganic molecules, such as nitrate, sulfate, or ferric ion, serve as the terminal ► [electron acceptor](#) of an electron transport chain.

Cross-References

- [Aerobic Respiration](#)
- [Electron Acceptor](#)
- [Respiration](#)

Analog Sites

- [Terrestrial Analog](#)

Anatexis

Daniele L. Pinti

GEOTOP Research Center for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Anatexis is a word of Greek and Latin derivation which means “melt down.” Anatexis is the process of melting of continental crust rocks, where the term “partial melting” is reserved to the ► [mantle](#). Anatexis is an important process

which bring lower crust rocks to partially melt forming *migmatites* (a rock composed of a layer of the original rock – or protolith – and a second layer derived from the melting and recrystallization of the protolith), the penultimate stage before complete melting of a rock. Most important, anatexis creates – by remelting of hydrated basaltic or ► [sedimentary rocks](#) – granitic magmas which crystallization contributes to the building and the evolution of the ► [continental crust](#) since the Archean and to the present-day felsic composition (e.g., Clemens 1990).

Cross-References

- [Archean Eon](#)
- [Continental Crust](#)
- [Granite](#)

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Anaximander

Richard Hutchins

Classics, University of Miami, Miami, FL, USA

Keywords

Presocratic philosophy · Ancient cosmology · Multiple worlds · Scientific revolution · Evolution · Naturalism · Infinity

Definition

Anaximander was a Presocratic philosopher from Miletus. Ancient Greek historians of philosophy usually listed him as the second philosopher after Thales. Nonetheless, Anaximander has the greatest claim to be considered the first Greek scientist and to have founded the ancient Greek tradition of naturalistic inquiry into nature.

Overview

Anaximander of Miletus may have been the first Greek scientist. Nonetheless, ancient Greeks typically considered him the second philosopher after Thales. The most secure date for Anaximander comes from the ancient Greek historian of philosophy Diogenes Laertius, who says that Anaximander was 64 years old in 547 BCE. Anaximander is said to have drawn the first map of the world, perhaps created a spherical model of the heavens, and is credited with introducing the gnomon. A gnomon is a stick set vertically in the ground to measure the sun's shadow and, thus, its altitude, paving the way for complex astronomical observations of the sun's movements. Anaximander is most famous for his claim that the starting point and original material of the universe is the "indefinite" or "boundless," i.e., the *apeiron*, in ancient Greek. By *apeiron*, Anaximander meant something that can be delimited neither internally nor externally, hence, the "indefinite" or "boundless." The *apeiron* may refer to the boundless beyond from which all worlds arose. Aristotle took Anaximander to mean an indeterminate substance out of which the opposite principles of hot and cold emerged. Either way, Anaximander's silence on the specific details of the *apeiron* seems to evince a rational caution about the origin of the universe (Schofield 2008).

As the material starting point, or *arche*, of the cosmos, the *apeiron* was in constant motion before the beginning of the universe (Hippolytus *Refutation of all Heresies* 1.6.2). Aristotle attributes mental and god-like qualities to it in his report that the *apeiron* "steers all" and is "indestructible" (*Physics* 203b7ff). Anaximander seems to have believed that the cosmos began when two fundamental material principles break out of the *apeiron*: the hot and the cold. Originally, the hot formed itself into a fiery sphere that encased the cold, growing around the earth "like the bark around a tree" (Pseudo-Plutarch = Clement *Stromata* 2), eventually becoming the celestial bodies. The cold became the sublunary air, or mist, and earth. It is through the reciprocal interactions of the hot and the cold that the multiple worlds become increasingly differentiated. Our world, Anaximander thought, was originally a

watery place that gradually dried up under the heat of the sun.

The only direct quotation we have from Anaximander seems to allude to the increasing differentiation of worlds through the reciprocal interactions of the hot and the cold. This sole fragment of Anaximander comes to us from the sixth-century Neoplatonist philosopher Simplicius (*Commentary on Aristotle's Physics* 24.13–21 = Laks & Most D6). Since the extent of the fragment is disputed by scholars, the full quotation from Simplicius is reproduced here, with Anaximander's likely words in bold: "He says that the *arche* [starting-point of the cosmos] is neither water nor any of the other things called elements, but some other nature, the *apeiron*, out of which come to be all the heavens (or "skies:" *ouranoi*) and the worlds (*kosmoi*) in them. The things that are perish into the things from which they come to be, **according to necessity. For they pay the penalty and retribution to each other for their injustice according to the order of time**, as he says in very poetical language." Anaximander not only posits a starting point, or *arche*, for the cosmos but describes the cosmos as behaving in an orderly, law-like way that is knowable by humans. The causes of the world are not random or dependent upon the whims of deities but follow a stable reciprocal process within a developing cosmos. Anaximander also may have anticipated the "principle of sufficient reason" in his claim that the earth is not supported by anything, but floats in space with its position fixed (Kahn 1994). Aristotle reports (*On the Heavens* 2.13295b11–16) that Anaximander said: "the earth stays fixed because of equality (*homoioteta*). For it is no more fitting for what is established at the center and is equally far from the extremes to move up or down or sideways. And it is impossible for it to move in opposite direction at the same time. Therefore, by necessity (*ex anankes*) it stays fixed."

Anaximander may have held proto-evolutionary views about the origins of species, including humans. While no ancient author thought that one species evolves into another (Campbell 2014), Anaximander is cited by the late second-century ACE bishop of Rome Hippolytus (*Refutation of All Heresies* 1.6.6) as saying that "living creatures

came into being from moisture evaporated by the sun. Man was originally similar to another creature—that is, to a fish.” But other reports of Anaximander’s thought suggest that he was not so much addressing human evolution as trying to solve the problem of how the first human infants survived before there were human parents. As the late antique author Pseudo-Plutarch reports (*Stromata* 2): “He [Anaximander] says that in the beginning man was born from creatures of a different kind; because other creatures soon become self-supporting, but man alone needs prolonged nursing.” The Roman grammarian Censorinus (*Censorinus. The Birthday Book* 4.7) attributes to Anaximander the idea that human infants were initially carried inside fish as if in embryos, until puberty when the self-supporting humans could step out onto dry land: “Anaximander of Miletus thought that when the water and earth were heated, there arose either fish or creatures very similar to fish (*piscibus simillima animalia*); in these human beings developed and were retained within as embryos (*fetus*) until puberty; then at last the fish-like creatures burst and men and women who were already able to nourish themselves stepped forth.” Thus, Anaximander may not have been claiming that humans evolved from a fish-like ancestor, but that the first human infants survived the originally watery world by living inside fish for nourishment and protection. This accords with what Anaximander is reported to have thought about other animal infants, as stated by first–second-century philosopher Aëtius (5.19.4 = Laks & Most D38): “Anaximander says that the first animals were born in moisture, enclosed in thorny barks. When their age advanced, they came out onto the drier part, and when their bark burst open they changed their mode of life (*metabionai*) in a short time.” Here, it is important to emphasize how Anaximander’s cosmological and biological hypotheses reinforce each other. There seems to be an analogy between how the principles of hot and cold broke off from the *apeiron*, how animals burst out of their bark-like encasings after the watery earth dried out, and how humans burst out of fish-like animals before setting foot on dry land. While Anaximander does not seem to think that one animal can evolve from another, he does seem to think that new forms and ways of life appear or develop by breaking out of old ones,

whether in the heavens or on earth. Thus, while obscure, Anaximander seems to have used a common structure of thought for his cosmology and biology: at first one kind of stuff encases another, then that inner material breaks out of its encasement so that new forms can appear.

Anaximander’s claim to be the first scientist rests on several innovations. Anaximander was the first to compose a book in prose about the natural world, called the *Peri phuseos*, or “On Nature.” In this book, he presented an all-embracing vision of the natural world, ordered by laws, and based on the stable interactions of the opposing principles of the hot and the cold. This laid the groundwork for a tradition of naturalistic inquiry in ancient Greece, *phusiologia*, that could be seen as forming the basis for all scientific revolutions to come. Anaximander was also the first geographer and biologist. Anaximander introduced important conceptual tools into the study of nature, using the concepts of “law” and “necessity” to rationally explain the observable world. He also held an entirely new view of the earth as floating, unsupported, in space. As theoretical physicist Carlo Rovelli has passionately argued, in his rebellion against the Greek mythological worldview, Anaximander came to realize that “scientific revolutions are possible: in order for us to understand the world, we must be aware that our world-view may be mistaken and we can redraw it (Rovelli 2011).”

Cross-References

- [Astrobiology](#)
- [Astrobiology as Science](#)
- [Astrometry](#)
- [Chronological History of Life on Earth](#)
- [Cosmogony: Greece](#)
- [Cosmogony: Mesopotamia](#)
- [Cosmogony](#)
- [Darwin’s Conception of the Origins of Life](#)
- [Earth](#)
- [Earth, Formation, and Early Evolution](#)
- [Earth’s Atmosphere, Origin and Evolution of](#)
- [Ecology, History of](#)
- [Life in the Solar System \(History\)](#)

- [Life, Concept of \(from Antiquity to the Eighteenth Century\)](#)
- [Materialism](#)
- [Origin of Life](#)
- [Origins of Life, History of](#)
- [Planetary Evolution](#)
- [Plurality of Worlds](#)

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Ancient Lakes

- [Mars, Paleolakes](#)

Angular Diameter

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The angular diameter of a celestial object, seen from Earth, is the apparent diameter measured in angular units. Planets in the solar system have typical angular diameters between a few arcsec up to 50 arcsec (0.25 m-radians).

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Angular Momentum

Jérôme Perez
Applied Mathematics Laboratory, ENSTA
ParisTech, Paris Cedex 15, France

Keywords

Rotating body

Definition

In mechanics, angular momentum is the vector cross product between the position vector and the momentum vector of a point mass system. This definition can be extended to a solid by summation.

Overview

The movement of a point mass m is defined by its position r and its velocity v . These quantities are **vectors** relative to some reference system. This movement splits into two parts: a movement of translation and a movement of rotation. The amount of movement is measured by the linear momentum (impulsion) $p = mv$ (for simple cases), which is a conserved quantity for a translation invariant system. The amount of rotation is measured by the angular momentum $L = r \times p$, which is a conserved quantity for a rotation invariant system. Note that the vector cross product $a \times b = ab \sin \theta n$, where θ is the smaller angle between a and b ($0^\circ \leq \theta \leq 180^\circ$), a and b are the magnitudes of vectors a and b , and n is a unit vector perpendicular to the plane containing a and b in the direction given by the right-hand rule.

Variations of velocity are produced by forces, in accordance with Newton's second law of dynamics. If forces that apply on the point are aligned with the position vector r , they are called central, the system is invariant under rotation, and its angular momentum is conserved. As ► [gravitation](#) is a central force, this conservation occurs frequently in astronomy.

When the system is extended, such as a solid planet described by a distribution of points whose relative distances are fixed, the total angular momentum is the sum of the contributions of all these points. In this case, it is distributed between the spin of the planet itself and the angular momentum of its orbit.

The conservation of angular momentum of celestial bodies is a fundamental tool for analyzing their properties. For example:

- In a two-body problem (see ► [“Gravitation”](#)), if one of the two bodies is much heavier than the other, the conservation of angular momentum implies Kepler's third law (see ► [“Orbital Resonance”](#)) and allows us to obtain the value of the large mass from observations of the period and of the semimajor axis of the small mass.
- If a planet is found to rotate slower than expected, one can suspect that this planet is accompanied by a satellite, because the total angular momentum is shared between the planet and its satellite in order to be conserved.
- The tidal torque the Moon exerts on the Earth implies a slowing down of the rotation rate of the Earth (at about 42 ns/day). As a consequence and because the total angular momentum of the whole system is conserved, the distance between the Earth and Moon gradually increases by 4.5 cm/year.

Cross-References

- [Gravitation](#)
- [Orbital Resonance](#)

Animalcules

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Definition

From the seventeenth century to the early nineteenth century, animalcule meant the very small living beings that were observed through a microscope. The famous microscopist, Antony van Leeuwenhoek (1632–1723), one of the major improvers of this instrument during the second part of the seventeenth century, used the expression *spermatic animalcules*.

Cross-References

- [Bacteria](#)
- [Protists](#)

Anion

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

An anion is an atom or molecule that has gained an electron (e.g., CN^- , OH^- , C_4H^-). Neutral molecules with large electron affinities (EAs) can attach an electron in a variety of chemical reactions, such as electron photo attachment. Long carbon-chain molecules have large EA values, and C_6H^- was the first anion discovered in the interstellar medium in 2006.

Cross-References

- [Circumstellar Chemistry](#)
- [Molecules in Space](#)
- [Photochemistry](#)

Annefrank

Stefano Mottola
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

(5535) Annefrank is a small S-class, main-belt asteroid named after the Jewish victim of Nazi persecution famous for her diary. The Discovery spacecraft Stardust encountered the asteroid on November 2, 2002 on its route to comet Wild 2. During the fast flyby, the space probe recorded an image sequence lasting about 15 min and consisting of over 70 images. Although the

imagery had a comparatively low resolution in the range of 300–185 km/pixel and covered only about 40% of the surface, the sequence revealed a body with approximate dimensions of $6.6 \times 5.0 \times 3.4$ km and an angular appearance, reminiscent of a contact binary or of a re-accumulated pile of fragments.

Anorthosite

Nicholas Arndt
ISterre, University Grenoble Alpes, Grenoble,
France

Definition

Anorthosite is an igneous intrusive rock. It is light colored (leucocratic) and has a medium to coarse grain size (phaneritic). It is mainly composed of plagioclase (andesine, labradorite, and bytownite), minor pyroxene, olivine, and iron-titanium oxides (ilmenite and magnetite). Proterozoic anorthosite forms large massifs associated with granitoids (North America, Scandinavia). Archean coarse-grained (megacrystic) anorthosite occurs in intrusions (dikes and sills) and flows of basaltic composition. Anorthosite is a common constituent of the lighter surfaces of the Moon called lunar highlands or terrae. Formation of anorthosite requires the concentration of plagioclase from mafic magma by flotation in a magma ocean (as is proposed to have occurred on the Moon), ascent of plagioclase-rich mushes, or low-pressure crystallization in magma chambers.

Cross-References

- [Archean Eon](#)
- [KREEP](#)
- [Moon, The](#)

References and Further Reading

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Anoxic

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Anoxic is a term used to describe a condition, environment, or habitat depleted of oxygen.

Cross-References

► [Anaerobe](#)

Anoxic Ocean

► [Sulfidic Oceans](#)

Anoxygenic Photosynthesis

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Anaerobic photosynthesis](#)

Definition

Anoxygenic ► [photosynthesis](#) is a bacterial photosynthesis that occurs under anaerobic conditions, using the photosynthetic electron transport chain in a noncyclic mode and reduced inorganic electron donors, such as hydrogen sulfide, hydrogen, or ferrous ion, as ► [electron donors](#). There are also cases of anaerobic photosynthetic electron transport chains acting cyclically; in this case, the generation of reducing power is not needed or

it is decoupled from the photosynthetic reaction. The prototypical noncyclic anoxygenic photosynthesis is present in green bacteria.

Cross-References

► [Electron Donor](#)
► [Oxygenic Photosynthesis](#)
► [Photosynthesis](#)

Anoxygenic Phototrophic Fe(II) Oxidation

► [Photoferrotrophy](#)

Antarctic Continent

► [Antarctica, Natural Analogue Site](#)

Antarctica, Natural Analogue Site

Daniele L. Pinti
GEOTOP, Research Centre on the Dynamics of
the Earth System, Université du Québec à
Montréal, Montréal, QC, Canada

Keywords

Glaciation · Ice sheets · Natural analogue site ·
Dry valleys · Mars · Extremophiles ·
Weathering processes

Synonyms

[Antarctic continent](#)

Definition

Antarctica is the ice-covered continent located in the Southern Hemisphere of the Earth. It is situated almost entirely south of the Antarctic Circle and is surrounded by the Southern Ocean.

Because it is the driest and coldest place on Earth, its natural surface environments have been considered to be a good analogue site of the Mars Northern Plains.

History

Since Aristotle, it was suspected that an important landmass was situated at the South Pole (*Terra Australis Incognita*), yet the continent of Antarctica was discovered only in 1820 by a Russian expedition onboard the *Vostok* and *Mirny* vessels and led by Fabian Gottlieb von Bellingshausen and Mikhail Lazarev. They discovered an ice shelf at Princess Martha Coast that later became known as the Fimbul Ice Shelf. Several land sightings followed in years, but only in 1841 the first expedition to the interior of Antarctica was organized and conducted by James Clark Ross, discovering mountains as the Erebus volcano.

With the progressive conquest of the Antarctica by numerous expeditions in the following century and the establishment of scientific bases by several countries, the Antarctica continent was deeply investigated, and scientific experiences settled. In 1903, US explorer Robert Scott discovered the dry valleys around the future McMurdo polar station. These valleys are the driest places in Antarctica, not covered by the ice sheets and presently showing morphological features identical to Martian Northern Plains. One turning point for future astrobiological investigation was the discovery of the subglacial Lake Vostok in the late 1960s, a potential niche of deep extreme biosphere.

Overview

Antarctica, the coldest and driest continent on Earth, is technically considered a desert, with only 166 mm per year of average precipitation. Antarctica also recorded the coldest temperature on Earth measured so far, of $-89.2\text{ }^{\circ}\text{C}$, at the

Vostok station. Ninety-eight percent of Antarctica's 14 million km^2 surface area is covered by a 1.6 km thick ice sheet, corresponding to 90% of the world's ice. It has been covered by ice for the past 15 Ma. About 380 subglacial lakes lie at the base of the continental ice sheet, the best-known being Lake Vostok. Lake Vostok has remained isolated for 14 million years, making it a valuable analogue for exploring deep biosphere niches. Antarctica's ice surface shares similarities with those of Jupiter's moon Europa and Mars. Further, the possible presence of subglacial oceans on the Saturn's moon Enceladus has sparked renewed interest in studying subglacial lakes such as Vostok Lake, for testing the possibility that life forms could have developed or survived on this far moon.

Antarctica has been for a long time a privileged natural analogue terrain for studying morphological and weathering processes shaping the Mars surface, for testing instrumentation and field exploration procedures, and training astronauts for routine space missions and future-manned Mars missions. Particularly, ice-free Antarctica McMurdo *Dry Valleys* reflect surface conditions similar to those of the Mars surface. Dry valleys are located mainly in the Victoria Land west of McMurdo Sound. Dry valleys are so named because of their extremely low humidity and their lack of snow and ice cover. Their surfaces are covered by loose gravel and show ice-wedge polygonal-patterned ground. Polygonal-patterned ground is a geometric landform with characteristic honeycomb patterns surrounded by ice crests that develop in periglacial regions which experience intense freezing and thawing cycles. High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter has clearly shown the same patterns on high latitudes of Mars and at the bottom of some Mars crater. Antarctica's Dry Valleys and Mars' midlatitudes soil formation histories share similarities, particularly involving slow processes of sublimation and poleward migration of water (Wentworth et al. 2005). Radiation-resistant bacteria from

Antarctic Dry Valleys were also isolated and studied to test whether extremophiles could survive large doses of UV-radiation in hostile environments such as Mars' surface (Musilova et al. 2015).

Antarctica's permafrost hard surfaces are a privileged site of several Mars analogue missions, because the soils share physical similarities with that of Mars. One of the most recent missions took place in the Marambio Island, Western Antarctic Peninsula, where field exploration, sample collection, instrument deployment, and spacesuit testing were carried out on a Mars-like rocky, permafrost-rich landscape (Rask et al. 2012). NASA is now testing a Buoyant Rover for Under-Ice Exploration (BRUIE), developed for underwater exploration in extraterrestrial, icy worlds such as Enceladus.

Cross-References

- [Europa Analogues](#)
- [Mars Analogue Sites](#)
- [Mars Analogues](#)
- [Vostok, Subglacial Lake](#)

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Anthony van Leeuwenhoek

- [Leeuwenhoek, Antony van](#)

Anthropology of Science

- [Social Study of Science](#)

Antibiotic

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Antimicrobial agent](#); [Functional inhibitor](#)

Definition

Antibiotics are chemical substances produced by a wide range of microorganisms, among them fungi and bacteria, that kill or inhibit the growth of other organisms. A large number of antibiotics have been identified in nature, most of them as products of secondary metabolism. Antibiotic producers must be resistant to the active form of the antibiotic. Important targets of antibiotics are the synthesis of ► [cell membrane](#) and ► [cell wall](#), replication, ► [transcription](#), and ► [translation](#). Antibiotics are considered regulators of microbial populations rather than part of microbial warfare. The susceptibility of organisms to individual antibiotics or other chemotherapeutic agents varies significantly and is the base of their pharmacological use.

Cross-References

- [Cell Membrane](#)
- [Cell Wall](#)
- [Replication \(Genetics\)](#)
- [Ribosome](#)
- [Sporulation](#)
- [Transcription](#)
- [Translation](#)

Antibody

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Antibody is a complex ► [protein](#) (immunoglobulin) produced as a response to a chemical agent (antigen) as a part of a defensive system (immune system) in multicellular animals. The combination of antibody and antigen is specific (albeit not necessarily absolute), non-covalent, and reversible. There are many methodological applications of antibodies, either as a heterogeneous population of immunoglobulins (polyclonal antibodies) or as a homogeneous preparation (monoclonal antibodies). Antibodies show a broad applicability in biotechnology, including the development of affinity biosensors.

Cross-References

- [Biosensor](#)
- [Protein](#)

Anticodon

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Anticodon is a triplet of nucleotides in a tRNA, complementary to a codon in the mRNA.

Cross-References

- [Codon](#)
- [Genetic Code](#)

- [RNA](#)
- [Translation](#)
- [Wobble Hypothesis \(Genetics\)](#)

Antimicrobial Agent

- [Antibiotic](#)

Antonie van Leeuwenhoek

- [Leeuwenhoek, Antony van](#)

Antonius a Leeuwenhoek

- [Leeuwenhoek, Antony van](#)

Antonj Leeuwenhoek

- [Leeuwenhoek, Antony van](#)

AOGCM

John Lee Grenfell

German Aerospace Center (DLR), Berlin,
Germany

Synonyms

[Atmosphere-ocean general circulation model](#)

Definition

An AOGCM refers to a 3D numerical model which solves the central conservation equations, e.g., mass, momentum, and energy, to derive the characteristic global-scale fluid dynamical flow (the “general circulation”) as well as temperature of a planetary atmosphere and ocean. The atmosphere and ocean modules are coupled via surface exchange fluxes of energy (e.g., via evaporation

and condensation) and momentum (e.g., via wind stresses at the ocean surface).

- [Mars Analogue Sites](#)
- [Microfossils](#)
- [Pilbara Craton](#)

Cross-References

- [GCM](#)

Apex Basalt Formation

- [Apex Chert, Microfossils](#)

Apex Basalt, Australia

Nicholas Arndt

Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Keywords

Chert · Australia · Pilbara craton · Traces of life

Definition

The Apex Basalt is a ca. 3.46-Ga-old formation comprising tholeiitic pillow basalts, komatiitic basalts, and komatiites intercalated with thin chert layers. It is located near Marble Bar in the ► [Pilbara Craton](#) of Western Australia. ► [Microfossils](#), morphological biomarkers, and filamentous carbon structures in the lower chert beds have been interpreted as fossil prokaryotes (mainly cyanobacteria but also thermophiles) and are claimed to represent the oldest fossil record of life on Earth. For this reason, outcrops of this formation are considered one of the most important astrobiological sites on Earth. However, for almost 20 years, many authors question this interpretation: considering that the Apex basalt “microfossils” are abiotic artifacts.

Cross-References

- [Apex Chert](#)
- [Apex Chert, Microfossils](#)

Apex Chert

Tanja Elsa Zegers

Paleomagnetic Laboratory, Institute of Earth
Sciences, Utrecht University, Utrecht, The
Netherlands

Definition

The 3.465 Ga Apex Chert is a chert unit within the Apex Basalt in the Warrawoona Group, which is part of the oldest greenstone sequence in the Pilbara granite-greenstone terrain. The Apex Basalt is stratigraphically below the Strelley Pool Chert, a unit known for hosting the oldest ► [stromatolite](#) on Earth. In the Apex Chert, small carbonaceous filaments with $\delta^{13}\text{C}$ as low as -22.5‰ to -25‰ were reported to represent evidence for ► [cyanobacteria](#) able to recycle inorganic carbon through ► [RubisCO](#). The Apex Chert microfossils occur in rounded grains of microcrystalline silica, which have been interpreted as clasts in a conglomerate deposited in a wave-washed beach or a stream mouth, an ideal environment for cyanobacteria. Subsequent work suggested that the chert was deposited from hydrothermal fluids with a temperature higher than 250 °C and that the microtextures may result from abiotic processes under those temperatures. If biogenic, microfossils could represent remains of thermophile chemotrophs living close to hydrothermal vents.

Cross-References

- [Apex Basalt, Australia](#)
- [Apex Chert, Microfossils](#)
- [Archaean Traces of Life](#)
- [Biomarkers, Morphological](#)
- [Cyanobacteria](#)
- [Pilbara Craton](#)
- [Rubisco](#)
- [Stromatolites](#)

Apex Chert, Microfossils

Wladyslaw Altermann¹ and Daniele L. Pinti²

¹Department of Geology, University of Johannesburg, Johannesburg, South Africa

²GEOTOP Research Centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Apex Chert · Apex Basalt · Biomarkers · Cyanobacteria · Microfossils, World's oldest fossils, Pseudofossils

Synonyms

Apex chert; Apex basalt formation; Schopf locality; Earth's oldest microfossils

Definition

The Apex Chert is a lenticular and bedded, laminated, microcrystalline silica (SiO₂) deposit interlayered with and crosscutting submarine lavas of the Apex Basalt Formation, Pilbara Craton, Western Australia. The Apex Basalt Formation, Salgash Subgroup of the Warrawoona Group dates at 3465–3458 Ma. The origin of the chert is disputed. The rivaling interpretations: diagenetic silicification (chertification) of clastic or carbonate sedimentary and volcano-sedimentary rocks *versus* primary silica deposition on the ocean floor or hydrothermal chert intrusion and replacement, do not necessarily contradict each other. Varying chert generations may coexist where black chert dikes and lenses crosscut dark gray and whitish stratiform cherts and interlayered volcanics of the Apex Formation (Marshall et al. 2012). Carbonaceous filaments found in the Apex Chert beds, Chinaman Creek near Marble Bar, were interpreted as world's oldest fossils and as evidence for the antiquity of life on Earth (Schopf 1993). The name “Schopf locality” was given to this outcrop after J. William (Bill)

Schopf, an American paleontologist and paleobiologist of the University of California, Los Angeles, who found and described these microfossils.

History

Because of geological recycling of rocks and their progressive destruction by diagenesis, metamorphism, and tectonic forces, Precambrian fossils rarely survive postdepositional processes. Further, they are difficult to trace for their evolutionary simplicity and microscopic sizes. Already Charles Darwin has desperately missed the fossil record of the pre-Cambrian. No fossils older than Cambrian advanced multicellular organisms were known at his time. They must have evolved from simpler Precambrian life forms of which, however, no vestige was available. With the development of microscopic techniques and geochemical methods, an increasing number of scientific reports on putative Archean microfossils, started to emerge in the 1980s (e.g., Awramik et al. 1983; Buick 1984). Schopf and Packer (1987) published a report on 3.5 billion years old microfossils from the Warrawoona Group in Western Australia, followed by more detailed descriptions of these then oldest fossil evidence of life on Earth (Schopf 1993).

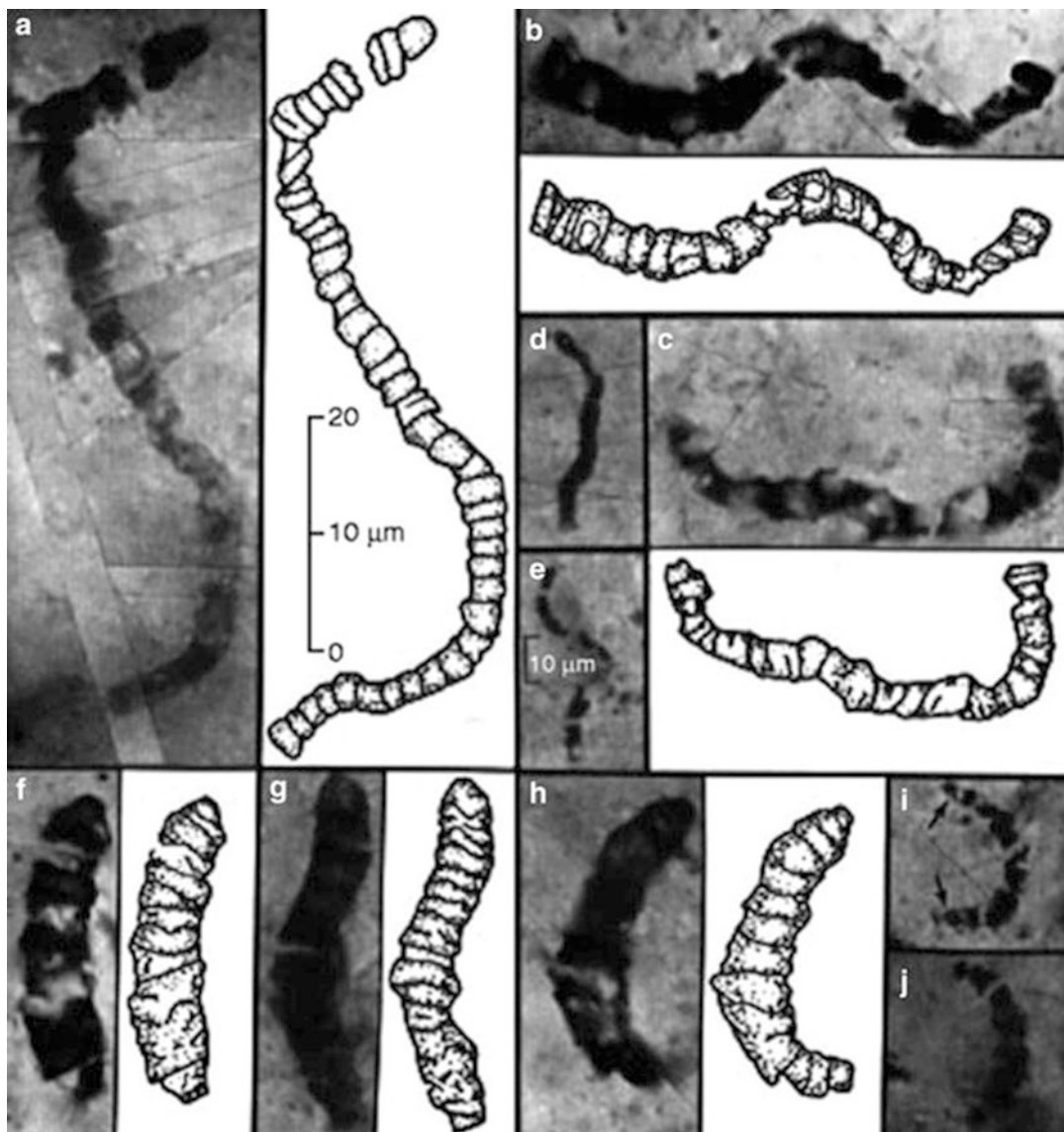
Twenty years later, an international group of researchers around the late Martin Brasier, paleontologist at Oxford University, questioned Schopf's (1993) interpretation, based on renewed microscopy of the same fossils and discredited them as “secondary artefacts formed from amorphous graphite” (Brasier et al. 2002). These claims triggered a turmoil discussion on the quality of all reports of Archean life remains and avowed that life might have developed only in the Proterozoic (Brasier et al. 2004), a view, however, which did not last for long.

Overview

Schopf (1993) reported 11 morphological taxa of filamentous and coccoidal prokaryotic

microfossils found in the bedded Apex Chert. He interpreted the host rock as chertified sedimentary beds containing kerogenous (carbonaceous) filaments, up to several tens of micrometers long and 1–20 μm wide. Most filaments displayed typical cyanobacteria-like septation and terminal cells of varying morphology (Fig. 1). The morphology of the filaments and their organic carbon isotopic

composition ($\delta^{13}\text{C}$ -22‰ to -26‰ vs. PDB, whole rock measurements), and the sedimentary environment interpreted as shallow marine, strongly suggested that they represent Earth's oldest microfossils, some of strong cyanobacterial affinity. The hypothesis of cyanobacterial life 3.5 billion years ago implied, for uniformitarianism, that oxygenic photosynthesis has acted very early



Apex Chert, Microfossils, Fig. 1 Apex Chert, Microfossils, Fig. 1 Microfossils from the early Archean Apex Chert of Australia (From Schopf 1993). Microfossils (A–J, holotypes) with interpretative drawings. All at a magnification

as shown in (A). (a–e) *Primaevifilum amoenum*; (f–j) *Primaevifilum conicoterminatum* (with conical terminal cells)

in the Earth's history and that life was already well advanced one billion years after the Earth's formation.

After Brasier et al.'s (2002, 2004) alarming claims of hydrothermal artefact origin of Schopf's microfossils, the turbulent debate on the Apex Chert and its putative microfossils greatly contributed to rising general interest in the origin and evolution of life. In the course of this debate our understanding of abiotic and biotic, evolutionary and taphonomic processes (by which organisms become fossilized) was vastly improved and new investigation methods and definitions of unambiguous biosignatures were developed. Schopf's microfossils are today largely regarded as genuine *bona fide* remains of Archean life, doubting reviews are, however, still valid (e.g., Javaux 2019; Lepot 2020). Nevertheless, Archean microbialites and stromatolites found in 3.7 Ga – 2.5 Ga rocks (Ueno et al. 2001; Kazmierczak and Altermann 2002; Allwood et al. 2006; Nutman et al. 2016; Homann et al. 2018) are abundant. Brasier et al. (2015) reported Archean microfossils from the 3.43 Ga Strelley Pool Chert (still disputing Schopf's 1993 findings). Up to date (2021), about a dozen of Archean, low metamorphosed stratigraphic formations are reported to contain microbialites, stromatolites, and microfossils of Archean age. Among such reports are findings from the Kaapvaal Craton and the Barberton Greenstone Belt (South Africa), from Pilbara Craton (Western Australia), Zimbabwe Craton and the Belingwe Greenstone Belt, Isua (Greenland), various occurrences in India (but mainly Singhbhum Craton), or from North America (e.g., Abitibi Greenstone Belt or the Slave Craton). Almost all of these reports are doubted one way or another and even the depositional environments are being controversially debated (e.g., Sugitani et al. 2009; Retallack et al. 2016; Sugitani et al. 2018, and many more).

Basic Methodology

The debate on the veracity of Schopf's microfossils provoked a radical change in the investigation

methods of putative fossils – initially based on optical and electron microscopic morphological assessment, and supported by whole rock $\delta^{13}\text{C}$ measurements. Micro- and nano-geochemical, mineralogical, and isotopic analytical methods were introduced. Laser Raman spectroscopy and H/C and N/C ratios measured on particulate kerogens isolated from bulk samples; atomic force microscopy (AFM), focused ion beam (FIB) techniques, and nano-SIMS analytical measurements were applied directly on filaments and coccoids as standard techniques, evidencing the organic or inorganic nature of the investigated materials (for further reading, comp. Schopf 2004; Schopf and Bottjer 2009). Optical microscopy on 30–60 μm thick petrographic rock sections in transmitted light is, however, still the basis of all such investigations for it allows to judge the fossil remnants in their embedding rock context.

Key Research Findings

Geology of the Schopf Locality

The Apex Chert is an informal unit within the 4 km-thick Apex Basalt Formation. It consists of greenschist facies metamorphosed basalts, komatiitic basalts; serpentized peridotites; tuffs and minor felsic volcanoclastic rocks; and locally developed chert dikes and stratiform cherts, intruded by dolerite sills and dikes at different levels. These rocks form part of the Marble Bar greenstone belt with several occurrences of cherts, stromatolites, and microfossil reports. The most important of such manifestations are the Dresser Formation chert (3490 Ma, stromatolites and microfossils), the Mc Phee Formation (ca. 3477 Ma) Awramik micro-fossiliferous locality (after Stanley Awramik et al. 1983), the Marble Bar Chert, and above the Apex Chert, the Strelley Pool Chert with stromatolites and microfossils, and finally the Wyman Formation stromatolitic chert (ca. 3315 Ma).

The “Schopf locality” (Schopf and Packer 1987; Schopf 1993), north of Marble Bar, with an assigned age of 3465 ± 5 Ma, displays white, gray- and black-layered chert, of up to 10 m thick,

interbedded with felsic tuff, which contains sills of massive black silica. The bedded deposits overlie a swarm of black silica veins radiating side-wards into sedimentary layers and extending up to 750 m down stratigraphy into meta-basalts, but not penetrating above the bedded chert horizon, cut by an unconformity. The veins migrate side-wards into sedimentary layers replacing them with silica.

Remapping and detailed petrology and mineralogy of the Apex Basalt Formation and the Apex Chert (Brasier et al. 2002; Van Kranendonk and Pirajno 2004) revealed that the Apex Chert is largely a breccia infilling of multiple generations of metalliferous hydrothermal veins which cross-cut pillow basalts and feed into, and are continuous with the overlying stratiform-bedded chert unit of the Apex Basalt Formation. The bedded chert of the Schopf microfossil locality is one of the stratigraphically lowest of five bedded chert units within the pillowed Apex Basalt, controversially within a black chert vein radiating from a bedded chert.

Microfossils at the Schopf Locality

The fossiliferous specimen deposited by Schopf at the Natural History Museum, London, show bedded structure and brownish color, implying that they come from a bedded part of the section. Microfossils were discovered in rounded grains of microcrystalline silica interpreted by Schopf (1993, 1999b) as conglomerate clasts deposited in a wave-washed beach or a stream mouth, an ideal environment for cyanobacteria. Fragments of stromatolites provide evidence that at least part of the clasts is of sedimentary origin. Schopf (1993) observed hundreds of bacterial filaments, up to few hundreds μm long and 20 μm wide, some resembling rather cyanobacteria through their size, septate division and terminal cell morphology (Fig. 1). Next to the filaments, hundreds of solitary unicell-like spheroidal structures resembling coccoidal microfossils were identified. Based on morphology, Schopf and Packer (1987) and Schopf (1993) recognized 11 morphotypes of putative microfossils in the Apex Chert, as listed below:

1. Narrow unbranched septate prokaryotic filaments *incertae sedis* cf. bacteria? (Archaeotrichion septatum)
2. Narrow unbranched septate prokaryotic filaments *incertae sedis* cf. bacteria? (Eoleptonema apex)
3. Narrow unbranched septate prokaryotic filaments *incertae sedis* cf. bacteria? or cyanobacteria? (Primaevifilum minutum)
4. Narrow unbranched septate prokaryotic filaments *incertae sedis* cf. bacteria? or cyanobacteria? (Primaevifilum delicatulum)
5. Intermediate-diameter unbranched septate prokaryotic filaments *incertae sedis* cf. cyanobacteria? (Primaevifilum amoenum)
6. Intermediate-diameter unbranched septate prokaryotic filaments having disk-shaped medial cells *incertae sedis* cf. cyanobacteria? (Archaeoscillatorioopsis disciformis)
7. Broad unbranched septate prokaryotic filaments having conical end cells *incertae sedis* cf. cyanobacteria? (Primaevifilum conicoterminatum)
8. Broad unbranched septate prokaryotic filaments having equant medial cells *incertae sedis* cf. cyanobacteria? (Primaevifilum laticellulosum)
9. Broad unbranched septate prokaryotic filaments *incertae sedis* cf. cyanobacteria? (Archaeoscillatorioopsis grandis)
10. Broad unbranched markedly tapering septate prokaryotic filaments *incertae sedis* cf. cyanobacteria? (Primaevifilum attenuatum)
11. Broad unbranched septate prokaryotic filaments having hemispheroidal end cells *incertae sedis* cf. cyanobacteria? (Archaeoscillatorioopsis maxima)

The Debate

The debate on Schopf's (1993) findings included claims that the filaments are branching, unlike prokaryotic filaments and do not contain carbon. The discussion climaxed in misconceptions of the "null hypothesis" that no prove of life older than ca. 2700 Ma can be yet accepted (Brasier et al.

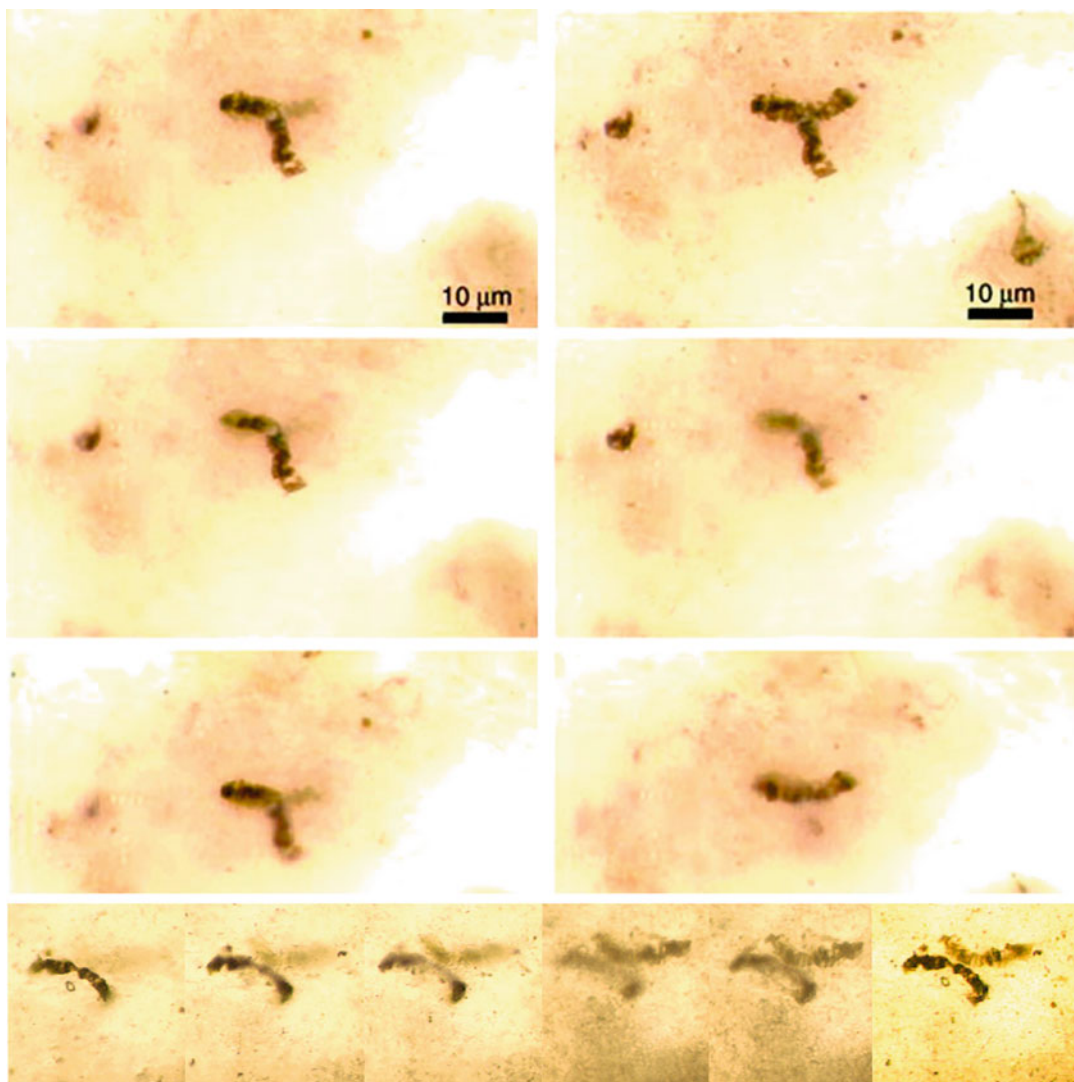
2004, 2006). It was suggested that the preserved morphological variation indicates biological behavior and fulfills the requirements for microfossil recognition (Buick 1990), although some lack of assessment of geological context of the Apex microfossil assemblage together with biological, diagenetic, and metamorphic degradation may cast doubts on the applied taxonomy (Altermann 2005). Thermal alteration may have caused taphonomic changes in cyanobacterial microfossils, resulting in the present form of microfossil preservation in the Apex Chert (Kazmierczak and Kremer 2002). Claims of branching of the filaments or of incomplete, selective photomontages of the microstructures, mimicking a biological appearance (Brasier et al. 2002, 2004) resulted from misinterpretation of auto-montages of photographs taken at different depths of focus and superimposed on each other (Altermann 2005 and Fig. 2). At reexamination by three-dimensional confocal laser scanning microscopy and Raman imagery, the Apex Chert was found to contain cellular-preserved kerogenous microfossil remains, revealing advanced biostratinomic (i.e., after an organism dies but before its final burial) to metamorphic, taphonomic changes (Schopf and Kudryavtsev 2009).

Scanning electron microscopy (SEM) showed the presence of metals (Ni, Cu, Zn, Sn), sulfides, barite, jarosite, alunite, phyllosilicates, and Fe oxides in the embedding cherts, suggesting a high-temperature hydrothermal environment where microbial life could hardly have survived (Brasier et al. 2002). But early microbes could have been chemo-autolithotroph thermophiles as controversially discussed (Brasier et al. 2006; Sugitani et al. 2007; Wacey et al. 2018) or simply extinguished and fossilized under hydrothermal conditions. An acid-sulfate epithermal environment of alteration, syn- or post-genetic with the precipitation of the chert, has been suggested by van Kranendonk and Pirajno (2004). The abundance of sulfate and lack of argillitic alteration indicate depositional temperatures up to 350 °C. Subsequently, Pinti et al. (2009) showed that medium-low temperature weathering processes could explain the mineralogy of the Apex Chert

so that high-temperature hydrothermal fluid-rock interactions are not required. Alternatively, the metal rich fluids might have passed at a much later time through these rocks.

Contradicting observations and interpretations invigorated the debate on the biogenicity of the carbonaceous filaments and their putative inclusion in the phylum cyanobacteria. Laser-Raman imagery of carbonaceous filaments (Schopf et al. 2002; Brasier et al. 2002) and of disseminated carbonaceous (kerogenous) matter in the Apex Chert gave controversial results. Schopf et al. (2002) interpreted the carbon as of biological origin. Brasier et al. (2002) proposed that it rather could be amorphous carbon reorganized in the form of filamentous strains after devitrification processes of the chert veins. De Gregorio and Sharp (2006) suggested that the carbonaceous material is similar in structure to microfossil kerogen, but may also be produced abiotically via Fischer-Tropsch-type (FTT) synthesis reactions, in an ancient hydrothermal vent. The results of 3-D laser scanning and Raman microscopy (Schopf and Kudryavtsev 2009) were questioned by Marshall et al. (2012) and Sforza et al. (2014) who investigated the Apex Chert material but not the original specimen described by Schopf (1993). In subsequent investigations, Wacey et al. (2016, 2019) have collected similar material from the same Apex Chert locality and used high spatial resolution electron microscopy to decode the morphology, chemistry, and taphonomy of the filamentous structures and concluded that they formed during fluid flow by hydration, heating, and exfoliation of potassic mica flakes within an active hydrothermal system.

The carbon isotopic composition of the rocks and microfossils is also controversial. The *in situ*, on single microfossil, measured $\delta^{13}\text{C}$ values from -27‰ to -34‰ versus PDB could be related to photosynthesis ($\delta^{13}\text{C} = -25\text{‰} - -10\text{‰}$; Schopf et al. 2002), methanogenesis (Brasier et al. 2002), or abiotic FTT reactions (e.g., McCollom and Seewald 2006). Buick (1984) suggested that carbonaceous filaments in the silica swarm dykes of the North Pole and Marble Bar, including Apex Chert, were contaminants introduced in the microfracturing of the silica veins during tectonic uplift

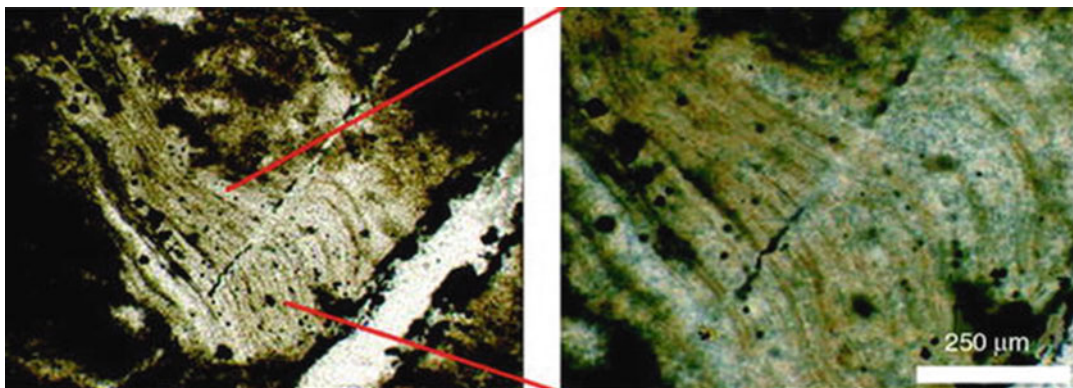


Apex Chert, Microfossils, Fig. 2 The same specimen of *Archaeosclerotriopsis disciformis* filament photographed from the original material deposited by Schopf at the Natural History Museum, London. Upper left, as depicted by Schopf (1993), and upper right, as shown by Brasier et al. (2002); the difference created the impression that Schopf (1993) has manipulated the microphotographs in reality showing a branching and therefore impossibly cyanobacterial filament. The following lower micrographs show the same filament at different depth of focus within the several tens of μm thick petrographic thin section (from left to right and downwards). It becomes clear that Schopf

(1993) has shown only one filament located closer to the surface of the section, while Brasier et al. (2002) have shown a sandwich photograph, including all depth of focus and exhibiting two filaments coincidentally superimposed one above the other within the thickness of the section. Lowermost series of six pictures show two neighbouring filaments of *Primaevifilum amoenum* located at different depth of focus. Viewed from a different angle in a sandwiched series of photographs taken at varying focus levels, they would appear as an “X”, or as branching, or crossing each other (Photograph by W. Altermann in M. Brasier’s lab, 2003)

of the region 2750 myr ago. Schopf et al. (2018) have used *in situ* – on microfossil, secondary ion mass spectroscopy (SIMS) to demonstrate that the

$\delta^{13}\text{C}$ measurements of the Apex taxa are consistent with extant phototrophic bacteria, with non-bacterial methane-producing Archaea and



Apex Chert, Microfossils, Fig. 3 Stromatolitic clast within the microfossiliferous samples deposited by Schopf at the Natural History Museum, London, exhibiting microbial lamination, pyrite grains, and dark organic matter. The

clast is cut by two parallel silica veinlets with pyrite enrichment (Photograph by W. Altermann in M. Brasier's lab, 2003)

with methane-metabolizing γ -proteobacteria, depending on the measured values and morphotypes. They concluded a cellular preservation and basal position (Archaea) in rRNA phylogenies of these microorganisms. On the other hand, Pinti et al. (2009) observed branched microstructures suggesting postdepositional colonization of microcracks and fissures by microbes. However, Schopf's kerogenous microfossils are embedded in sedimentary clasts deposited within the Apex Chert. Some clasts contain stromatolitic laminae and relict carbonate minerals and therefore must have been silicified during early diagenesis at their source of origin (Fig. 3). The hydrothermal chert distinctly differs from these clasts. However, in some places, hydrothermal recrystallization strongly affects the clasts and they become almost non-discernible from the hydrothermal chert matrix. The clasts must be older than the hydrothermal dikes (Altermann and Kazmierczak 2003; Altermann 2007). The Apex Chert has been affected by several hydrothermal and supergene episodes of alteration.

Whether the carbonaceous filaments of J. William Schopf are genuine ancient, fossilized prokaryotes (Schopf 1993; Kazmierczak and Kremer 2002; Altermann 2005), later biological contamination (Buick 1984; Pinti et al. 2009), or abiotic products (Brasier et al. 2002, 2004), this rock is still one of the most fascinating challenges

in Archean paleobiology and astrobiology. Each time Schopf reinforced his arguments for microfossils, introducing new data and new investigation techniques he was again challenged by his opponents (e.g., Schopf and Kudryavtsev 2012, 2013; Schopf et al. 2018; Pinti et al. 2013; De Gregorio and Sharp 2006; Sforza et al. 2014, Wacey et al. 2016, 2019; Lepot 2020). The critical point in views opposing the microfossil interpretation is that most of these investigations were not made on the original specimen described and deposited in the Natural History Museum, London, by Schopf (1993), but on rocks collected years later, in the same outcrops but not exactly the same location and on geochemical investigations not available in the 1980s–1990s. Nims et al. (2021) have shown that chemical artifacts mimicking microfossils are abundant in Archean cherts and have a much higher chance of preservation than genuine microfossils. This is not new and although unequivocally true, such findings do not contradict the overwhelming evidence for Archean life since ca. 3.7 Ga and Schopf's findings and interpretations. While new interpretations and debates are welcome in science, legitimate allegation of misinterpretation require investigations of the same samples, from exactly the same place and with exactly the same content. Whether they are right or wrong, they can add to the knowledge, asking and answering important questions.

Applications

Most of all the techniques available for determining the biogenicity and syngenicity of Archean traces of life have been tested on Apex Chert. Several among them were specifically developed to resolve the dilemma of Schopf's microfossils. This rock represents thus the best challenge for determining the reality of very ancient traces of life and developing successful methodologies and strategies of search for extraterrestrial life. With the development of new techniques and their automatic, remote-controlled extraterrestrial application, problems in understanding the contents of an ancient rock on nanometer scale (e.g., Kempe et al. 2005) will grow and fierce controversies on possible alien fossil remains (Schopf 1999a).

Future Directions

The uniqueness of Archean microfossils constrains the use of destructive methods for determining the environmental context of deposition of this chert unit and the reality of these microfossils. New nondestructive techniques such as NanoSIMS imagery of microfossils (e.g., Oehler et al. 2009; Schopf et al. 2018) or a combination of analytical techniques could be useful for determining whether the chemical structure of such putative microfossils is consistent with a biological origin (e.g., Derenne et al. 2008). Detailed investigation of the varying generations of cherts by, for example, fluid inclusion micro-geothermobarometry and decrepitation geochemistry of such fluid inclusions would certainly add tremendously to understanding of the history of the Apex Chert.

Cross-References

- ▶ Apex Basalt, Australia
- ▶ Apex Chert
- ▶ Archean Traces of Life
- ▶ Biogenicity
- ▶ Biomarkers
- ▶ Biomarkers, Morphological

- ▶ Cyanobacteria, Diversity and Evolution of
- ▶ Dubiofossil
- ▶ Earth, Formation, and Early Evolution
- ▶ Microfossils
- ▶ Microfossils, Analytical Techniques
- ▶ Pilbara Craton
- ▶ Pseudofossil
- ▶ Syngenicity

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Aphelion

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The aphelion is the point on a body’s orbit around the Sun (planets, comets, asteroids) where the body is farthest from the Sun.

Cross-References

- [Keplerian Orbits](#)
- [Orbit](#)
- [Periastron](#)

Apolar Molecule

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Nonpolar molecule](#)

Definition

In interstellar chemistry, apolar molecules are molecules lacking a permanent electric dipole moment. The lack of a dipole moment results from the symmetry of the charge density distribution in the molecule. Such molecules have no pure rotational transitions; hence, in the gas phase, they must be observed via their vibrational or electronic transitions.

Cross-References

► [Polar Molecule](#)

Apollo Asteroid

Alan W. Harris
DLR, Institute of Planetary Research, Berlin,
Germany

Definition

An Apollo ► [asteroid](#) is a near-Earth asteroid with a semimajor axis of more than 1 astronomical unit (AU) and a perihelion distance of less than 1.017 AU (the Earth’s aphelion distance). The ► [orbit](#) of such an ► [asteroid](#) may intersect that of the Earth, giving rise to an impact hazard. Apollo asteroids are named after the asteroid 1862 Apollo, which is the first to be discovered having these dynamical characteristics.

Cross-References

- [Asteroid](#)
- [Near-Earth Objects](#)
- [Orbit](#)

Apollo Mission

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Keywords

Biological effects of space · Exposure
experiments · Human space flight · Lunar
missions

Synonyms

[NASA lunar landing mission](#)

Definition

The Apollo missions were the heart of NASA's manned Lunar Landing Program that took place between 1969 and 1972 with 6 successful landings of 12 astronauts on the Moon.

History

On July 20, 1969, the astronauts N. A. Armstrong and E. E. Aldrin were the first humans to set foot on the Moon. Herewith, NASA had reached the ambitious goal of its manned Lunar Landing Program. It was made possible by the strong commitment of the United States to manned lunar exploration with President J. F. Kennedy's announcement in 1961 of sending an American safely to the Moon before the end of the decade and at same time the progress in the

technical capabilities of space transportation. The Apollo program ultimately placed 12 men on the lunar surface. In 1972, with Apollo 16 and 17, the era of human exploration beyond Earth's orbit was terminated and so far it has not been resumed.

Overview

The Apollo missions to the Moon were performed between 1968 and 1972 (Table 1).

The Apollo missions were the first and so far only human space missions beyond Earth's orbit. They provided in-depth knowledge of the geology of the Moon (Schaber 2005) and biomedical data on human health issues during space flight (Johnston et al. 1975). Biological responses to the parameters of outer space were studied in the following experiments:

- ► [Biostack](#) experiments on board of the Apollo 16 and 17 Command Module on the responses of a variety of biological systems in resting state to the heavy ion component of cosmic rays (Bücker and Horneck 1975)
- ALFMED experiment during the Apollo 16 and 17 mission that demonstrated that the light flash phenomenon observed by the crew members after dark adaptation was attributed to the passage of cosmic ray ions through the retina of the eye (Johnston et al. 1975; Benton et al. 1977).
- BIOCORE experiment during the Apollo 17 mission that studied brain effects in pocket mice caused by the passage of single heavy ions (► [HZE particles](#)) of cosmic radiation (Klein 1981)
- MEED during the Apollo 16 mission that studied the effects of space vacuum and solar UV radiation on different functions of microorganisms (Taylor 1974)

The radiobiological experiments performed during the Apollo missions are the only ones that studied the biological effects of the complete interplanetary radiation field, not attenuated by the Earth's magnetic field.

Apollo Mission, Table 1 Summary of human flights in the Apollo program to the Moon

Apollo mission	Mission description	Launch date day/month/year	Stay lunar surface (h)	Astronauts
7	Earth orbit test	11/9/68	–	Schirra, Cunningham, Eisele
8	Circumlunar flight	21/12/68	–	Borman, Lovell, Anders
9	Earth orbit test of LM	3/3/69	–	McDivitt, Scott, Schweickert
10	Circumlunar flight, LM separation	18/5/69	–	Stafford, Cernan, Young
11	Lunar landing, sample return	16/7/69	22.2	Armstrong, Collins, Aldrin
12	Lunar landing, surface experiment package	14/11/69	31.5	Conrad, Gordon, Bean
13	Lunar landing aborted	11/4/70	–	Lovell, Swigert, Haise
14	Lunar landing, highland exploration	31/1/71	33.5	Shepard, Roosa, Mitchell
15	Lunar landing and rover, geological sampling	26/7/71	67	Scott, Worden, Irwin
16	Lunar landing and rover, geological sampling, Biostack and MEED experiments	16/4/72	71	Young, Mattingly, Duke
17	Lunar landing and exploration of the Moon’s geology and history, Biostack experiments	7/12/72	75	Cernan, Evans, Schmitt

LM lunar module

Cross-References

- [Biostack](#)
- [Cosmic Rays in the Heliosphere](#)
- [HZE Particle](#)
- [MEED](#)
- [Microorganism](#)
- [Moon, The](#)
- [Radiation Biology](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Vacuum Effects](#)

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(99942) Apophis

- [Apophis Asteroid](#)

Apophis Asteroid

Gerhard Hahn

Asteroids and Comets, DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

(99942) Apophis

Definition

(99942) Apophis is an Aten-type asteroid, which will make a very close approach to our planet on April 13, 2029, passing within less than 40,000 km, close to the ring of geostationary satellites. Its size is about 375 m and its rotation period 30.6 h. This close approach will change the orbit substantially, from Aten type to Apollo.

History

Apophis was discovered on June 19, 2004 by R. A. Tucker, D. J. Tholen, and F. Bernardi at Kitt Peak. It was temporarily lost and rediscovered in December 2004. Shortly thereafter, the close approach in 2029 was realized; even a collision at that time was possible. This has been ruled out based on extensive observations, including radar; the orbital evolution after 2029 is still uncertain allowing an impact probability of 5.7×10^{-6} (see impact monitoring sites at JPL and the University of Pisa).

Cross-References

► [Near-Earth Objects](#)

References and Further Readings

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Apparent Motion

► [Proper Motion](#)

Apsidal Angle

Rory Barnes

Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planetary dynamics, the apsidal angle is the angle between the directions of closest approach (the apse) of two planets, as measured from the origin of the coordinate system (usually the center of the star). This angle may change with time and is coupled to the eccentricities of the orbits. The apsidal angle may oscillate about a fixed value (called apsidal libration) or circulate.

Cross-References

► [Secular Dynamics](#)
► [Secular Resonance](#)

Aptamer

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

Molecular evolution · In vitro evolution · RNA world · Combinatorial nucleic acid library · Ribozyme · Peptide

Definition

An aptamer (from the Latin *aptus*, fit, and Greek *meros*, unit or part) is an in vitro selected oligonucleotide or peptide molecule that binds to a specific target molecule. Nucleic acid aptamers are target-binding DNA or RNA molecules obtained by in vitro evolution. A peptide aptamer is an individual member of a library of random peptide sequences that can be selected for its ability to interact with a target molecule.

History

By the end of the 1980s, the possibility to chemically synthesize nucleic acid pools of random sequence, as well as the availability of all the required enzymes for nucleic acid amplification, allowed the selection of target-binding RNA molecules from combinatorial nucleic acid libraries. The term “aptamer” was coined to denote the in vitro evolved, target-binding RNA (Ellington and Szostak 1990), while the amplification-selection process was termed “systematic evolution of ligands by exponential enrichment” or SELEX (Tuerk and Gold 1990). The RNA aptamers selected in those two pioneering experiments were able to specifically bind different organic dyes and a viral enzyme – the bacteriophage T4 DNA polymerase – respectively. Three years later, the first RNA aptamer targeted to a small biomolecule was directed at ATP (Sassanfar and Szostak 1993).

Over the last two decades, a growing number of RNA and DNA aptamers have been developed against a variety of molecular targets, including simple ions; small molecules, such as amino acids, nucleotides, antibiotics, or metabolites; peptides; proteins; nucleic acids; macromolecular assemblies; viruses; organelles; or even whole cells (Klussmann 2006; Stoltenburg et al. 2007). In 2004, the first aptamer-based drug, called *Pegaptanib*, brand name *Macugen*, was approved by the US Food and Drug Administration in treatment for age-related macular degeneration (Gragoudas et al. 2004).

In parallel, peptide aptamers were obtained by high-throughput selection methods aimed at

identifying members of a randomized peptide library – usually attached at both ends to a given protein scaffold – by means of their interaction with a target molecule (Colas et al. 1996). Additionally, a method termed “mRNA display” allowed the in vitro selection of peptides and proteins with the desired target-binding properties (Roberts and Szostak 1997).

Overview

The preparation of a nucleic acid aptamer is currently easy and quick, since only 6–15 rounds of in vitro selection or evolution are typically required, using a combinatorial nucleic acid library as the starting material. Moreover, the sensitivity and specificity of the molecular recognition between a nucleic acid aptamer and its target rival those of the antibody-antigen pairs. Additionally, different ways to increase the resistance of aptamers to degradation by nuclease enzymes have been reported. These reasons, together with their cost-effectiveness, make nucleic acid aptamers not only relevant model systems to address the RNA world hypothesis (Joyce and Orgel 2006) but very useful tools in biotechnology with increasing applications in biosensing, diagnostics, and therapy (Klussmann 2006; Mayer 2009; Germer et al. 2013).

The outcome of an in vitro evolution process is usually monitored at the level of genotype, nucleotide sequence of the evolved aptamer, and phenotype, secondary/tertiary structure of the oligonucleotide, affinity and specificity of the aptamer for its target molecule. Although nucleic acid aptamers are artificial molecules, riboswitches have been considered “natural aptamers” embedded in messenger RNAs since they act as regulatory elements for gene expression by directly sensing small effector molecules (Zhang et al. 2010). Allosteric ribozymes that fuse one aptamer and one nucleic acid enzyme have been developed, the ribozyme activity being modulated by the binding of an effector molecule to the aptamer domain. The biotechnological applications of such “aptazymes” – also known as artificial riboswitches – are increasingly recognized (Wieland and Hartig 2008). Recently, the unveiled

ability of certain nucleic acid analogues to fold into three-dimensional structures allowed the in vitro evolution of aptamers harboring different molecular scaffolds, some of which bind their targets with an affinity similar to that of RNA or DNA aptamers (Pinheiro et al. 2012).

In addition to nucleic acid aptamers, the peptide aptamer approach has utilized small inert scaffold proteins to expose the randomizable peptide region. Alternatively, the mRNA display technique has been used to develop peptide aptamers, and “stand-alone” interfering peptides have also been selected. The ability of peptide aptamers to specifically interact with different proteins and other target molecules offers broad applicability in biochemistry and biomedicine (Mayer 2009; Li et al. 2011).

Cross-References

- [Amplification \(Genetics\)](#)
- [Aptasensor](#)
- [Combinatorial Nucleic Acid Library](#)
- [DNA](#)
- [Evolution, In Vitro](#)
- [Evolution, Molecular](#)
- [Peptide](#)
- [Ribozyme](#)
- [RNA](#)
- [RNA World](#)
- [Selection](#)

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Aptamer-Based Biosensor

- [Aptasensor](#)

Aptasensor

Miguel Moreno

Centro de Astrobiología, CSIC, Madrid, Spain

Keywords

Aptamer · Biosensor · DNA · RNA

Synonyms

[Aptamer-based biosensor](#)

Definition

An aptasensor is a particular class of biosensor where the biological recognition element is a DNA or RNA aptamer. In an aptasensor, the aptamer recognizes the molecular target against which it was previously *in vitro* selected. The aptamer-target reaction is independent of both the type of detection system and the kind of transducer employed. Aptasensors can be easily multiplexed to detect a variety of aptamer-target reactions simultaneously.

History

Since the development of the first glucose biosensor in 1962 (Clark and Lions 1962), an extensive choice of biosensors has been developed. Among them, nucleic acid-based biosensors are of particular interest due to their practical applications in different fields of genomic research. In 1990 two independent groups simultaneously described aptamers as target-binding nucleic acid molecules (Tuerk and Gold 1990; Ellington and Szostak 1990). Adapting both technologies, aptamer-based biosensors were established in 1996 when Drolet and coworkers (Drolet et al. 1996) described a modification of the renowned enzyme-linked immunosorbent assay (ELISA) which utilized an aptamer instead an antibody as biorecognition element. The assay was named “enzyme-linked oligonucleotide assay” (ELONA), and this evidence opened the door to novel ways of biosensing using nucleic acids to detect a wide range of molecules in a variety of formats.

Overview

Aptamers are attracting interest in the areas of therapeutics and diagnostics and offer themselves as ideal candidates for use as the recognition elements in biosensors since they possess many advantages over the state-of-the-art affinity sensors. Aptasensors show very high sensitivity, specificity, and reproducibility against a wide

variety of targets. Thus, they are rapidly emerging as promising candidates for high-throughput analytical methods that have to deal with tiny quantities of the queried analytes. Analogous to immunoassays (those based on the antigen-antibody interaction), aptamer-based bioassays can adopt different configurations to transduce biorecognition events, including aptamer-based microarrays (Collett et al. 2005), aptamer-capped gold nanoparticles (Song et al. 2012), quantum-dot aptamer conjugates (Levy et al. 2005), and electrical (Willner and Zayats 2007) and electrochemical (Moreno et al. 2011) aptasensors, among many others (Citartan et al. 2012).

Aptamers offer an extensive range of advantages over other existing biological recognition elements in terms of stability, design flexibility, and cost-effectiveness. To name a few, aptamers can bind to their targets with affinities and specificities equivalent to those of monoclonal antibodies and can be selected to bind a wide range of targets including those that are toxic or not inherently immunogenic. Additionally, the affinities and specificities of aptamers can be easily tailored (in contrast to those of antibodies) and can be more readily engineered than antibodies for their use as biosensing elements. Finally, aptamers can be synthesized, chemically modified, and stored until needed and are resistant to denaturation and degradation. The in-depth knowledge of aptamer conformational properties and ligand-binding mechanisms has triggered profound attention among researchers for developing aptasensor bioassays, as reflected in the exponential increase of published articles (Citartan et al. 2012).

Nevertheless, aptasensors compete with other well-established biosensors, essentially antibodies-based ones, and they have been mainly focused on the applications where antibodies cannot achieve the desired goals. The most straightforward application of aptasensors lies in the fields of food safety testing and environmental pollution control. Thus, aptasensors developed for the detection of small molecule contaminants including antibiotics, toxins, pesticides, and heavy metals (that may be present in a wide variety of food products and environmental samples)

are of particular interest (Cho et al. 2009; Fischer et al. 2007).

In astrobiology, aptasensors are called to be a functional tool for the detection of both molecules with limited antigenicity present in different extreme environments and biosignatures of extinct or extant life in planetary exploration. In the field of biomarker detection in space missions, robust and very stable aptasensors might be developed with extended capabilities to overcome the extreme conditions of long travel time and planetary exploration.

Cross-References

- [Antibody](#)
- [Aptamer](#)
- [Biomarkers](#)
- [Biosensor](#)
- [Combinatorial Nucleic Acid Library](#)
- [Evolution, In Vitro](#)

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Aqueous Alteration

Yoko Kebukawa¹ and Michael E. Zolensky²

¹Faculty of Engineering, Yokohama National University, Yokohama, Japan

²ARES, NASA Johnson Space Center, Houston, TX, USA

Keywords

Meteorites · Asteroids · Water · Minerals · Organic matter

Definition

A secondary process whereby liquid water modified the nature of anhydrous primary nebular components. In general, this process induced decomposition and changed the structures and compositions of primary minerals and formed secondary minerals in their place. This process occurred in the early history of meteorite parent bodies that contained water ice. The most effective heat source is considered to be the decay of short-lived radioactive nuclide such as aluminum 26, but other causes have been suggested. The degree of aqueous alteration of meteorites is categorized as type 1 (most altered) to type 3 (least altered), according to mineralogy and petrology.

Overview

Some meteorites provide evidence that liquid water was widespread and very active during the early history of some meteorite parent bodies—asteroids and comets. Characteristic secondary minerals are hydrous minerals such as

serpentines, smectites, micas, and tochilinite, as well as sulfides, oxides, phosphates, and carbonates (e.g., Brearley 2006). Hydrous phases are observed spectroscopically on C-complex asteroids (C-, G-, F-, and B-type asteroids) that are plausibly to the source of some carbonaceous chondrites (e.g., Vilas and Gaffey 1989). The degree of aqueous alteration is classified into petrologic types 1–3, based on the abundances of chondrule glass and metal, sulfide compositions, matrix mineralogy and quantity, carbon and water content, and stable isotopic compositions (Van Schmus and Wood 1967). Type 1 is most aqueously altered and type 3 is least altered. CI, CM, and CR carbonaceous chondrites are extensively aqueously altered. CI group contains type 1, the CM group contains type 1 and 2, and the CR group contains type 1–3. CM chondrites have been further assigned to subtype, least altered CM2.6 to most altered CM2.0 (=CM1) (Rubin et al. 2007). There are no type 1 and 2 meteorites in other groups of carbonaceous chondrites (e.g., CV and CO) and ordinary chondrites; however, some samples of all of these latter groups show some degree of aqueous alteration (e.g., Grossman et al. 2000). In many cases, the effects of aqueous alteration have been obscured by subsequent thermal metamorphism (Tonui et al. 2014).

The most widely accepted location of aqueous alteration is meteorite parent bodies. There are also possibilities for limited alteration with water ice or vapor in the nebula (e.g., Ciesla et al. 2003). After accretion of planetesimals, water ice melted due to either heating by decay of short-lived radioactive nuclides, impacts, or solar heating, triggering aqueous alteration. Isotopic chronologies based on Mn-Cr isotope measurements of carbonates revealed that aqueous alteration occurred as long as $4563.4 \pm 0.4/-0.5$ Myr ago (~ 4.8 Myr after calcium-aluminum-rich inclusion (CAI) formation) for CM chondrites (Fujiya et al. 2012). However, these dates are now being reassessed.

Aqueous alteration models have been constructed based on mineralogic assemblages, stable isotopes, and thermal evolution (e.g., Clayton and Mayeda 1999; Grimm and Mccsween 1989; Zolensky et al. 1989). Depending on the

heating mechanism, thermal evolution largely depends on the canonical values of ^{26}Al , porosity, water/rock ratio and size of body, and orbital histories. Conditions of aqueous alteration varied for the different meteorite groups. Temperatures have been estimated approximately as 20–150 °C for CI, 0–80 °C for CM2, and 50–150 °C for CR (Brearley 2006 and references therein). Estimation of water/rock ratios are 1.1–1.2 with $\text{pH} = 7\text{--}10$ and $f\text{O}_2 > 10^{-55}\text{--}10^{-70}$ for CI, and water/rock ratios are 0.3–0.6 with $\text{pH} = 7\text{--}12$ and $f\text{O}_2 < 10^{-85}$ for CM2 (Zolensky et al. 1993; Zolensky et al. 1989). Again, these estimates depend on model assumptions.

During the aqueous alteration, formation and evolution of organic matter would be expected. For example, during early stages of aqueous alteration, macromolecular organic matter and amino acids can be produced from simple molecules such as formaldehyde and ammonia (e.g., Cody et al. 2011; Kebukawa et al. 2017). Further alteration modifies the compositions of organic matter, e.g., decreases H, N, O contents and aliphatics and oxygen-bearing functional groups (e.g., Alexander et al. 2007, 2014). Among amino acids, ω -amino acids dominate in heavily altered chondrites in contrast to α -amino acids which dominate in the less-altered ones, probably due to lower stabilities of α -amino acids and/or formation of ω -amino acids by Fischer-Tropsch-type (FTT) reaction (e.g., Elsila et al. 2016). Larger L-isovaline enrichments in the aqueously altered compared to less-altered meteorites suggest that aqueous alteration promoted L-isovaline excesses on meteorite parent bodies (Glavin and Dworkin 2009).

Aqueous alteration provided abundant water in the form of hydrated minerals (e.g., Alexander et al. 2012), as well as a diverse suite of organic compounds formed in parent bodies in addition to pre-accretional organic matter (e.g., Schmitt-Kopplin et al. 2010) to the early Earth.

Cross-References

- Asteroid
- CAIs

- Carbonaceous Chondrite
- Comet
- Fischer-Tropsch-Type Reaction
- Meteorites
- Parent Body

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Aqueous Interfaces

Veronica Vaida and Elizabeth C. Griffith
University of Colorado, Boulder, CO, USA

Keywords

Water surface · Unique reaction environment ·
Amphiphilic molecules · Surfactant film

Definition

An aqueous interface is the dividing surface between two media, one of which is water.

History

Atmospheric interfaces including rocks and clays have long been considered in the origin of life scenarios. Aqueous interfaces (water surfaces) as found on oceans, lakes, rivers, and atmospheric aerosols were first suggested by Goldacre (1958) to be interesting in a prebiotic context due to their ability to concentrate organic molecules and subsequently fold and pinch off into enclosures reminiscent of cells. The use of Global atmospheric aerosols were pointed out in this context (Shah 1972) and suggested as effective prebiotic micro-reactors in different contexts later (Lerman 2010; Dobson et al. 2000; Tverdislov and Yakovenko 2008). In addition, aqueous interfaces have recently been suggested as favorable environments for biomolecular synthesis that is difficult or impossible in the bulk ocean (Dobson et al. 2000; Ruiz-Bermejo et al. 2010; Griffith et al. 2012).

Overview

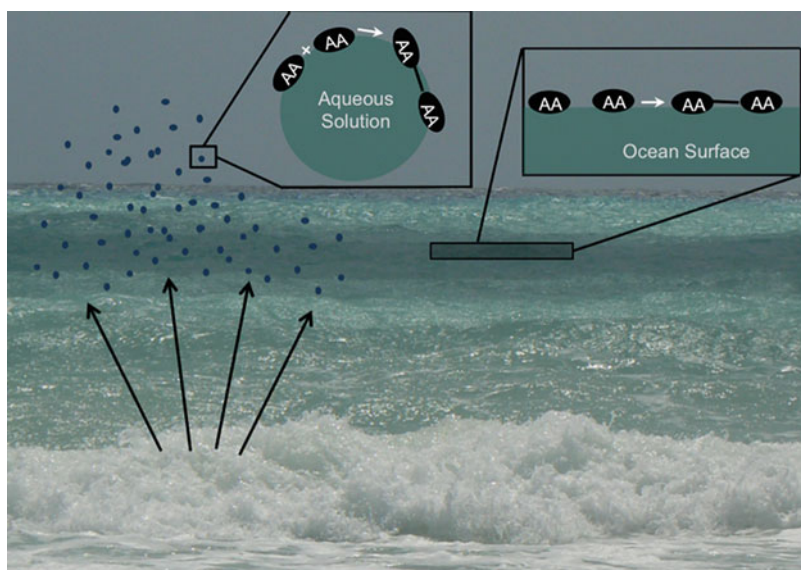
Aqueous interfaces are found throughout nature: at the surface of lakes and oceans, at the surface of atmospheric aerosol particles, or even at the interface between a membrane and its surrounding

bulk water environment. Air-aqueous interfaces are particularly interesting in an astrobiological context due to their provision of a unique reaction environment, having the ability to concentrate and align surface active molecules (Goldacre 1958; Shah 1972). It was pointed out that the vast collective surface area of atmospheric aerosols provides diverse and fluctuating environments for chemistry and is applicable to any rotating planetary body with a liquid ocean (Dobson et al. 2000; Griffith et al. 2012). A planet rotating on a tilted axis results in thermal and pressure gradients that produce wind. This wind acting on a liquid ocean produces sea spray from which aqueous atmospheric aerosols are born (as depicted in the Fig. 1). Any organic material residing at or near the ocean surface will be entrained in these aerosols and can partition to their surface (an aqueous interface), forming a surfactant film around an aqueous core.

These interfaces allow for concentration of reactant species over the bulk aqueous solution, alteration of the ionization state of surface-residing reactants, and orientation of amphiphilic molecules, and they can even promote chemistry that is inaccessible in bulk water (Griffith and Vaida 2013). One example of a key reaction made possible by an aqueous interface is the formation of peptide bonds in the absence of

Aqueous Interfaces,

Fig. 1 Depiction of birth of aerosols from sea spray as well as schematic representation of peptide bond formation at the air-aqueous interface from amino acid (AA) precursors



enzymatic catalysis (Griffith and Vaida 2012) illustrated schematically in Fig. 1. Peptide bonds are a key bond in modern biology as they are the link between amino acid building blocks in proteins (one of the three principle biopolymers along with RNA and DNA). In addition, theoretical and experimental studies have been devised to investigate the interaction and folding of bimolecular assemblies at the surface of liquid water to model systems of biophysical interest (Pratt and Pohorille 2002).

Cross-References

- [Aerosols](#)
- [Amino Acid](#)
- [Amphiphile](#)
- [Membrane](#)
- [Water, Solvent of Life](#)

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Aqueous Minerals

- [Mars, Hydrated Minerals](#)

Aquifer (Mars)

Alessandro Airo
Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Definition

It is widely accepted that liquid water was present on the surface of Mars during its early history. Although parts of this water have vanished into space or were consumed in chemical reactions, substantial amounts are still present today. The current physical conditions on Mars' surface usually do not allow liquid water to be stable, and therefore, it occurs as water ice within the pore space of the permafrost soil or as few km-thick polar ice caps. It can be assumed that at a certain depth below the surface, usually estimated to be a few kilometers, the cryosphere transitions into an aquifer (Lasue et al. 2013). The depth at which the water ice turns into groundwater depends on not well known factors, such as the water salinity, the soil porosity and permeability, or the geothermal gradient and thermal conductivity of the subsurface. The presence of groundwater on Mars is

insofar of interest to astrobiologists as aquifers on Earth are populated by microbial life down to a depth of a few kilometers (Michalski et al. 2013).

Cross-References

- [Crater Lakes \(Mars\)](#)
- [Gullies](#)
- [Habitability on Mars](#)
- [Heat Transfer, Planetary](#)
- [Outflow Channels](#)
- [Polar Caps \(Mars\)](#)

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Arachnoid

Jörn Helbert
DLR, Institut für Planetenforschung, Berlin,
Germany

Definition

An Arachnoid is a type of landform only seen on the surface of ► [Venus](#), which is believed to have a volcanic origin. Arachnoids get their name from their resemblance to spider webs. They appear as concentric ovals surrounded by a complex network of fractures, and are spanned up to 200 km. Over 30 arachnoids have been identified on Venus, so far.

Cross-References

- [Venus](#)

Archaea

Antonio Ventosa and Rafael R. de la Haba
Department of Microbiology and Parasitology,
Faculty of Pharmacy, University of Sevilla,
Sevilla, Spain

Keywords

Domain · Evolution · Extremophiles ·
Molecular adaptation · Phylogeny · 16S rRNA
sequencing

Synonyms

[Archaeobacteria](#)

Definition

The *Archaea* are a phylogenetically coherent group of prokaryotes that have a different organization than the *Bacteria*.

History

Woese and Fox (1977) proposed that prokaryotes were not a monophyletic group. Based on the comparison of their small subunit ribosomal RNA sequences, the prokaryotes comprise two distinct evolutionary lineages that are represented by the *Bacteria* and the *Archaea* (that formerly were designated as Archaeobacteria by Woese et al. 1978). The concept of a third domain of life, which explained several structural, metabolic, and molecular differences with respect to other prokaryotes, was initially poorly accepted by the scientific community. However, the concept of the *Archaea* was advanced through studies and meetings carried out by O. Kandler, W. Zillig, and K.O. Stetter, among others. The *Archaea* have similarities and are considered phylogenetically more closely related to the *Eukarya* (Woese et al. 1990).

Overview

Archaea have distinct molecular characteristics that clearly distinguish them from the *Bacteria* and the *Eukarya*, and evolutionary studies have highlighted their role in the development of life on our planet. *Archaea* have been associated with extreme environments and many of them are extremophilic microorganisms, showing interesting characteristics and applications for industrial and other purposes. Many of them are considered to be microorganisms that are able to grow on the limits of life. Their ability to thrive in extreme environments has expanded the horizons for Astrobiology as they are considered counterparts for extraterrestrial life.

The *Archaea* are characterized by a cellular morphology similar to those of most *Bacteria* (rods, cocci, irregular cells, etc.). However, myceliar or multicellular stages with cellular differentiation have not been described. On the contrary, unique morphologies have been described for some *Archaea*, such as the square flat cells of some haloarchaea (*Haloquadratum walsbyi*) or amoeba-like cells (*Thermoplasma* and other microorganisms). Other characteristics of the *Archaea* that define their differential status with respect to the other living organisms are: (1) the presence of phytanyl ether instead of fatty acid ester lipids in their membranes; (2) the absence of peptidoglycan (murein) in their cell walls and a frequent presence of proteinaceous S-layers (only a few have a polysaccharide cell wall), as well as the absence of a periplasmic space; (3) their complex DNA-dependent RNA polymerases (early in vitro studies using several inhibitors showed that the transcription machinery in *Archaea* is more closely related to that of *Eukarya* than to *Bacteria*); the sequences of the archaeal RNA polymerases resemble some eukaryotic RNA polymerases and consist of up to 13 different units; and (4) although the translation machinery of *Archaea* is similar to that of bacteria (70S ribosomes with 50S and 30S subunits, similar length ribosomal RNAs, transcriptional and translational coupling, etc.), there are an important number of specific features not present in

Bacteria, some of which are specific to *Archaea*, while others are similar to *Eukarya*. For example, almost all antibiotics that inhibit bacterial translation are ineffective in the *Archaea*; *Bacteria* use *N*-formyl-methionyl-tRNA for translational start codons, while *Archaea* use unmodified initiator methionine in translation, similar to *Eukarya*. Besides, *Archaea* and *Eukarya* share a common characteristic, elongation factor 2 (EF-2), which is ADP-ribosylated by diphtherial toxin.

The *Archaea* are subdivided into five phyla, of which two, the *Crenarchaeota* and the *Euryarchaeota*, are most extensively studied. The classification of *Archaea* has been widely discussed and several proposals have been published. The most widely accepted include the *Archaea* as a higher taxon with the range of *Domain*, which includes the following five phyla: *Crenarchaeota*, *Euryarchaeota*, *Nanoarchaeota*, *Nanohaloarchaeota*, and *Thaumarchaeota* (Parte et al. 2020). The phylum *Crenarchaeota* includes a single class, *Thermoprotei*, with five orders: *Acidilobales*, *Desulfurococcales*, *Fervidococcales*, *Sulfolobales*, and *Thermoproteales*. The phylum *Euryarchaeota* includes nine classes: *Archaeoglobi*, *Halobacteria*, *Methanobacteria*, *Methanococci*, *Methanomicrobia*, *Methanonatronarchaeia*, *Methanopyri*, *Thermococci*, and *Thermoplasmata*. The phylum *Nanoarchaeota* includes a sole genus, *Nanoarchaeum*. Finally, the phylum *Thaumarchaeota* includes the class *Nitrososphaeria*, with two orders: *Nitrosopumilales* and *Nitrososphaerales*. Other phyla including noncultivated *Archaea* have been recently described: *Candidatus* Aigarchaeota, *Candidatus* Diapherotrites, *Candidatus* Hadarchaeota, *Candidatus* Huberarchaeota, *Candidatus* Hydrothermarchaeota, *Candidatus* Korarchaeota, *Candidatus* Lokiarchaeota, *Candidatus* Parvarchaeota, *Candidatus* Thermoplasmata, *Candidatus* Undinarchaeota, and *Candidatus* Verstraetearchaeota.

The phylum *Euryarchaeota* includes two of the most typical groups that were identified in the early studies by Woese and coworkers as members of the *Archaea*: the methanogens and the haloarchaea (also designated as halobacteria).

The methanogenic *Archaea* are anaerobic organisms that produce methane as the major end product of their metabolism. Phylogenetically, methanogens are very diverse and are represented by a large number of species belonging to many genera, grouped into 16 families within eight orders. They are found in a variety of anoxic environments such as ocean and lake sediments, hydrothermal vents, animal digestive tracts, and anaerobic sludge digesters. The typical growth compounds of methanogens are H_2 and CO_2 , or short-chain (C_1 - C_5) organic compounds (formate, acetate, ethanol, trimethylamine, etc.). H_2 is used as electron donor for CO_2 reduction, and electrons can also be derived from formate, CO, or specific alcohols. Among the microorganisms that have been used as models for studying methanogenesis are species of the genera *Methanobacterium*, *Methanothermobacter*, *Methanobrevibacter*, *Methanosarcina*, and *Methanococcus*, among others (Rosenberg 2014; Madigan et al. 2020).

Haloarchaea are represented by a group of extremely halophilic aerobic or anaerobic *Archaea* (Sorokin et al. 2016), which taxonomically are placed within a single class, *Halobacteria* (Oren et al. 2017), which comprises three orders and six families. Currently they are represented by over 70 genera and a large number of species that are characterized by their Na^+ requirements. They are considered to be organisms that are able to grow under higher salt concentrations, in saturated NaCl habitats. Their optimal NaCl requirements are in the range 3.5–4.5 M NaCl and they are not able to grow in media without NaCl. Thus, they have a specific requirement for NaCl, which has led to detailed studies of their mechanisms of haloadaptation. In contrast to most other prokaryotes, which accumulate intracellular organic compounds designated as compatible solutes, haloarchaea compensate for the high salt concentration in the environment by accumulating ions, mainly up to 5 M KCl. They are normal inhabitants of hypersaline environments, being the predominant microbiota of saturated ponds of salterns and salt lakes (they may reach high cell densities, $>10^7$ cell ml^{-1}); they are also found in salt or salted

products (salted fish or meats, salted fermented foods), salt deposits (mines), salted hides, and saline soils. Most haloarchaea grow at neutral pH values but some species are haloalkaliphilic, being able to grow optimally at alkaline pH and inhabiting soda lakes. Other typical features of haloarchaea are: their production of red- to pink-pigmented colonies due to the presence of bacterioruberins (C_{50} carotenoids), although there are a few exceptions; the presence, in some of them, of retinal-based pigments (bacteriorhodopsin) that act as a proton pump driven by light energy; or the presence of typical archaeal polar lipids, with ether-linked phosphoglycerides that can be easily detected by thin-layer chromatography (a feature that is widely used for the taxonomic differentiation of most genera of haloarchaea) (Oren et al. 2017). Haloarchaea are excellent models for the study of the molecular biology and other structural features of *Archaea*, as well as their mechanisms of adaptation to extreme conditions of salinity, alkaline pH, and moderate temperature, and several species have been used for such purposes due to their ease of manipulation under laboratory conditions: they grow in complex media (with the appropriate salt content) under aerobic conditions using the standard procedures utilized for most non-fastidious prokaryotes. Some species used for such studies include *Halobacterium salinarum*, *Haloarcula marismortui*, *Haloferax volcanii*, and, more recently, the square haloarchaeon *Haloquadratum walsbyi* (isolated and referred to as “Walsby’s square bacterium”). In addition, several biotechnological applications have been suggested, such as the commercial production of bacteriorhodopsin, the production of extracellular hydrolytic enzymes or exopolysaccharides, the use of polyhydroxyalkanoates (PHAs) as bioplastics, or the production of halocins (archaeocins, proteinaceous archaeal antimicrobials).

With a few bacterial exceptions, most hyperthermophiles (defined as organisms showing optimal growth at 80 °C or higher) are species of *Archaea*. They are inhabitants of hot springs, solfataric and volcanic areas, deep-subsurface aquifers, submarine vents (“black smokers”),

etc. Hyperthermophiles include several methanogens, as well as members of a variety of genera of the *Archaeoglobales*, *Thermococcales*, *Acidilobales*, *Desulfurococcales*, *Sulfolabales*, and *Thermoproteales*. They are excellent models for the study of the metabolisms of sulfur and inorganic sulfur compounds; many species use inorganic sulfur compounds as electron acceptors or donors. Some of the most hyperthermophilic organisms known are *Pyrolobus fumarii* (optimal growth at 106 °C, range 90–113 °C), *Pyrodicticum occultum* (optimal growth at 105 °C, range 85–110 °C), *Pyrococcus furiosus* and *Pyrococcus woesei* (optimal growth at 100–103 °C, range 70–105 °C), *Pyrobaculum aerophilum* (optimal growth at 100 °C, range 75–104 °C), and *Pyrobaculum islandicum* (optimal growth at 100 °C, range 74–102 °C).

The phylum *Nanoarchaeota* is known for a single species, *Nanoarchaeum equitans*, to date a hyperthermophilic archaeon that lives in a symbiotic association with the Crenarchaeote *Ignicoccus*, a sulfur-dependent anaerobic hyperthermophile. The cells are spherical and only about 400 nm in diameter; they grow attached to the surface of a specific archaeal host (Hubber et al. 2002). This archaeon was isolated from a submarine hot vent, but recent studies have shown that nanoarchaea may be widely dispersed in hyperthermophilic and mesophilic halophilic environments (Casanueva et al. 2008; Rinke et al. 2013). Cultivated *Archaea* belonging to the phylum *Nanoarchaeota* are also known to associate with other haloarchaea, thereby compensating for their own auxotrophies. These diminutive but ubiquitous microorganisms thrive in hypersaline habitats that they share with haloarchaea (Hamm et al. 2019; La Cono et al. 2020).

Basic Methodology

The study of the *Archaea* can be accomplished using the classical culture-dependent methods and the more recently developed culture-independent sequencing techniques which have provided access to unknown genomic data from until now inaccessible archaeal lineages.

Key Research Findings

The *Archaea* play a key position in the Tree of Life and constitute an important fraction of the microbial diversity with a wide metabolic potential.

Future Directions

Discovery of novel major archaeal taxa is still challenging. The origin of this domain and its relationships with *Bacteria* and *Eukarya*, as well as its role in the environmental ecology and in human health and disease, is not yet clear.

Cross-References

- [Bacteria](#)
- [Compatible Solute](#)
- [Crenarchaeota](#)
- [Domain \(Taxonomy\)](#)
- [Eukarya](#)
- [Euryarchaeota](#)
- [Extreme Environment](#)
- [Halophile](#)
- [Hyperthermophile](#)
- [Korarchaeota](#)
- [Membrane](#)
- [Methanogens](#)
- [Nanoarchaeota](#)
- [Phylogenetic Tree](#)
- [Prokaryote](#)

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Archaeon Biosignatures

► Archaeon Traces of Life

Archaeon Traces of Life

Nicola McLoughlin

Department for Geology, Rhodes University,
Makhanda (Grahamstown), South Africa

Keywords

Earliest evidence of life on earth · Emergence of life · Oldest fossils

Synonyms

Archaeon biosignatures

Definition

The Archaeon is the period of geological time between 3.8 and 2.5 billion years ago when life is thought to have emerged on Earth. Traces of Archaeon life are preserved in rare, fragmentary, and often highly altered rock sequences. Morphological evidence for Archaeon life is provided by

microfossils, stromatolites, and microbially induced sedimentary structures. Chemical evidence for life is recorded by stable isotope ratios of carbon and sulfur in particular. These various biosignatures provide insights into the nature of early Archaean ecosystems and much remains to be learned about the predominant microbial metabolisms at this time and their distribution. Recognizing and distinguishing abiotic mimics from bona fide microbial also remains an important challenge. The effort to refine our understanding of microbial biosignatures in the Archaean rock record is essential to designing strategies for seeking life elsewhere in our universe and for ratifying this evidence.

Overview

This review first explains *where* to look for Archaean traces of life, *what* evidence Astrobiologists seek, and *how* these rocks are investigated. Then, a review of current research findings is given focusing on selected case studies of microfossils, stromatolites, and endolithic microborings.

Basic Methodology

Locating Well-Preserved Archaean Rocks from Habitable Environments

The search for Archaean traces of life relies upon geological mapping and radiometric dating to locate rocks of the Archaean age. Worldwide, there are two cratons that preserve intact sequences of the Early Archaean age where now metamorphosed volcanic and sedimentary rocks are preserved in greenstone belts – so-called because of the green color conferred by their typical metamorphic minerals. The first of these is the Pilbara of Western Australia and the second is the Kapvaal Craton of South Africa and Swaziland, a region known as the Barberton Mountainland. In recent years, there have been several scientific drilling projects that have targeted these Archaean sequences to seek the earliest evidence for life. Scientific drilling yields continuous sequences of rock unaffected by alteration at the

earth's surface allowing more complete investigation of well-preserved biosignatures within their geological context. Older Archaean rocks of between 3.8 and 3.7 Ga from Greenland and Labrador are of much higher metamorphic grade and more intensely deformed. Thus, any potential traces of life in these rocks have been heavily modified and/or completely destroyed.

The search for Archaean morphological traces of life has traditionally centered on meta-sedimentary rocks, in particular cherts and carbonates (Javaux 2019). Geological environments where microbial remains are most likely to be preserved are those where rapid, contemporaneous mineralization entombs and permineralizes living organisms. Precipitation of microcrystalline silica is a good example and can preserve cellular remains with exceptionally high fidelity. Cherts are formed in the vicinity of hydrothermal vents and hot springs, and as chemical sediments on the Archaean seafloor. Likewise, chemical traces of life are normally sorted in meta-sedimentary rocks formed at or near the Earth's surface. Metasediments that have experienced greater than greenschist facies-grade metamorphism have proven controversial when interpreting putative biosignatures.

An important criterion for establishing the biogenicity of a candidate, Archaean traces of life is the demonstration that the geological environment was viable for life. This translates to the assessment of habitability or, in other words, mapping out the environmental limits to life. There are a number of first-order differences between the Archaean world and the recent earth that should be borne in mind. Firstly, Archaean surface environments were largely anoxic, the atmosphere was probably rich in carbon dioxide and methane and there was no ozone layer. Secondly, seawater was supersaturated with silica, its pH, temperature, and salinity are widely debated and certainly differed from today, with the ocean likely being warmer. Thirdly, exactly when Archaean plate tectonics began and the nature of early tectonic processes is unclear with profound implications for the cycling of nutrients on the earth and the oxidation of key geological reservoirs.

Demonstrating Syngenetic and Endogenicity

All candidate traces of life must be shown to be truly ancient and **syngenetic**, that is, contemporaneous to the host rock. It is not possible to date organic remains and fossils directly, but it is often possible to use radiometric techniques to date the host rocks. These methods are described elsewhere in this encyclopedia, and the radiometric system chosen will depend on the minerals available, the fluid and metamorphic history of the rock, also the anticipated age and precision required.

Microbial remains and carbonaceous matter found within rocks can be **endogenetic** and formed at the same time as the host rock, or they can be derived from external fluids that entered the rock at a later stage via circulating fluids, or younger microbes that entered through fractures/pore space. The latter type of material is unreliable biosignatures. Careful thin-section observations are required to establish the context of the candidate biosignature and to establish that they are hosted by primary mineral phases and are therefore endogenetic, and hopefully cross-cut by any later-stage mineral veins or fractures. Early biological remains may also show evidence of compaction, for example, large spherical organic microfossils can be flattened to ellipses during compaction, although if the rocks have experienced early silicification, this criterion will not hold. Raman spectroscopy can also be useful in this regard, to compare the metamorphic history of organic remains to material in the surrounding rock. For, carbonaceous remains to be syngenetic their thermal maturity as measured by Raman geothermometry should match that of the host rock.

Textural Evidence of Life: Testing Abiotic Scenarios

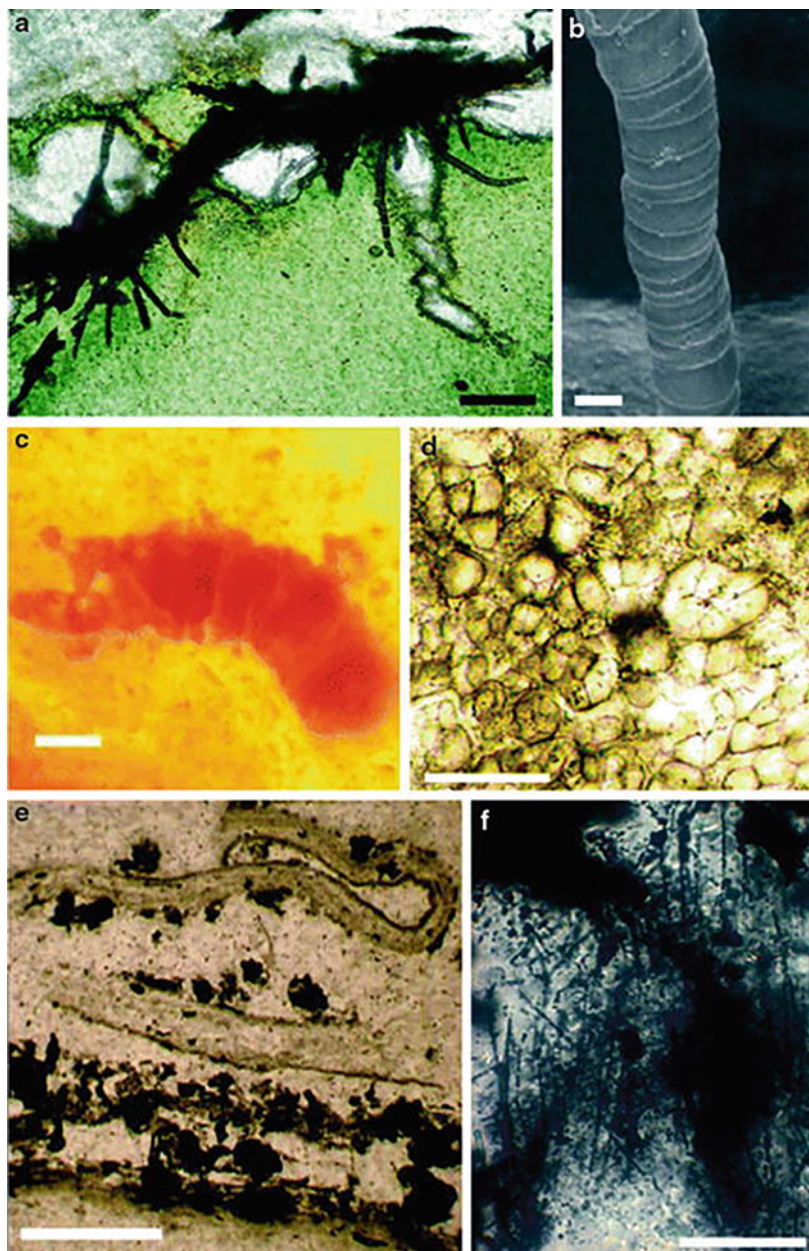
Morphological complexity is often regarded as a diagnostic criterion for life. But it must be remembered that complex shapes do not require complex causes and can arise naturally in physio-chemical systems, as shown, for example, by snowflake growth. The interpretation of candidate morphological evidence for life, therefore, proceeds together with exploration and refutation of potential abiotic mimics, reviewed briefly here.

With reference to stromatolites, it has been recognized for some years that abiotic processes can generate laminated abiotic deposits, for example, in numerical simulations (Grotzinger and Rothman 1996) and laboratory experiments (McLoughlin et al. 2008), and that these can produce complex morphologies such as branching. Chemical precipitation can also form laminated deposits, but an understanding of the geological environment can identify localities where this may be most likely, for example, in supersaturated water columns, or terrestrial sinter deposits. Also, the laminar geometries, in particular isopachous laminae, that is, of constant thickness, and with radiating crystal fabrics at the microscale can be used to identify production by chemical precipitation. Conversely, evidence of the trapping and binding of detrital sediment on steep-sided microbialites would support biological involvement. Further exploration of the biological versus abiological contribution to stromatolite growth can be found elsewhere in this volume. In Archaean rocks, where the primary microfabrics have been overprinted and organic remains destroyed, caution must be exercised before inferring a biological origin.

Concerning microfossil remains, the challenge of demonstrating biogenicity is particularly acute for simple-spheroidal bodies found in Archaean cherts. Here, processes such as the recrystallization of silica gel leading to the displacement of organic matter can generate spheroidal shapes, even conceivably filamentous and segmented morphologies (Brasier et al. 2005). Here, the examination of the carbonaceous ultrastructure to demonstrate whether the candidate microfossil is hollow and shows evidence of a cell wall or sheath can be helpful. Also looking at the size distribution of the population to test if this resembles a biogenic population, or a large abiotic community (Brasier et al. 2006). Crystal-garden-type experiments that precipitate microfossil-like biomorphs from metal salts mixed with sodium silicate gels (García-Ruiz et al. 2003 and Fig. 1b) have emphasized the diversity and complexity of microtextures that can be generated abiotically. Even more worrying, is the discovery that organic compounds produced by the abiogenic

Archaean Traces of Life,

Fig. 1 Precambrian morphological traces of life (a) photomicrograph of mineral “biotextures” from the 3.45 Ga Hooggenoeg Formation of the Barberton Greenstone Belt, South Africa; (b) scanning electron micrograph of a twisted filamentous pseudofossil produced experimentally by precipitating barium-carbonate crystals in sodium silicate gel; (c) branched, septate “microfossil” composed of carbonaceous material (orange) in a silica matrix (yellow) from the ~3.45 Ga Apex chert of West Australia; (d) transmitted light image of coccoid microfossils from the ~1.0 Ga Boorthana Chert of South Australia; (e) putative microbial mat rip up fragments showing plastic rheology from the ~3.4 Ga Buck Reef Chert of South Africa; overlying rounded, composite, carbonaceous grains; (f) transmitted light image of intertwined filamentous microfossils from the 3.2 Ga Sulfur Springs Group of W Australia. Scale bars: (a) 50 μm , (b) 20 μm , (c) 10 μm , (d) 50 μm , (e) and (f) 50 μm



breakdown of iron-carbonate can condense onto these biomorphs during mild heating, thereby mimicking both the morphological and chemical signatures of ~3.5 Ga “microfossils” (García Ruiz et al. 2003).

Concerning candidate endolithic microborings, several abiotic microtunnelling processes have been postulated (McLoughlin et al. 2010). The first are so-called “ambient inclusions trails” formed by the migration of a mineral grain, usually pyrite through a mineral matrix, most commonly chert, leaving a hollow cavity behind that can sometimes be lined by organics. If the terminal inclusion is a corrosive bitumen droplet rather than pyrite, the microtunnel cross-section may be less angular and therefore more difficult to identify as abiotic (McLoughlin et al. 2010 and refs therein). A second group of processes that may mimic candidate microborings especially in meta-volcanic glass, is the growth of metamorphic minerals during low-grade seafloor or regional metamorphism to form chains or strings of crystals with morphologies and distributions that resemble mineralized microtunnels. Possible examples will be discussed and reviewed below.

Lastly, it should be appreciated that organic matter or kerogen with carbon and nitrogen isotope ratios that are similar to life can be found in a wide range of environments, including the interstellar medium, meteorites and comets, and also a range of geological environments. Most relevant to discussions concerning candidate Archaean traces of life are seafloor-hydrothermal processes, spanning high to relatively low-temperature conditions that can generate negatively fractionated C isotope values (Sforna et al. 2018 and refs therein). When attempting to identify unambiguous biogenic traces of life, it is important that all available lines of evidence are combined, integrating morphological, chemical, and geological evidence across the outcrop (meters), thin section (mm- μ m), and ultrastructural (nm) scale to try distinguishing biotic from abiotic remains.

Chemical Evidence of Life: Elemental and Isotopic Signatures

Isotopic ratios preserved in ancient rocks may record past biological activity and can be

measured by mass spectrometry to test for the presence of life and often constrain the microbial metabolisms involved. Here, the focus is on carbon and sulfur isotopes, which are the main isotopic tools used in the search for Archaean life. A key distinction is made between bulk stable isotope studies, which give information about global systems and reservoirs, versus in-situ studies that can be texturally connected to specific morphological biosignatures and are therefore very powerful tools in evaluating biogenicity.

Carbon Isotopes

The ratio of ^{12}C to ^{13}C preserved in organic matter and associated carbonates provides constraints on ancient microbial processes. Different microbial metabolisms and various abiotic processes impart differing ranges in C isotope fractionation that are described in detail elsewhere in this volume. If ancient organic matter can be shown to be syngenetic and endogenetic to the host rock, then its carbon isotopic values can be used to constrain the ancient microbial metabolisms. Typical Archaean organic matter is found to have a $\delta^{13}\text{C}$ value of -20‰ relative to inorganic carbonate leading many researchers to claim that biological activity began 3.8 billion years ago (Schidlowski 2001). A range in C isotope values is found in Archaean organic matter, especially from high-magnification in-situ studies and so a variety of microbial metabolisms have been proposed, including anoxygenic photosynthesis from C isotopes in the range of -20‰ to -30‰ measured on kerogen, for example, (Tice and Lowe 2004); and methanogenesis from very low C ratios of -56‰ measured on methane-bearing fluid inclusions (Ueno et al. 2006). These $\delta^{13}\text{C}$ values are certainly consistent with life but, unfortunately, carbon isotope fractionation patterns when taken alone are not a uniquely biological signal. This is because there are alternative non-biological explanations for such light carbon isotopic values that need to be excluded and these can be the source of much debate in Archaean rocks. For example, Fischer–Tropsch type (FTT) reactions between CO and metals, or the

metamorphic reduction of siderite can generate carbon isotope fractionations that lie within the “biological domain.” Thus in the early rock record, carbon isotope values need to be integrated with other isotope systems along with an understanding of the geological context to be accurately interpreted.

Sulfur Isotopes

Microorganisms that metabolize sulfur compounds are one of the most deeply rooted groups in the Tree of Life. Sulfur isotopes preserved in ancient sulfides, especially pyrite, along with sulfate minerals like barite, are used to trace ancient microbial metabolisms. The sulfur cycle on the early Earth was markedly different from the later Precambrian, because in the absence of atmospheric oxygen the photolysis of volcanic S_2 could produce elemental S and sulfate aerosols. Sulfate ions can be used by microbial sulfate reducers and may also be used to oxidize organic compounds by anaerobic respiration, whilst elemental S could be metabolized via microbial disproportionation. (For further explanation of microbial sulfur cycling see elsewhere in this volume.) Both microbial sulfate reduction and abiotic photolysis reactions can impart large fractionations in ^{34}S relative to ^{32}S and by investigating the isotope fractionation patterns recorded by the four stable isotopes of sulfur (^{32}S , ^{33}S , ^{34}S , ^{36}S) it is possible to distinguish microbial signatures from abiotic processes in the atmosphere and hydrothermal-volcanogenic systems.

The S isotope record from ~2 Ga onwards shows $\delta^{34}S$ fractionations of 50–60‰ between sulfides that are depleted relative to co-existing sulfates and this has been attributed to microbial sulfate reduction. In older rocks, such fractionations are much smaller with most sedimentary sulfides older than ~2.7 Ga showing a narrow $\delta^{34}S$ range. Evidence of microbial sulfate reduction is found in rocks between 3.5 and 2.7 Ga, particularly from in-situ studies of microscopic sulphides but not in bulk samples (Shen and Buick 2004). This has been taken to suggest that microbial sulfate reduction was present locally, but not widespread because of low-sulfate concentrations in the Archaean oceans.

Key Research Findings

Microfossils

Microfossils are the remains of carbonaceous microbial cells and display a range of shapes that include: coccoids (simple spheres), filaments that may be septate and/or branched, and lenticular/ellipsoidal bodies. Microfossils found in Archaean rocks have experienced diagenetic alteration often followed by multiple metasomatic and metamorphic events, and commonly extended weathering histories. Combined with the fact that these microorganisms are amongst the most primitive with simple morphologies, their identification as *bonafide* traces of life can be challenging, with many instances of candidate Archaean microfossils being subsequently reidentified as abiotic mimics. Several workers have therefore developed and advanced criteria to establish the biogenicity of ancient microfossils (Brasier et al. 2005 and refs therein) and examples of how these are applied will be reviewed below.

An instructive example of how the biogenicity of candidate Archaean microfossils is assessed comes from the ~3.45 Ga Apex Chert of Western Australia that is now famous for engendering a vigorous debate regarding the oldest microfossil-like objects (Fig. 1c). In the 20 years since their discovery, these “microfossils” have become the cornerstone of textbook descriptions of an early Archaean biosphere. This changed, however, when a re-examination of the “microfossils” called into question their biogenicity (Brasier et al. 2002). These authors argued that the geological context, morphology, and distribution of the “microfossils” are more consistent with an origin as abiotic graphite artifacts, produced by the recrystallization of amorphous silica to spherulitic chert. The principal lines of evidence from (Brasier et al. 2002) are summarized in Table 1 and contrasted with the original interpretation of (Schopf and Packer 1987), an origin for these “microfossils” as oxygen-producing cyanobacteria-like organisms now seems highly unlikely. There have been several subsequent studies that have investigated the morphology of the Apex microfossil-like structures and compared them to younger less-metamorphosed samples, also studies that have

Archaean Traces of Life, Table 1 Contrasting lines of evidence and their interpretation collected from the ~3.45 Ga Apex Chert of Western Australia and containing “microfossil” structures

Lines of evidence	Brasier et al.	Schopf et al.
Environment of deposition	Deep marine seafloor cherts with intrusive hydrothermal dyke cherts	Shallow marine silicified sediments
“microfossil” morphology	Sheets and wisps of carbonaceous material concentrated around the rims of silica spherulites and rhombic crystal inclusions	Eleven taxa of filamentous “microfossils”
Laser Raman analysis	The carbonaceous material has a graphitic Raman signature, and the “microfossil” signature is indistinguishable from the matrix carbonaceous material	The “microfossils” have a Raman signature that is argued to be comparable to disordered kerogenous carbon from younger biogenic assemblages
Carbon isotopes	$\delta^{13}\text{C}_{\text{org}}$ of -30 to -26‰ which cannot exclude abiotic Fischer-Tropsch synthesis	$\delta^{13}\text{C}_{\text{org}}$ of -30 to -23‰ lies within the range of biological fractionation
Interpretation	Abiotic artifacts created by the recrystallization of amorphous silica that displaced graphitic margins forming a spectrum of arcuate to dendritic artifacts	Silica permineralization of filamentous “microfossil” cells that could have included oxygen-producing cyanobacteria and possibly larger, beegiatocean microfossils

looked at the Raman spectra, carbon ultrastructure, and compared these to younger biogenic microfossils. Notably, a recent in-situ carbon isotope study found C-isotope heterogeneities within filamentous structures in the Apex chert and argued that this was compatible with a biogenic origin, and not an origin from a single remobilized hydrothermal (Fischer Tropsch) source (Schopf et al. 2018). However, given the complex multistage hydrothermal alteration history of the Apex Chert characterized by several workers, this could also explain the carbon isotope heterogeneities. In summary, the Apex Chert has proven to be a highly controversial, but also an instructive example of how the biogenicity and antiquity of microfossil-like structures can be tested.

Evidence for microbial life in a sub-seafloor environment may come from putative microfossils of the c. 3.24 Ga Sulfur Springs Group of the Pilbara, a volcanogenic, massive sulfide deposit, interpreted to contain pyritized filaments of thermophilic, chemotrophic prokaryotes (Rasmussen 2000 and Fig. 1f). These straight, curved, or sinuous filaments exhibit putative biological behavior including preferred orientations, clustering, and intertwining. They are found in an early chert fabric in a subsurface drill core that is cross-cut by later fractures thereby satisfying syngenetic requirements. A study of the

ultrastructure of these filaments found them to be comparable to pyritized Palaeoproterozoic *Gunflintia* microfossils, although abiotic origins could not be excluded, especially as the filaments were solid rather than hollow (Wacey et al. 2014).

Several putative examples of microfossils and microbial mats have been proposed from the Onverwacht Group of South Africa with a range of supporting evidence. These included filamentous, coccoid, and lenticular microtextures from the 3.43–3.41 Ga Kromberg-Chert based largely on petrographic evidence (Javaux 2019 and refs therein). Integrated C-isotope and ultrastructural data was not provided in these early studies and subsequent workers have emphasized the impact of hydrothermal fluid migration on these carbonaceous cherts, and the possible similarity to organics condensed onto volcanic particles (Wacey et al. 2018) thereby casting doubt on these microfossils. Stronger, evidence of silicified microbial mat remains has been presented from several other Onverwacht cherts summarized in (Lepot 2020 and refs therein) including: the 3.47 Ga Middle Marker Chert, 3.416 Ga Buck-Ridge Chert (Tice and Lowe 2004), and the 3.33 Ga Josefdal Chert. Key lines of evidence to support a microbial origin include rheological arguments based on the observation of plastically deformed, ripped-up organic fragments. Also, the

depth-controlled distribution of the various chert fabrics and carbonaceous microtextures found in, for example, the Buck Ridge Chert, that is consistent with a depth and light controlled ecosystem (Tice and Lowe 2004). It should be emphasized, however, that there is no compelling evidence of cellular preservation in these cherts, and that cell walls and cellular sheaths are not preserved, in other words these are not microfossils, rather laminated organic textures interpreted as microbial mat remains.

Intriguing large lenticular or spindle-shaped microstructures from the 3.4 Ga Strelley Pool Chert (Sugitani et al. 2015) and 3.0 Ga Farrel Quartzite of Western Australia have been proposed as microfossils. These structures are 20–100 μm across, lenticular in shape often with an equatorial flange, can form chains up to 7 individuals long, and have a central body that may contain vesicles and carbonaceous globules. Measurement of texture-coupled C isotope heterogeneities (Lepot 2020 and refs therein) also H/C and N/C ratios have been taken to support an origin for the microstructures from biological organic matter. It should be noted, however, that the same rocks can contain volcanic vesicles with organic and titaniferous coatings that must be carefully distinguished from the lenticular microfossils (Wacey et al. 2018). The exact biological affinity of these lenticular microfossils is not clear, whether they are large single cells or bacterial colonies as suggested by the reticulate wall of some examples (Javaux 2019). Large, hollow spherical organic-walled microfossils termed acritarchs, have also been described from siliclastic sediments of the ~ 3.2 Ga Moodies Group of S Africa (Javaux et al. 2010). These structures pass syngenicity and endogenicity tests and appear to be the oldest and largest organic-walled spheroidal microfossils reported to date and may represent stem-group eukaryotes, predating the currently recognized fossil record of crown-group eukaryotes by more than 1.5 Ga.

Stromatolites and Microbially Induced Sedimentary Structures

Stromatolites comprise laminated, centimeter to decimeter scale domes, cones, columns, and

planiform surfaces that are built through the interplay of physical, chemical, and biological processes. The first c. 2 billion years of the fossil record is dominated by stromatolites. The processes that lead to the growth of stromatolites and how these can be identified from laminar geometries and microfabric evidence are reviewed elsewhere in this volume. Here, a non-genetic definition of a stromatolite is adopted because it can be difficult to demonstrate active biological participation in stromatolite growth, especially in Archaean rocks where diagenetic recrystallization and low-grade metamorphism can overprint and destroy any organic microtextures that were once present. There have been many attempts to develop stromatolite biogenicity criteria (discussed elsewhere in this volume), and these will be discussed below, in an effort to distinguish laminated seafloor precipitates formed by purely chemical processes, from microbially mediated deposits.

Among some of the oldest and best-preserved Archaean stromatolites are coniform stromatolites of the 3.35–3.426 Ga Strelley Pool Chert of Western Australia. These were first proposed as biogenic in origin, although this was later rescinded by (Lowe 1994) because of the extreme continuity of the laminae, the absence of fine-scale “crinkly” laminae, the paucity of detrital material, lack of fenestrae or “gas bubbles” together with their evaporitic setting, which was argued to be more consistent with an abiogenic origin through chemical precipitation. Subsequent discoveries near the Trendall locality of large coniform stromatolites with rare branching on the flanks, also domal and laterally linked pseudocolumnar morphologies have supported biogenic interpretations, with these more complex morphologies being difficult to explain by purely abiotic processes (Hofmann et al. 1999). Improved characterization of the depositional environment and geological setting especially in the Panorama Belt of the North Pole dome, has led to the development of shallow-water to evaporitic carbonate platform depositional model for the Strelley Pool stromatolites (Allwood et al. 2018).

Slightly older, stromatolitic material comes from the 3.48 Ga Dresser Formation of the North

Pole Dome, which records an active volcanic environment with vigorous hydrothermal circulation forming complex barite-chert-carbonate deposits. These rocks have been the target of intense biosignature investigations on surface and drill core material that contain candidate stromatolites, microfossils, MISS, sulfur, and carbon isotope evidence, although many of these have been strongly debated. The stromatolite evidence comprises wavy-laminated convex-up precipitates of ferruginous carbonates that are variably silicified and contain sulfates (barite and gypsum pseudomorphs), and sulfides, the biogenicity of which has been debated based on morphological evidence (Lowe 1994). Moreover, the depositional environment has been variously interpreted as sub-seafloor hydrothermal “white smoker” type deposit, and more recently, as terrestrial hot-spring biogenic geyserite deposit (Djokic et al. 2017). Associated potential chemical biosignatures include heterogeneous sulfur isotope compositions of pyrite found in pyritized organic layers interpreted as derived from microbial mats, although a thermochemical origin could not be completely excluded (Lepot 2020 and refs therein), as is the challenge for many of the microscopic signatures in the Dresser Formation.

Older still, convex-up structures interpreted as stromatolites were described from metasediments of the Isua greenstone belt (Nutman et al. 2016) and are a cautionary example of how to employ strict biogenicity criteria. These structures occur in tightly folded rocks and comprise both convex-up structures adjacent to convex-down structures and therefore fail the requirements for syn-sedimentary structures with a predominance of convex-up morphologies and have thus been reinterpreted as deformation features (Allwood et al. 2018). In addition, the depositional setting of these rocks has been questioned, with geochemical signatures suggesting that the carbonate is more likely secondary in origin (metasomatic/metamorphic) and not shallow marine (Allwood et al. 2018).

In siliclastic rocks, especially sandstones and siltstones macroscopic evidence of life can be preserved by wrinkled bedding surfaces, tufted and dome-shaped structures interpreted to record

biostabilization of the sediments by microbial mats, and when a biogenic origin can be confirmed, these are termed microbially induced sedimentary structures (MISS). Some of the best-characterized examples come from the 3.22 Ga Moodies Group of South Africa that contain wrinkle structures, desiccation cracks, and roll-up structures that record the previous existence of microbial mats that effectively stabilized sediment on these ancient tidal flats (Noffke et al. 2006). Moreover, it has been shown that the distribution of the various MISS structures is tightly controlled by the changing shallow-water tidal to terrestrial deposition environment (Heubeck 2009). In the thin-section, the MISS preserve laminated carbonaceous fabrics that drape sand grains and preserve $\delta^{13}\text{C}$ isotope ratios that are consistent with microbial photosynthesis, which could be anoxygenic or possibly even oxygenic (Lepot 2020 and refs therein). Older possible MISS are described from the 3.48 Ga Dresser Formation of Western Australia described elsewhere in this volume.

Microborings

Microborings are micron-sized cavities created by the activities of rock-dwelling microorganisms termed endoliths. Undisputed fossilized examples come from 1.7 Ga silicified carbonates with downward-facing traces in stromatolitic laminae interpreted as cyanobacterial borings. On the early Earth, a sub-surface rock-dwelling mode of life may have offered many attractions, including: protection from more intense UV radiation and elevated impact-flux, proximity to geothermal heat, access to both oxidants and carbon sources carried by circulating fluids. Microorganisms that can adopt an endolithic mode of life include some cyanobacteria found in carbonates, also fungi that produce hyphae found in sandstones, and fractures in volcanic lavas. Traditionally, the sedimentary rock record has been the focus of efforts to find endolithic microborings, however, in the last 15+ years the discovery of microbial life in the modern sub-seafloor and associated microbial alteration textures has driven the search for endolithic microborings in Archaean lavas.

Microtextures argued to be mineralized endolithic microborings have been reported from the formerly glassy rims of pillow basalts and inter-pillow breccias from both South Africa (Furnes et al. 2004 and Fig. 1a) and West Australia (Banerjee et al. 2007). The original examples come from the ~3.46 Ga Hooggenoeg Complex of South Africa and are mineralized by titanite (CaTiO_3) found in a greenschist facies metamorphic mineral assemblage. These microtextures are 1–10 μm wide filaments, up to 200 μm long and extend away from “root zones” of fine-grained titanite that are associated with fractures in the original volcanic glass (Fig. 1a). Similar microtextures have been reported from inter-pillow breccias within the ~3.35 Ga Eurobasalt Fm of Western Australia. These are also infilled with titanite and were interpreted to have been formed by microbial tunneling on the seafloor that was subsequently infilled by the growth of metamorphic titanite. These microtextures have been questioned, however, with recent studies disputing both their syngeneticity and biogenicity (Grosch and McLoughlin 2014; McLoughlin et al. 2020).

Key findings that led to the refutation of Archaean titanite infilled microborings were the discovery from South Africa that these microtextures were not syngenetic to the Archaean seafloor (Grosch and McLoughlin 2014). In-situ U-Pb dating of the titanite found that the microtextures were 2.819 ± 0.2 Ga and therefore considerably younger than the 3.45 Ga eruptive age of the host pillow lavas. It was also found that the microtextures exhibit a morphological continuum and show a size distribution that is very different to that observed in modern seafloor lavas, being on average much thicker and showing a broader size range inconsistent with a biological population. Furthermore, the filaments are concentrated in a zone located within the contact aureole of a 2.913 ± 0.31 Ga sill (a younger intrusive body) and therefore an alternative abiotic origin, involving the growth of metamorphic titanite porphyroblasts in a thermal contact aureole was proposed (Grosch and McLoughlin 2014). In addition, quantitative microscale compositional mapping, combined with chlorite thermodynamic modeling of the greenschist facies matrix, revealed that the titanite filaments are

best developed in relatively low-temperature microdomains of the chlorite matrix, suggesting that they record retrograde cooling in the pillow lava host rock (Grosch et al. 2017).

Concerning, the Eurobasalt microtextures from Western Australia, reexamination of these titanite filaments, particularly focusing on their ultrastructure (McLoughlin et al. 2020), revealed new information that also questioned their origin and growth by the infilling of previously hollow microtunnels by titanite. Serial sectioning using FIB-TEM (focused ion beam, transmission electron microscopy) found that the microtextures were formed of discontinuous strings of titanite and anatase with coalescing crystallites forming the filaments. The TEM investigations also confirmed the absence of carbonaceous linings on the margins of the microtextures, previously argued to be the decayed remains of microbial cells. Considering the mineral assemblage found within the EuroBasalt metavolcanics, an alternative origin for the microtextures through the growth of titanite-anatase in an early seafloor-hydrothermal environment under fluctuating CO_2 - H_2O rich conditions has been proposed (McLoughlin et al. 2020).

In light of the reevaluation of candidate microbial microborings in Archaean metavolcanic glass described above, what then is the oldest fossilized microboring? An intriguing discovery comes from the 2.4 Ga Ongeluk lavas of the Transvaal Supergroup South Africa, and a study that reported branched filamentous microtextures in mineralized vesicles in the lava with morphologies suggesting an origin from fungal hyphae (Bengtson et al. 2017). These microfossils were interpreted to represent chasmoendolithic fungi dwelling in cavities in the lavas and may therefore represent a new type of evidence for life in the Proterozoic sub-seafloor.

Carbon Isotopes

One of the oldest claims for life comes from isotopically light carbon found in ~3.8 Ga rocks from the island of Akilia off the West coast of Greenland. The material analyzed was graphitic carbon found as inclusions within grains of apatite, with a $\delta^{13}\text{C}$ signature of -20 to -50%

(Mojzsis et al. 1996). The debate that has surrounded these observations provides an illustrative example of the need to understand the complete geological history of a rock argued to contain chemical traces of life. The original authors argued that this carbon was sealed within apatite grains from a low-temperature sedimentary environment and that the isotopic signature was indigenous and could be used as evidence to support life at ~3.8 Ga. A few years later, however, a different team examined the Akilia site and determined that the outcrop is not sedimentary. They found the outcrop to be purely metamorphic and argued that the carbon was also metamorphic in origin and thus of no biological relevance (Fedó and Whitehouse 2002). Several similar discussions have surrounded evidence of graphite from other Eoarchaeon and Hadean metasediments and zircon grains as reviewed by Lepot (2020); in these environments, metamorphic and metasomatic processes must first be rejected before biological possibilities can be explored.

In Mesoarchaeon rocks, combining in-situ measurements of C isotopes with texture-specific studies can be a powerful approach to testing biogenicity and exploring potential microbial metabolisms. Instructive examples described above, include the Strelley Pool lenticular microfossils, and disputed Apex-Chert microfossils (Schopf et al. 2018; Lepot 2020). In younger, Neoarchaeon rocks $\delta^{13}\text{C}_{\text{org}}$ values have been used in conjunction with other isotope systems especially, S, to explore the expansion of microbial metabolisms such as methanogenesis and acetogenesis, see below.

Sulfur Isotopes

In-situ studies of S isotope fractionations in Paleoarchaeon sulfides by (nano)SIMS (nanoscale-secondary ion mass spectroscopy) have found evidence of microbial sulfate reduction (MSR) which may have been either chemoautotrophic or heterotrophic. For example, microscopic sulphides contained within barite crystals in the ~3.49 Ga Dresser Formation of North Pole, Western Australia show multiple S isotope fractionations supporting the presence of MSR and microbial sulfur disproportionation

(Philippot et al. 2007). A heated debate has centered on the interpretation of the mass-independent S isotope fractionation (MIF) in these and rocks of similar age, centered on the contribution of abiotic, especially atmospheric, and thermochemical processes. However, the four S isotope patterns measured in the Dresser Formation are best explained by MSR. In slightly younger sedimentary rocks of the 3.4 Ga Strelley Pool Chert investigation of detrital and diagenetic pyrites also supports the operation of both MSR and microbial disproportionation in an open-marine, sedimentary-hosted ecosystem (Wacey et al. 2010). While sulfur isotope studies of a range of sedimentary and volcanic rocks from the Paleoarchaeon Barberton Greenstone Belt of South Africa (Grosch and McLoughlin 2013) have also found evidence of MSR, and the processes that control the mass independent fractionation (MIF) of sulfur appear to be different in the Barberton rocks compared to Pilbara.

Depletions in $\delta^{34}\text{S}$ in bulk sulphides are highly muted until c. 2.7 Ga interpreted to mean that MSR was only localized to an extent up until this time. In younger Neoarchaeon rocks, sulfur isotope evidence in conjunction with carbon isotopes (and sometimes rare earth element data) gives further insight into the emergence of sulfur metabolisms. For example, investigations of the 2.7–2.6 Ga Belingwe Belt of Zimbabwe have found pyrites in sulphidic shales with a wide range of $\delta^{34}\text{S}$ values from –21.1‰ to +16.7‰ that have been interpreted to indicate sulfate reducing and possible sulfur-oxidizing bacteria (Grassineau et al. 2001). Likewise, in-situ studies of the wide range in $\delta^{34}\text{S}$ of sulphides in lacustrine stromatolites from the 2.72 Ga Tumbiana stromatolites have been taken to support the presence of MSR, that combined with $\delta^{13}\text{C}_{\text{org}}$ values of –50‰ may indicate sulfate-fuelled anaerobic methanotrophy (Lepot 2020 and refs therein).

Future Directions

In the last decade, a clearer picture of the emergence of life in the Mesoarchaeon has appeared with several localities now providing robust

evidence of benthic and planktonic microbial life. This has been achieved through the refinement of biogenicity and syngenicity criteria; the discovery of new localities; the investigation of a wider range of rock types; and the application of high-resolution imaging combined with in-situ isotopic analyses. Many interesting questions still remain, especially concerning the timing of the appearance of different microbial metabolisms and in which geological environments they emerged. Taken together, our improved understanding of the earliest traces of life, along with the techniques and approaches developed, provides invaluable guidance for designing strategies to seek life elsewhere in our universe.

Cross-References

- ▶ Abiotic
- ▶ Apex Chert
- ▶ Archean Drilling Projects
- ▶ Archean Environmental Conditions
- ▶ Archean Eon
- ▶ Archean Tectonics
- ▶ Barberton Greenstone Belt
- ▶ Barberton Greenstone Belt, Traces of Early Life
- ▶ Biogenicity
- ▶ Biomarkers, Morphological
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- ▶ Carbon Isotopes in the Solar System
- ▶ Chemolithoautotroph
- ▶ Complexity
- ▶ Craton
- ▶ Cyanobacteria
- ▶ Dresser Formation, Traces of Life
- ▶ Endolithic
- ▶ Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation
- ▶ Fossil
- ▶ GC/MS
- ▶ Geochronology
- ▶ Greenstone Belt
- ▶ Isotopic Ratio
- ▶ Isua Supracrustal Belt
- ▶ Kerogen
- ▶ Metasediment
- ▶ Microbial Mats

- ▶ Microbially Induced Sediment Structures (MISS)
- ▶ Microfossils
- ▶ Nitrogen Isotopes
- ▶ North Pole Dome (Pilbara, Western Australia)
- ▶ Oxygen Isotopes
- ▶ Photosynthesis
- ▶ Pilbara Craton
- ▶ Pillow Lava
- ▶ Precambrian Oceans, Temperature of
- ▶ Pseudofossil
- ▶ Raman Spectroscopy
- ▶ Steranes, Rock Record
- ▶ Stromatolites
- ▶ Sulfur Isotopes
- ▶ Synchrotron Radiation
- ▶ Syngenicity
- ▶ Tumbiana Formation (Pilbara, Western Australia)

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Archaeobacteria

► Archaea

Archean Drilling Projects

Nicholas Arndt

Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

Keywords

Pilbara craton · Barberton greenstone belt · Barite · Archean traces of Life · Drilling Project

Definition

During the past decade, several scientific drilling programs that have been carried out in Archean terrains. Other ones are planned in the near future. The aim of most of these drilling projects is to recover relatively well-preserved rock samples from below the present weathering profile and to obtain continuous rock cores that retain soft or friable units that outcrop poorly at the surface. Astrobiology-related studies such as search of pristine morphological or chemical traces of early life form an important part of these projects.

Overview

To date, in greenstone belts, both volcanic and sedimentary sequences have been targeted. The recovered cores have been analyzed to investigate conditions prevailing at the surface of the Archean Earth – the composition, temperature, and redox

state of the Archean ocean and atmosphere and the volcanic and sedimentary processes that operated early in Earth history – and, above all, to search for evidence of primitive life. The focus has been the ► [Pilbara Craton](#) in Western Australia, where four separate programs have been carried out, each involving collaboration between geologists from Australian universities, the Western Australian Geological Survey, and foreign agencies. The four programs are:

1. The Archean Biosphere Drilling Project (ABDP) cosponsored by several Japanese Universities,
2. The Deep Time Drilling Project (DTDP) of the NASA Astrobiology Institute
3. The Pilbara Drilling Project (PDP) of IPG Paris
4. The Dixon Island-Cleaverville Drilling Project (DXCL-DP) supported by the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT)

In South Africa's ► [Barberton Greenstone Belt](#), two French-driven drilling projects were completed to date:

1. The Barberton Barite Drilling Project (CNRS, IPGP) had the objective to obtain a representative sequence of black cherts, shales, tuffaceous sandstones and siltstones, jasper deposits, and bedded barite, which is a conspicuous assemblage of rock types typically observed from Early Archean seafloor hydrothermal settings. They well penetrated a section in the west limb of the Baryte Syncline to a depth of 182 m.
2. The Barberton Drilling Project (ICDP; July 2011–May 2012) included five diamond-core holes, each several hundred meters long. BARB-1 and BARB-2 targeted komatiitic rocks near Tjakastad in the southern part of the belt, whereas BARB-3 drilled 899.5 m through the Buck Reef Chert, both of the ► [Onverwacht Group](#). BARB-4 targeted turbidites and banded-iron formation and BARB-5 ► [barite](#), turbidites, and ► [spherules](#), both of the Mapepe Formation (lower Fig Tree Group). A total of 3052 m of core was recovered.

Two programs focused on the Archean-Proterozoic transition. After the Kola Superdeep Borehole (12,262 m deep), a series of short holes have been drilled in Russian Fennoscandia to sample the 500-million-year interval defining the Archean-Paleoproterozoic transition; the Agouron Griqualand Paleoproterozoic Drilling Project straddled a similar interval in the Northern Cape province of South Africa.

Cross-References

- [Archaean Traces of Life](#)
- [Barberton Greenstone Belt](#)
- [Microfossils](#)
- [Pilbara Craton](#)
- [Proterozoic Eon](#)

Archean Environmental Conditions

Christoph Heubeck¹ and Nicholas Arndt²

¹Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

²ISTerre, Université Grenoble Alpes, Grenoble, France

Keywords

Chert · Komatiite · Oceans · Sediment · Traces of life · Carbonates

Definition

The term “Archean environmental conditions” refers to the geological, physical, and chemical conditions of the surface of the Earth during the ► [Archean eon](#). The surface of the Archean Earth was in many ways similar to that of today. Oceans likely covered most of the globe, but there were also regions of dry land. However, the oceanic crust was almost as thick as the ► [continental crust](#), mountain ranges were not very high, and parts of oceanic ridges and plateaus (thick piles of flat-lying lava flows) were

emergent. Geological processes such as volcanism, erosion, and sediment deposition operated but were influenced by a lack of vegetation, higher ocean temperatures, different water composition, and a hotter, more aggressive, acidic atmosphere. In addition, coastal settings may have been subjected to more intense reworking by high and more frequent tides.

Overview

The surface of the Archean Earth was in many ways similar to that of today. Oceans covered most of the globe, but there were also regions of dry land. The total area covered by oceans was greater than now for three reasons. First, the volume of continental crust may have been less, if continental crust indeed grew (progressively or in spurts) through time (Benn et al. [2006](#)). Second, the oceans might have been more voluminous because high temperatures in the mantle (Nisbet et al. [1993](#)) destabilized hydrous minerals and drove water to the surface. Third, oceanic crust was thicker. Its top lay at a shallower depth than today’s sea floor, thus displacing water which inundated low-lying margins of continents (Eriksson [1999](#)).

Mountain ranges existed but were not as high as those of today because the continental crust was heated internally and rendered more ductile by more abundant radioactive elements. Continental crust was relatively thin, while oceanic crust, produced by high-degree melting of the hotter mantle, was far thicker (Sleep and Windley [1982](#)). The subdued topography, the limited contrast between the thicknesses of oceanic and continental crust, combined with bigger oceans, meant that much of the continental crust was flooded (Arndt [1998](#)).

Just as during more recent geological history, global temperatures waxed and waned. The world’s oldest glaciation is reported from the 2.9 Ga-old Mozaan Group on South Africa’s Kaapvaal Craton (Young et al. [1998](#)) but on the whole temperatures appear to have been clement or high. The O and Si isotopic compositions of Archean ► [cherts](#) suggest that ocean temperatures

were commonly above 40 °C and possibly as high as 80 °C (Knauth and Lowe 2003). The atmosphere contained very little or no free oxygen but was richer in CO₂; rainwater was thus somewhat acid. Due to the absence of a protective ozone shield, UV flux at the Earth's surface was high. The atmosphere also contained SO and SO₂, causing sulfuric acid haze; haze from nitrous oxides and organics likely occurred as well. The normal cycle of erosion, transport, and deposition of sediment operated, but the rivers flowed through a landscape that was very different from that of today.

The feature that most starkly distinguished the Archean and modern land surface was the lack of vegetation. Microbes doubtlessly colonized the subsurface and constructed ► [biofilms](#) and thicker biomats which covered moist areas, possibly including low-lying fluvial floodplains, but most of the landscape likely had the appearance of bare rocks we see on recent Mars. The rate of weathering was enhanced by higher temperatures and a more aggressive atmospheric composition, possibly also by violent thunderstorms, but was slowed down by a lack of humic acid and thick soils that today greatly enhance weathering rates. These processes and rates are difficult to quantify. Erosion was likely enhanced by the lack of vegetation and thus lack of stabilized river banks, but restrained by the overall more modest mean elevation of continents. Active volcanism covered much of the surface with lava flows or pyroclastic deposits. The Moon, in a closer orbit and rotating faster about the Earth, caused higher and more frequent tides which may have raked the barren shorelines in much wider tidal belts than we see today.

The oceanic crust was composed of basaltic lavas like that of modern crust, but was more magnesian (picritic) in places (Sleep and Windley 1982). Parts of mid-ocean ridges and the summits of oceanic plateaus may have been emergent, forming what might be called “melano- (dark-colored) continents.” The pelagic sediment that covered this crust was different from that of today. An absence of shell-forming organisms precluded the formation of biogenic calcareous or siliceous oozes;

in their place occurred Si- or Fe-rich sediments that precipitated directly from the high-temperature seawater that contained high concentrations of these elements. Depending on the intensity of weathering of mafic material on exposed regions, much clay may have been produced, washed into the sea and deposited on oceanic crust. Hydrothermal venting of Si-charged seawater resulted in rapid silicification of most near-surface sediments and exposed igneous rocks, along with the formation of primary ► [cherts](#). Expulsion of fluids at hydrothermal vents led to the deposition of exhalative sediments, variably composed of sulfides, sulfates, carbonates or silica minerals (Russell et al. 2005).

The earliest Archean coincided with the end of the ► [Late Heavy Bombardment](#), a time of more frequent meteorite impacts. The largest of these would have vaporized parts of the oceans, raised oceanic and atmospheric temperatures significantly, and resurfaced parts of the Earth's surface. Whether their overall impact, in particular on the biosphere, was local or global, possibly extending to sterilization of Earth's surface environments, is debated (Abramov and Mojzsis 2009).

Cross-References

- [Archean Eon](#)
- [Archean Tectonics](#)
- [Barberton Greenstone Belt](#)
- [Chert](#)
- [Continental Crust](#)
- [Craton](#)
- [Earth, Formation, and Early Evolution](#)
- [Hydrothermal Environments](#)
- [Isua Supracrustal Belt](#)
- [Komatiite](#)
- [Late Heavy Bombardment](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygen Isotopes](#)
- [Pilbara Craton](#)
- [Silicon Isotopes](#)
- [Snowball Earth](#)
- [Weathering](#)

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Archean Eon

Hervé Martin¹ and Daniele L. Pinti²

¹Laboratoire Magmas et Volcans, Université Clermont Auvergne, OPGC, CNRS, IRD, Campus des Cézeaux, Aubière Cedex, France

²GEOTOP Research Center for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Greenstone belts · Komatiite · Plate tectonics · TTG · Sagduction

Synonyms

► [Precambrian](#)

Definition

The Archean (Archaean in British English) eon (the largest division of geological time defined in ► [stratigraphy](#)) is the second major period in geological history. Preceded by the ► [Hadean](#) eon and followed by the ► [Proterozoic eon](#), its beginning is usually taken as that corresponding to the age of the oldest preserved rocks, either the 4.0 Ga-old (Ga = 10⁹ years = billion years) ► [Acasta gneisses](#) (Canada) or the 3.85–3.80 Ga-old Amitsôq gneisses (Greenland).

Overview

The International Commission on Stratigraphy (ICS, July 2021) sets its beginning at the *Global Standard Stratigraphic Age* of 4.0 Ga, corresponding to the radiometric age of the gneiss of Acasta in Canada, though possible older rocks are those found in the ► [Nuvvuagittuq Greenstone Belt](#), Canada (4.3 Ga-old; O'Neil et al. 2008) (controversial). The transition to the Proterozoic is taken at 2.5 Ga (ICS, July 2021), which was thought to mark a major change in the Earth's geodynamic style and corresponds roughly to the ► [Great Oxygenation Event](#). The Archean eon thus encompasses an approximately 1.5-Ga-long period during which the oldest well-preserved rocks formed, and life likely originated. Together with the Hadean and the Proterozoic, it forms the supereon “Precambrian,” thence its synonym. Its tectonic style was different from today, with more abundant mantle plumes, greatly fragmented tectonic plates, and longer mid-oceanic ridges. The geochemical composition of some Archean rocks suggests plate tectonics could have started in this period that ► [plate tectonics](#) started in this period.

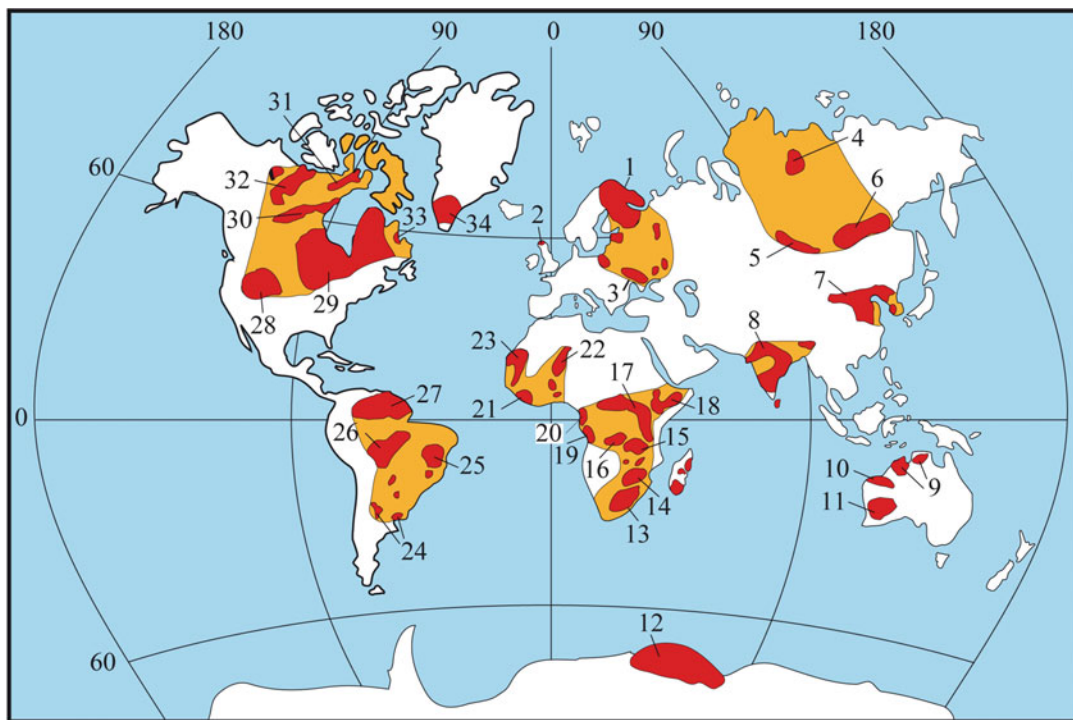
Geographical and Temporal Distribution of Archean Terranes

The Archean eon is characterized by the extraction from the mantle and the subsequent differentiation of significant amounts of ▶ [continental crust](#). Indeed, at the end of the Archean eon, probably about 75% of the juvenile continental crust had formed (e.g., Hawkesworth et al. 2020 for a review). Large parts of this Archean crust, named ▶ [cratons](#) or shields, have been preserved on all continents (Condie 1994; Fig. 1), including:

- In Europe, the 3.1–2.5 Ga-Baltic (sometimes referred to as Fennoscandian) and 3.8–3.2 Ga Ukrainian shields as well as a few outcrops in

northern Scotland (Lewisian gneisses in the Hebrides with a debated age of 3.52 ± 0.16 Ga)

- In Asia, the Siberian Aldan ▶ [Shield](#) (3.5–3.0 Ga), the Indian Dharwar (3.6–2.5 Ga), and the Sino-Korean cratons (3.8–3.0 Ga)
- In Australia, the Pilbara (3.6–2.5 Ga), Yilgarn (2.94–2.63 Ga), Gawler (2.5 Ga), and Northern Australia cratons
- In Antarctica, the Napier complex (orthogneisses dated at 3.95–2.46 Ga)
- In Africa, the Kaapvaal (3.6–2.5 Ga), Zimbabwe (3.5–2.5 Ga), and Madagascar cratons, as well as the Central and West Africa cratons



Archean Eon, Fig. 1 Distribution of Archean provinces (after Condie 1994; redrawn by Martin 1994). The exposed Archean terranes are in red, and the areas underlain by Archean rocks are in orange. (1) Baltic Shield; (2) Scottish Shield; (3) Ukrainian Shield; (4) Anabar Shield; (5) Baikal, Sayan, and Yienisei fold belts; (6) Aldan Shield; (7) Sino-Korean, Tarim, and Yangtze cratons; (8) Indian Shield; (9) Litchfield, Rul Jungle and Nanambu Complexes; (10) Pilbara block; (11) Yilgarn block; (12) Napier Complex; (13) Kaapvaal Craton; (14) Zimbabwe Craton;

(15) Zambian Block; (16) Kasāi Craton; (17) Central Africa Craton; (18) Ethiopian Block; (19) Chaillu Craton; (20) Cameroon N'tem Complex; (21) Man Shield; (22) Tuareg Shield; (23) Reguibat Shield; (24) Rio de la Plata and Luis Alves Massifs; (25) São Francisco Craton; (26) Guapore Craton; (27) Guiana Shield; (28) Wyoming Province; (29) Superior Province; (30) Kaminak Group; (31) Committe Bay Block; (32) Slave Province; (33) Labrador Shield; (34) Greenland Shield

- In South America, the São Francisco and Amazonian cratons (3.5–2.4 Ga) in Brazil and the 3.4 Ga Guyana Shield
- In North America, the Wyoming Province, USA (3.5–2.5 Ga); the Superior Province ((4.3)3.7–2.7 Ga); the Slave Province (dominated by 2.73–2.63 Ga greenstone sequences but with the ► [Acasta gneisses](#) dated to 4.03 Ga); the Labrador Shield (Canada) with the 3.9–3.7 Ga Iqaluk and Uivak gneisses of the Saglek-Hebron complex; and the Greenland Shield (3.8–2.6 Ga with older units at ► [Akilia](#) and Isua up to 3.88 Ga)

Among the Archean terrains older than 3.8 Ga, the largest continuous exposures are the Amitsoq gneisses in Greenland, which covers an area of 3000 km². The protolith of these rocks consists of older granitoids, metamorphosed into gneisses with emplacement ages of 3.822 ± 0.005 Ga. The oldest supracrustal rocks (volcaniclastic and sedimentary) are in Akilia island and the Isua supracrustal belt with older ages at 3.872 ± 0.010 Ga, together with banded iron formation of the Nuvvuagittuq greenstone belt (3.817 ± 0.016 Ga or older). The recognized oldest rocks on the Earth (covering a surface of about 20 km²) are the ► [Acasta gneisses](#) in Canada (Slave Province) with an age of 4.030 ± 0.003 Ga (Bowring and Williams 1999), while the oldest known minerals are the famous Jack Hills detrital zircons (Western Australia) with recorded ages as old as 4.404 Ga (Wilde et al. 2001). Similarly, inherited cores in zircons from Acasta provided an age of 4.20 ± 0.06 Ga (Iizuka et al. 2006). Other hadean zircons were reported in Brazil (Paquette et al. 2015) and in India (Miller et al. 2018). Recently, the short-lived ¹⁴⁶Sm–¹⁴²Nd isotope system yields an isochron suggesting an age of 4.13 Ga for the Ujaraaluk unit (amphibolite rocks), outcropping in the ► [Nuvvuagittuq Greenstone Belt](#) (O’Neil et al. 2012), though this age is strongly disputed and debated (Cates et al. 2013; Guitreau et al. 2013).

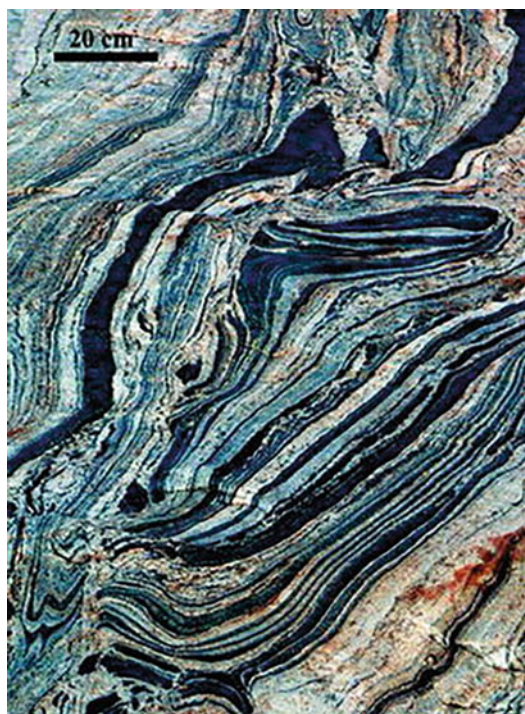
Geology of Archean Terranes

Archean terranes all show similar lithological associations, independent of their age: (1) granite-

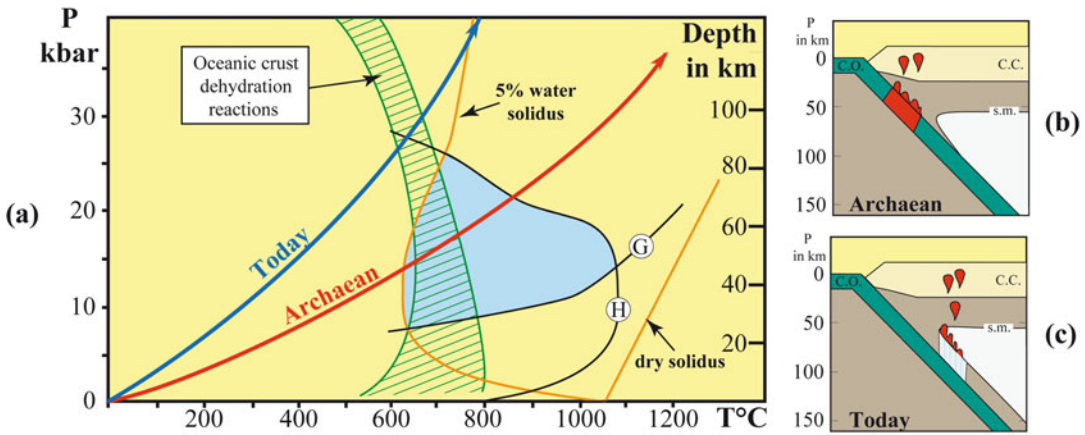
gneiss, (2) ► [greenstone belts](#), and (3) late granitoids. In addition, some show a cratonal cover.

The granitic gneisses are the most abundant, composing up to 80% of the Archean continental crust. Better known under the acronym TTG for ► [Tonalite-Trondhjemite-Granodiorite](#) association (Jahn et al. 1981), these rocks are coarse-grained, gray orthogneisses (which means derived from magmatic rocks, in this case granitoids) with well-developed banding consisting of the alternation of whitish quartz-plagioclase layers with gray to black biotite- and amphibole-rich layers (Fig. 2). Contrary to typical modern granites, the TTG contains a very low proportion of potassic feldspar (KAlSi₃O₈).

The parent magma from which TTG derived results from the melting at high pressure of a hydrated mafic rock of basaltic composition (Fig. 3a). Indeed, when the pressure increases, basalt is transformed into amphibolite



Archean Eon, Fig. 2 Photo of typical gray gneisses (TTG) from Sand River, Limpopo, South Africa. These 3.283 ± 0.008 Ga-old rocks consist of the alternation of whitish quartz-plagioclase layers with gray biotite and amphibole-rich layers. (Photo H. Martin)



Archean Eon, Fig. 3 Pressure-temperature (P-T) diagram and schematic cross-section of both Archean (b) and modern (c) subduction zones. (a) The P-T diagram shows the dry and 5% hydrous solidus of tholeiite as well as main dehydration reactions of the oceanic lithosphere. Abbreviations: H is hornblende out, A is anthophyllite out, C is chlorite out, Ta is talc out, Tr is tremolite out, Z is zoisite out. G outlines the stability field of garnet. The blue field is the P-T domain where slab melts can coexist with hornblende- and garnet-bearing residue. In the Archean (inset b), the geothermal gradient along the Benioff plane

was very high; the subducted slab melted at shallow depth before dehydration could take place. After 2.5 Ga, Earth was cooler and the geothermal gradient along the Benioff plane was lower (inset c) such that slab dehydration generally occurred before its melting began. The liberated volatiles (mainly water) ascended through the mantle wedge, thus lowering its solidus temperature, which induced its melting. Abbreviations: CO is oceanic crust, CC is continental crust, sm is solidus of hydrated mantle, and red teardrops indicate magma

(amphibole $\pm$ garnet $\pm$ plagioclase feldspar-rich rock) and then into eclogite (pyroxene + garnet rock). These products melt to give the parental magmas of TTG (e.g., Martin and Moyen 2002). Although all geologists agree on the basaltic source of TTG, the geodynamic environment where melting took place is still debated: (1) $\blacktriangleright$ **basalts** from a subducted oceanic crust (Fig. 3; Martin 1994; Martin and Moyen 2002); or (2) underplated basalts melted during the passage over a mantle plume (Smithies 2000). The first hypothesis appears realistic since the Archean heat production was several times greater than today. This assertion is inferred by the genesis of high-temperature (Mg-rich) magmatic rocks called $\blacktriangleright$ **komatiite**, during the Archean, which require a mantle 100–350 °C hotter than today (e.g., Arndt et al. 2008). It is also consistent with the subduction of young and consequently hotter oceanic plates.

In modern tectonic regimes, the subducted plate is old and cold, such that it dehydrates during its descent into the mantle. Volatiles, mainly water, are liberated and ascend through the mantle

wedge, lowering its melting temperature (the mantle wedge lies between the descending or subducting oceanic plate and the continental (or oceanic) plate). Mantle wedge melting generates magmas with andesitic to granitic compositions that are accreted to form new continental crust (Fig. 3b). Modern subduction systems (both mantle and oceanic crust) are normally too cold to allow the subducted basalt to melt. If a hotter Archean mantle associated or not to the subduction of a younger oceanic crust is assumed, then the latter cannot rapidly dehydrate and direct melting of hydrated basalts is possible, resulting in TTG magma genesis (Fig. 3c).

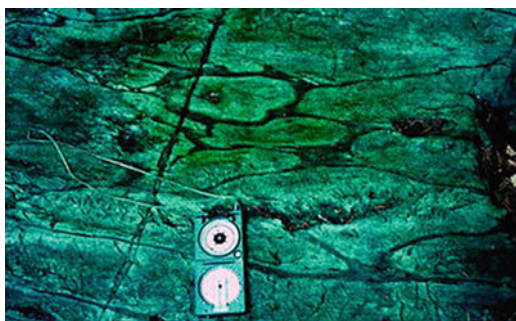
$\blacktriangleright$ **Greenstone belts** represent only 5–10% of the Archean terrains. These elongated structures (typically $>100 \times 20$ km) contain variable amounts of metamorphosed mafic to ultramafic volcanic sequences associated with sedimentary rocks. The name “greenstone” comes from the green hue imparted by the color of the metamorphic minerals within the mafic rocks. Chlorite, actinolite, and other green amphiboles are the usual green minerals. In some cases, greenstone

belts show a specific stratigraphic sequence, with ultramafic lavas (komatiites) at the base of the sequence, followed by basalts (often erupted under water with typical pillow structures). Variably metamorphosed sedimentary rocks (► [metasediments](#)) are emplaced at the top of the sequence. Greenstone belts are in complex contact relationships with adjacent plutons or metamorphic rocks: commonly, the contacts are structurally modified (thinned or thickened) contact-metamorphism aureoles; brittle-ductile fault planes are also common.

► [Komatiites](#) are ultramafic volcanic rocks (Arndt et al. 2008), almost exclusively restricted to the Archean eon, which are distinguished from the more common basalts by a higher content of MgO ($\geq 18\%$) and low content of most of the other elements. The high Mg content is explained by a higher degree of melting of the mantle; the melting temperatures of komatiites range between 100 °C and 1650 °C (Arndt et al. 2008) compared to 1100–1300 °C for modern basalts. Their occurrence demonstrates that the internal Earth heat production in the Archean was higher than today. After emplacement, these magmas cooled very rapidly, resulting in acicular and dendritic textures of olivine or pyroxenes phenocrysts, referred to as “spinifex” textures, which are typical of komatiites. Earth almost totally ceased to produce komatiites after 2.5 Ga. Archean mafic volcanics were mainly tholeiitic basalts (Fig. 4), while calc-alkaline lavas, in particular andesite, were rare. At the top of the sequence, more felsic rocks (dacites to rhyolites)

can occur interbedded within the sedimentary successions.

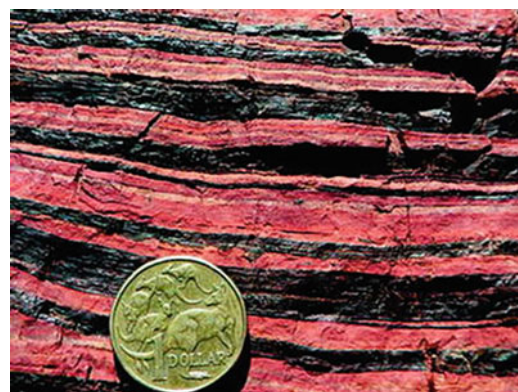
Sedimentary successions include thick lithic sandstones (also called litharenites which are sandstones containing more than 25% detrital rock fragments, and more rock fragments than feldspar grains) deposited in deep water as ► [turbidites](#) (Fig. 5) and in subordinate order, conglomerates. Well-preserved 3.5 Ga-old turbidites can be observed in the Komati River valley of the ► [Barberton Greenstone Belt](#), South Africa. They are overlain by and interbedded with siltstones, shales, ► [chert](#), and ► [banded iron formations](#) (BIF; Fig. 6). Cherts and BIF are common lithologies in Archean greenstone belts and are likely the result of intense hydrothermal activity



Archean Eon, Fig. 4 Pillow lavas of 2.65 Ga-old tholeiitic basalt from Kuhmo (Finland). (Photo H. Martin)



Archean Eon, Fig. 5 Clastic sediments (conglomerate) from the base of the 3.22 Ga-old Moodies group, Barberton, South Africa. (Photo H. Martin)



Archean Eon, Fig. 6 Banded Iron Formation (BIF) from Copping Gap (Australia). These rocks consist of alternating silica- and iron-rich layers. (Photo H. Martin)



Archean Eon, Fig. 7 Dyke of high-Mg granodiorite (sanukitoid) intrusive into the 2.65 Ga-old Kuhmo greenstone belt (Finland). (Photo H. Martin)

on the ocean floor (Westall 2005; Van Kranendonk 2006).

Both the TTG basement and the greenstone belts were later intruded by high-Mg granitoids or sanukitoids (Fig. 7). These calc-alkaline granites are rich in potassic feldspars and magnesium. They might have derived by melting of a mantle peridotite, whose initial composition was modified by assimilation of TTG (Martin et al. 2009).

Archean Geodynamics

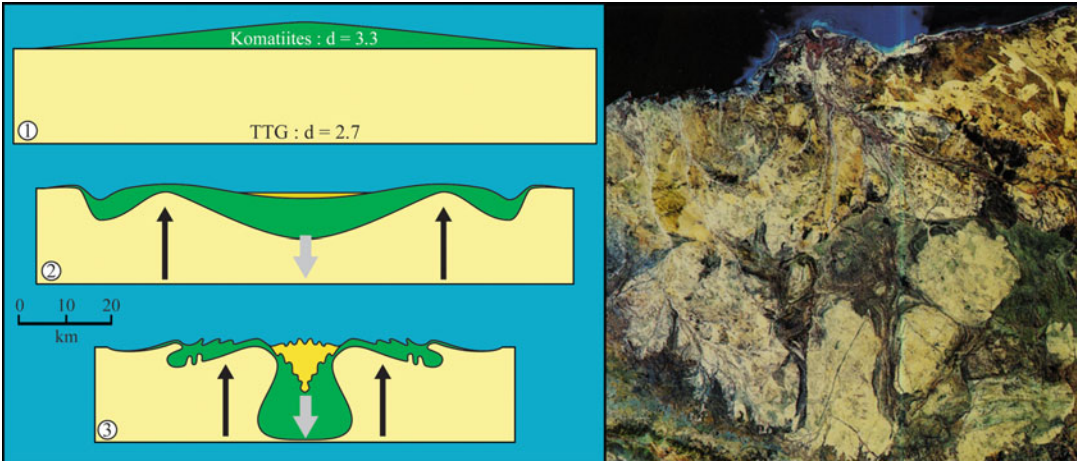
Modern plate tectonics induces horizontal forces that cause thrusting during orogenesis. These structures are known in most Archean terranes, indicating that tectonic forces similar to those controlling movement of modern tectonic plates could have operated since at least 3.8 Ga ago. However, Archean terranes also show large evidence of major vertical deformation that produces dome-and-basin structures (Fig. 8), which are exclusive to the Archean eon. This type of tectonics is driven by gravity (as opposed to plate tectonics which is driven by mantle convection) and this process has been known as sagduction since the 1970s (Gorman et al. 1978). Sagduction structures result from the down motion of high-density greenstone terranes (such as komatiites; density = 3.3 g/cm^3) into the TTG basement (density = 2.7 g/cm^3) and the concomitant upward motion of low-density TTG into the greenstones creating inverse diapirs. At the top of the inverted diapirs, a basin is created allowing deposition of sedimentary rocks. Several authors

have suggested that horizontal forces acted mainly at the plate boundaries (as today) while sagduction processes were concentrated within plates.

Another difference compared with today is the supposed length of the mid-ocean ridges, that is, the divergent boundaries between two tectonic plates, where new oceanic crust is produced. Indeed, the large amounts of internal heat produced during the Archean eon had necessarily been released to the surface. Otherwise, the accumulated heat should have resulted in melting the external part of our planet, which is not attested by the geological record. Heat was certainly greater in those remote times than today because the latent heat of accretion and the heat derived from the radioactive decay of elements such as U, Th, and K, present in higher amounts (e.g., the uranium stock on Earth in the Hadean was twice the present-day one). As conduction is not efficient to evacuate the internal heat, Archean convection should have played this role and, as today, heat must have been released through the mid-ocean-ridge systems. As the amount of heat to evacuate was greater, it can be concluded that the excess of heat has been released through convective processes. Convection rate could have been slightly greater, but mainly the ridge length was significantly greater than today. Indeed, the amount of heat dissipated is correlated with the cubic square of the ridge length (Hargraves 1986). Because the Earth volume and surface did not significantly change since 4.5 Ga, it means that a greater ridge length was present to evacuate the larger amount of heat. In turn, a longer ridge system results in smaller tectonic plates (Fig. 9). Today, mid-oceanic ridges are the place of an intense hydrothermal activity, which is attested by the presence of black and white smokers. If the total ridge length was greater in the Archean, the hydrothermal activity should also be more vigorous; which is corroborated by the great abundance of hydrothermal cherts in all terrains older than 2.5 Ga.

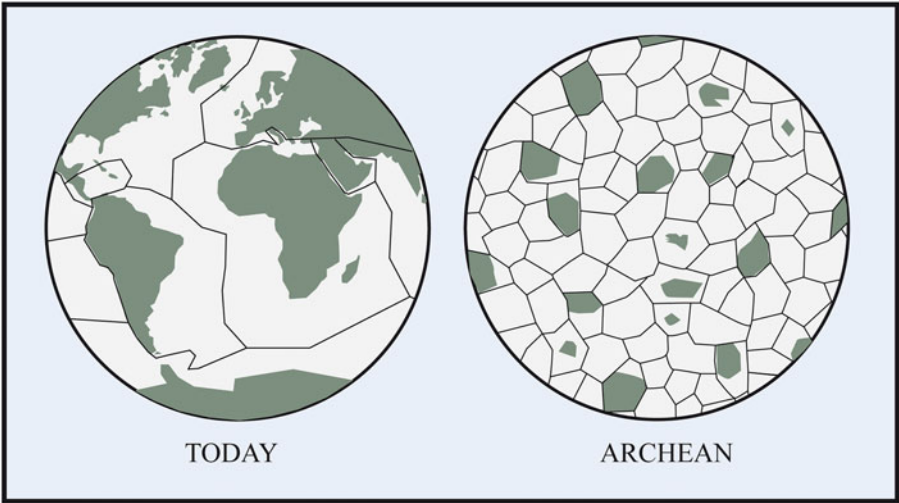
Hydrosphere, Atmosphere, and Climate

There is good evidence that oceans were present on the Earth already in the early Archean (~ 3.8 Ga ago) after the ► **Late Heavy Bombardment** (Abe



Archean Eon, Fig. 8 (Left) Sketch depicting the three main steps of sagduction: (1) In a greenstone belt, high-density komatiites ($d = 3.3 \text{ g/cm}^3$) emplace over lower-density ($d = 2.7 \text{ g/cm}^3$) TTG basement rocks, thus generating an inverse density gradient; (2) komatiites sink downward into the TTG basement, which favors a relative upward motion of the TTG; (3) the movement is amplified

creating a sedimentation basin at the center of the greenstone belt. Green is komatiites, pale yellow is TTG basement, and yellow gold is sediment. (Right) Satellite photo of the sagduction structures at the Pilbara craton, Western Australia. The greenstone belts (in dark green and black) are localized between TTG domes (yellowish). The width of the photo is $\sim 300 \text{ km}$



Archean Eon, Fig. 9 Sketch representing the size of the tectonic plates that presently cover the surface of the Earth (left) and that supposed for the Archean plates (right)

1993; Sleep et al. 2001), and possibly during most of the Hadean (e.g., Mojzsis et al. 2001; Wilde et al. 2001; Martin et al. 2006). The convincing evidence comes from one of the oldest areas of volcanic and sedimentary rocks on Earth – the ► **Isua**

Supracrustal Belt, Southwest Greenland. The ages of the rocks have been established at about 3.7–3.8 Ga. In the Isua Supracrustal Belt, pillow basalts provide evidence of underwater eruption and metasedimentary rocks (banded iron

formations, metapelite, and ferruginous quartzite) are the products of erosion, fluvial transport, and subaqueous deposition (Rosing et al. 1996).

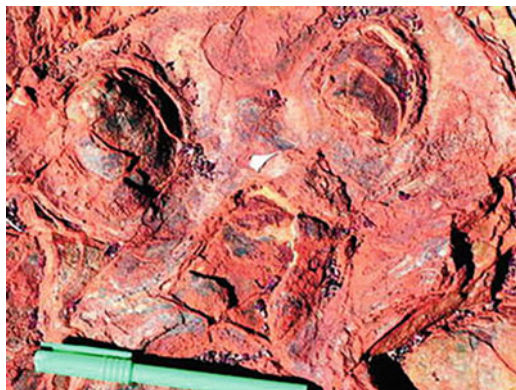
Primary fluid inclusions were found in quartz crystals in iron oxide structures from the 3.5 to 3.2 Ga ► [Barberton greenstone belt](#), South Africa (Channer et al. 1997), intra-pillow quartz from the Dresser Formation (3.49 Ga), ► [Pilbara craton](#), Western Australia (Furiel et al. 2004; Marty et al. 2018), and in the 2.7 Ga Abitibi Greenstone Belt, Ontario, Canada (Weiershauser and Spooner 2005). The analysis of major cations and anions indicates that the chemistry of the seawater was like today, but with some noticeable differences in iron, iodine, and bromine abundances indicating a larger influence of hydrothermal fluids (today, the chemistry of seawater is mainly controlled by weathering of continents with a minor role for hydrothermal fluids). Salinity was basically NaCl-dominated, though salinities up to ten times the present values have been measured, possibly related to seawater evaporation in closed basins (Furiel et al. 2004).

The secondary atmosphere of the Earth in the Archean was possibly mildly reduced. It was likely composed of N₂ and CO₂, with other gases (Ar, CH₄, H₂O, etc.) in minor amounts as observed today in the primitive atmospheres of Venus and Mars (Pinti 2021). The amount of N₂ was possibly close to the present level (Kasting 1993; Marty et al. 2013; Som et al. 2012) though it has been suggested that could have been as high as 2–3×, the present-day level (Wordsworth and Pierrehumbert 2013). The CO₂ concentration might have been up to 1% in volume or higher (Kasting 1987), while oxygen was likely ~1 parts per million by volume (ppmv) against the 21% today. Oxygen concentrations rose only at the end of Archean to values close to 1% of their present-day level, probably because of shifts in the competition between the production of oxygen derived from cyanobacteria photosynthesis and the rate of consumption of oxygen by reductants such as volcanic gases (e.g., Kump and Barley 2007). The amount of CO₂ in the atmosphere is still a matter of debate, but the occurrence of larger amounts of greenhouse gases (CO₂, CH₄) may have been needed in the Archean atmosphere to counterbalance the lower radiation from the

faint young Sun, which was ~30% less than the present-day value (Kasting 2010). Archean terranes do not contain evidence for major glaciations during the first two billion years of the Earth's history indicating that a warmer climate (as suggested by high ocean temperatures; Robert and Chaussidon 2006) dominated during the eon.

Traces of Life

Though the timing of the origin of life is unknown, the Archean world likely saw the emergence of the first organisms. Several morphological, molecular, and chemical traces of life punctuate the Archean sedimentary record. Currently, it is difficult to declare with certainty what the oldest trace of life is, and importantly what its nature and habitat were. Life can be traced unambiguously to approximately 2.7–3.0 Ga ago (Lopez-Garcia et al. 2006). Beyond this point, many claims for biological processes have been made, and all of them have to some degree been questioned. Some of the intriguing but controversial early Archean traces include (1) isotopically light graphite inclusions in rocks older than 3.8 Ga from Akilia island and the Isua Supracrustal Belt in southwest Greenland (Mojzsis et al. 1996; Van Zuilen et al. 2002); (2) kerogenous microstructures, stromatolites, and diverse stable isotope ratio anomalies in 3.5 Ga cherts from the Pilbara Granitoid-Greenstone Belt in Western Australia (Schopf 1993; Brasier et al. 2005; Ueno et al. 2006; Pinti et al. 2009) (Fig. 10); (3) kerogenous



Archean Eon, Fig. 10 3.5 Ga-old stromatolites from the North Pole (Pilbara, Australia)

microstructures, stromatolites, and diverse stable isotope ratio anomalies in cherts, as well as microscopic tubes in altered pillow basalts from the 3.4 to 3.2 Ga Barberton Greenstone Belt in South Africa (Staudigel et al. 2008); (4) in the Saglek-Hebron gneiss complex, based on carbon isotopic signatures of graphite and carbonates found in 3.95 Ga-metasedimentary rocks (Tashiro et al. 2017); (5) micrometer-scale hematite tubes and filaments – with morphologies similar to those of filamentous microorganisms from hydrothermal vent precipitates – found in BIFs from the Nuvvuagittuq Greenstone Belt (Dodd et al. 2017).

Basic Methodology

The knowledge of the primitive Earth has improved notably in the last 20 years, thanks to extensive U-Pb zircon geochronological studies which allowed identify new fragments of ancient cratons of the Archean age or even Hadean. Exposure of these terranes and the petrogenetic study of rocks by radiogenic and stable isotopic techniques are improving the general knowledge on the geological evolution of the ancient cratons. In particular, application of short-lived nuclides, such as $^{146-147}\text{Sm}$ - $^{142-143}\text{Nd}$, are evidences that Archean cratons could be the product of reworking of even older Hadean (≥ 4.2 Ga) mafic crust (e.g., O'Neil and Carlson 2017), pushing back in time the beginning of the differentiation of the continental crust, and possibly of potential habitats for primitive forms of life.

Key Research Findings

1. Most Archean terranes are composed of ► **Tonalite-Trondhjemite-Granodiorite** rocks (or TTG) of intermediate-felsic composition. Contrary to typical modern granites, the TTG contains a very low proportion of potassic feldspar. The parent magma from which TTG derived results from the melting at high pressure of hydrated basalts. The closest modern analogues of TTG are adakite that form in “hot

subduction” environment, that is, by melting of the basaltic oceanic crust subducting at low angle and thus reaching rapidly high temperatures able to melt the oceanic hydrated crust. Generation of TTGs suggest the occurrence of plate tectonics similar to the modern one;

2. Numerous Archean cratons show dome-and-basin structures suggesting vertical forces acting on the continental plates. This phenomenon called sagduction results from the down motion of high-density greenstone terranes composed of komatiites into the lighter TTG basement and the concomitant upward motion of low-density TTG into the high-density greenstones creating inverse diapirs. To reconcile these structures with the TTGs genesis in subduction-related environments, it has been suggested that horizontal forces acted mainly at the plate boundaries (as today) while sagduction processes were concentrated within plates;
3. The Archean mantle was 100–350 °C hotter than today as inferred by the occurrence of komatiite, high-temperature (Mg-rich) magmatic rocks typical and exclusive of the Archean eon, and TTGs which required a hotter mantle around subduction zones;
4. To dissipate the latent heat of accretion and higher heat fluxes provoked by decay of higher amounts of radioactive elements present in the crust than today, it has been suggested that mid-ocean ridges were longer and consequently tectonic plates, smaller than the present-day ones;
5. Occurrence of marine sediments such as turbidites and banded iron formation indicate that water environments were abundant in the Archean eon, where first life forms could have evolved; even if the origin of first micro (pseudo)fossils is largely debated, stromatolite forms in the Pilbara terrane of Australia strongly suggest that a biosphere was present.

Applications

The study of the Archean eon is extremely important because there are evidence of a planet progressively evolving towards geological

complexity: a continental crust formed and differentiated from primitive Hadean mafic crust; modern-like plate tectonics developed, contributing to exchange volatiles, metals, and other elements between the interior to the surface, possibly furnishing potential nutrients and energy fluxes to developing prokaryotic form of life; atmosphere-ocean system likely modified its chemistry towards less aggressive environments (lower salinity, acidity, etc.) preparing to its major change at the end of the eon, its oxygenation.

Future Directions

There are numerous open questions on the geological evolution of Archean environments and potential habitats for life. Likely, research is moving in two main directions: (1) try to answer the still very much debated question, when and how modern-like plate tectonics started? (2) are there surface environments sufficiently preserved from geological and tectonic forces that could have preserved pristine forms of life that could help in rebuilding back the tree of life on our planet?

Cross-References

- [Akilia](#)
- [Amphibolite Facies](#)
- [Archean Traces of Life](#)
- [Barberton Greenstone Belt](#)
- [Basalt](#)
- [Canadian Precambrian Shield](#)
- [Chronological History of Life on Earth](#)
- [Craton](#)
- [Earth, Formation, and Early Evolution](#)
- [Gneiss](#)
- [Granite](#)
- [Greenstone Belt](#)
- [Igneous Rock](#)
- [Isua Supracrustal Belt](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Metasediment](#)
- [Pilbara Craton](#)
- [Pillow Lava](#)

- [Shield](#)
- [Volcaniclastic Sediment](#)

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Archean Mantle

Nicholas Arndt¹ and Daniele L. Pinti²

¹Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

²GEOTOP Research Center on the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Archean mantle · Convection · Archean thermal regime · Continental crust extraction · Oxidation state

Definition

Archean mantle refers to the terrestrial mantle during the Archean eon, which differed both physically and chemically from the modern-day mantle.

Overview

The mantle is that part of Earth or other planets which is between the ► [crust](#) and the core. The upper mantle, from the base of the crust at about 9 km (oceanic) or 30 km (continental) to the transition zone at 660 km, is composed mainly of ► [peridotite](#), an ultramafic rock mainly composed of ► [olivine](#) ((Mg,Fe)₂ SiO₄), pyroxene ((Mg, Fe, Ca) SiO₃), and minor garnet ((Mg, Fe, Ca)₃ Al₂ (SiO₄)₃). In the lower mantle, which extends to the core at 2990 km, the minerals are mainly Mg- and Ca-perovskite ((Mg,Ca)TiO₃) and magnesio-wüstite ((Mg, Fe)O). The mantle is solid except for localized zones of partial melting, but it convects with velocities of a few tens of centimeters per year.

The Archean mantle differed from the modern mantle in several important ways. Because the main sources of heat – ► [radioactivity](#), residual heat from accretion, and core crystallization – were more active than today, the mantle was hotter and it convected more vigorously. Higher temperatures in mantle upwelling beneath ► [mid-ocean ridges](#) produced larger melt volumes and a thicker oceanic crust. Higher temperatures at depth may have resulted in larger and hotter mantle plumes. The abundance of ► [komatiite](#) only in the Archean provides evidence of higher mantle temperatures.

The composition may also have been different, if, as many authors believe, the continental crust was less voluminous through the Archean. Continental crust contains far higher concentrations of elements such as Si, Al, K, and the “incompatible” trace elements, and the segregation of this crust has left the upper part of the modern mantle depleted in these elements. If crustal growth were incomplete in the Archean, either the volume of depleted mantle or the degree of depletion would have been less. The isotopic composition of rocks from the Archean mantle should, in theory, cast some light on the problem but at present, the message is ambiguous. The Hf isotope compositions of zircons show evidence of extraction prior to 4 Ga ago of enriched material, perhaps continental crust; the Nd isotopic compositions of rocks from the oldest areas of West Greenland have been interpreted to indicate derivation from strongly depleted mantle. Either these rocks were extracted from a small and localized volume of mantle or a large volume of continental crust had formed at this time.

If the mantle was significantly hotter, it would have been drier because the reactions that liberate water in upwelling mantle, where degassing takes place, or in subduction zones, where the mantle is rehydrated, are temperature-dependent. The proportion of water on the surface was larger and therefore the volume of the oceans may have been greater. The oxidation state of the Archean mantle has been investigated using redox-sensitive elements such as vanadium; no significant difference from that of the modern mantle has been established.

Cross-References

- [Archean Environmental Conditions](#)
- [Archean Eon](#)
- [Archean Tectonics](#)
- [Isua Supracrustal Belt](#)
- [Jack Hills \(Yilgarn Craton, Western Australia\)](#)
- [Komatiite](#)
- [Mantle, Oxidation of](#)
- [Peridotite](#)
- [Ultramafic Rocks](#)

Archean Tectonics

Martin J. Van Kranendonk
School of Biological, Earth and Environmental
Sciences, University of New South Wales,
Sydney, NSW, Australia

Keywords

Archean · Continents · Crust · Lithosphere ·
Non-uniformitarian · Plate tectonics ·
Tectonics · Thermal evolution of the Earth ·
TTG

Synonyms

[Crustal deformation](#); [Early earth](#)

Definition

Archean tectonics is the study of the formation, interaction, and deformation of the Earth's continental and oceanic crust during early Earth history (the Archean Eon; ca. 4.0–2.5 Ga) and the driving forces behind these processes, including mantle plumes, subduction, and accretion/collision. This topic remains highly controversial due, in part, to a fragmentary rock record, but also to nonunique interpretations of complex geological datasets in the absence of actualistic plate configurations. Historically, Archean tectonics has been polarized into uniformitarian (i.e., analogous with modern, or Phanerozoic Earth) and non-uniformitarian views, but recent studies have favored modern

Earth processes in the Archean, complicated by problems arising mainly from greater heat production and higher mantle temperatures (Condie 1994; Benn et al. 2006; Brown and Rushmer 2006). The discussion revolves around the basic question if and how tectonics in the Archean was different from modern-style plate tectonics.

History

Although the relative antiquity of some parts of the continental crust was recognized more than 150 years ago (Logan 1857), it was not until the advent of radiometric dating, 100 years later, that the antiquity of much of the continental crust was fully appreciated (Stockwell 1961). Only in the past decade it has been discovered that the preserved crustal record on Earth extends back to within 150 Ma of the age of formation of the Solar System (Wilde et al. 2001). Early geological studies found that continental crust older than about 2.5 Ga was different from younger crust. Archean crust showed distinct regional patterns defined by overlapping, elliptical areas of granitic rocks (gregarious batholiths; Macgregor 1951); steeply dipping, generally synclinal, greenstone keels (granite-greenstone crust: Hickman 1984; Chardon et al. 1996); and a unique type of ultramafic lava known as ► [komatiite](#) derived from high-temperature mantle melts (Viljoen and Viljoen 1969; Arndt 2003). Many authors also noted that Archean granite-greenstone crust lacked the diagnostic features of modern subduction/collision zones, including accretionary tectonic mélange, ophiolites, and high-pressure/low-temperature metamorphism, leading some to suggest – even recently – that plate tectonics either did not operate in the Archean (Hamilton 1998; McCall 2003; Stern 2005) or operated in conjunction with other processes (e.g., Rey et al. 2003; Sandiford et al. 2004).

Overview

The Archean ► [mantle](#) was probably 100–300 K hotter than today, which significantly affected the

dominant tectonic style. Geochemical, geophysical, and modeling evidence suggests some form of ► [plate tectonics](#) in the Archean, although the absence of key characteristics such as ophiolites and blueschists implies that it probably differed from modern ► [plate tectonics](#). Evidence for Archean plate tectonics was recognized quite early on in the type of Archean ► [crust](#) known as high-grade gneiss terranes. This evidence included the presence of large-scale recumbent isoclinal folds associated with crustal thickening (Bridgwater et al. 1974; Myers 1976; Wilks 1988; Hanmer and Greene 2002), voluminous sodic granitoids derived from high-pressure melting of basalt (Martin et al. 2005; Rapp et al. 1991), high-pressure metamorphism (Riciputi et al. 1990; Harley 2003), and structures consistent with terrane accretion (Nutman et al. 2002; Windley and Garde 2009). Over the past three decades, abundant evidence for Archean plate tectonics has also been found in some Archean granite-greenstone terrains in the form of thrusts and recumbent isoclinal folds, coupled high-pressure-low-temperature metamorphism, fossil subduction zones, accreted terranes, rift sequences, and subduction-zone magmatism (Card 1990; Heubeck and Lowe 1994; Calvert et al. 1995; Smithies et al. 2005; Moyen et al. 2006; Wyman et al. 2006; Van Kranendonk 2007; Van Kranendonk et al. 2010). However, an absence of hallmark characteristics of modern subduction-accretion zones in many granite-greenstone terrains (Hamilton 1998; McCall 2003; Stern 2005), the autochthonous nature of some major greenstone successions, and suggestions that mantle roots form through in situ melting events rather than through subduction stacking indicates local crustal development as volcanic plateaus developed on top of older continental basement (e.g., Blenkinsop et al. 1993; Bleeker et al. 1999; Van Kranendonk et al. 2007). Indeed, many studies suggest that some pieces of Archean crust contain features that cannot be ascribed to uniformitarian, Phanerozoic-type, plate tectonics, but rather formed as a result of large-scale intra-crustal differentiation accompanying periods of mantle-plume-related magmatism (Stein and Hofmann 1994; Whalen et al. 2002; Rey et al. 2003;

Smithies et al. 2009; Van Kranendonk et al. 2009). The fact that different processes have been recognized from studies of different pieces of Archean crust indicates that there was no single Archean tectonic process, but rather that – as with modern Earth – Archean continental crust formed through a variety of processes, including plate tectonics and mantle-derived upwellings, and probably through the interaction between these two end-member processes.

Basic Methodology

Direct field evidence from Archean continental lithosphere provides a record of Archean tectonic processes. Geophysical methods include paleomagnetism and seismic evidence. Solidifying magma registers the paleo-latitude and thus can record (relative) continental motion. Seismic profiles through Archean crust indicate the presence of dipping seismic reflectors, which could be interpreted as the remnants of a fossil subduction zone. Among the geological evidence, ophiolites (slivers of oceanic lithosphere that escaped subduction), blueschists, and ultrahigh-pressure metamorphic rocks (partly subducted rocks that emerged again at the Earth's surface) are all well-understood features associated with modern plate tectonics. Their occurrence throughout Earth's history is thought to provide clear indicators of plate-tectonic activity. Large-scale tectonic structures can be indicative as well: linear structures are often interpreted as remnants of subduction trenches, whereas large oval-shape structures are thought to be diapir- or dome-related that might not need any plate-tectonic activity.

Geochemical and petrologic techniques provide the “fingerprints” of the chemical processes associated with Archean tectonics. Mantle melting will deplete the mantle of “incompatible” elements (Rollinson 2007). Another form of element separation occurs due to differences in fluid mobility, so that some elements will preferentially move with any pore fluids, while others will stay in the residue. These processes will leave geochemical fingerprints that can be used to recognize ancient subduction processes (e.g., Shirey

et al. 2008). In addition, geochemical dating of crustal rocks and mantle material shows how mantle material was depleted through time by continent formation. Since continents today are formed primarily at subduction zones, this has been interpreted as another indication for the presence of ancient subduction and therefore plate tectonics.

Various modeling techniques are used to further constrain the range of dynamically viable tectonic processes during the Archean. Tectonic vigor is related to mantle convection and intimately couples to the cooling rate of the Earth: tectonic activity leads to increased heat loss from the mantle, and mantle temperature influences the vigor of tectonic activity. Mantle temperature through time therefore provides an important constraint, and parameterized and numerical modeling techniques provide a means to link mantle temperature and tectonic activity. Today's plate tectonics is primarily driven by the subduction process, and subduction dynamics is, to a large extent, influenced by mantle temperature due to melting events and the temperature-dependent strength of the lithosphere. The viability and style of subduction in an early, hotter Earth is investigated using parameterized and numerical modeling techniques.

Key Research Findings

Field evidence has been used to argue for or against modern-style plate tectonics in the Archean. Ophiolites are preserved pieces of old oceanic lithosphere that escaped subduction, and the occurrence of old ophiolites is therefore a clear indicator of plate-tectonic activity. They are widespread since ~1 Ga, but are much rarer before that. Recently, Furnes et al. (2007) reported a 3.8 Ga-old ophiolite in Isua, West Greenland, although their interpretation has been disputed. Other direct types of evidence for plate tectonics are blueschists and ultrahigh-pressure metamorphic rocks, which are both generally believed to form within subduction zones, where they are brought down to large pressures and temperatures, and subsequently make it back to the surface. The

oldest blueschists are ca. 850–700 Ma old, while the oldest UHP localities are ~600 Ma old. These data could indicate that modern-style plate tectonics did not start until the Neoproterozoic (Stern 2005) or that the appearance of plate tectonics evolved over time (van Hunen and van den Berg 2008).

Earth's thermal evolution provides further constraints. Today, plate tectonics forms the dominant cooling mechanism for the Earth and is therefore closely linked to the thermal evolution of the Earth. The Archean Earth had an amount of radiogenic heat production two to three times larger than today due to the gradual decay of the dominant heat-producing elements uranium, thorium, and potassium in the mantle. Today, the surface geothermal heat flux (heat escaping the Earth's interior) is ~30% provided by internal radiogenic heating while the remaining 70% comes from cooling of the Earth (Turcotte and Schubert 2002; Korenaga 2006). This shows that surface heat flow from radiogenic heating was a lot more important in the Archean which implies that either surface tectonics were such that the total surface heat flux was higher or that Earth was not cooling (significantly) or was perhaps even heating up. Inferred liquidus temperatures from ophiolites and greenstone belts suggest a gradual mantle temperature drop of ~200 K since the Archean. Komatiitic melt data suggest a mantle potential temperature (i.e., mantle T extrapolated to surface P , T -conditions) reduction by ~300 K for dry melting to ~100 K if melting took place under much wetter conditions. Jaupart et al. (2007) provide a recent overview of the thermal evolution of the Earth.

The dynamical viability of subduction in the Archean has been questioned. Today, plate tectonics is primarily driven by dense slabs sinking into the mantle, and thereby pulling the trailing lithosphere across the surface. Archean plate tectonics would require a similar driving mechanism. A hotter mantle provides more melt and therefore a thicker, low-density mafic crust (up to 20 km thick instead of today's 5–8 km) that doesn't easily subduct. Although dehydration during melting will make the plate compositionally stronger and could allow for similar plate-tectonic rates in the Archean as today (Korenaga 2006), thermal weakening would probably dominate if the mantle

was substantially hotter and would result in weaker plates. The combined buoyancy and plate strength effects make subduction inefficient for mantle temperatures more than 150 K hotter than today (van Hunen and van den Berg 2008).

Today's continental crustal rocks (loosely termed andesites) differ significantly in trace-element composition from their Archean counterparts (trondhjemite-tonalite-granodiorite, or TTGs). Whereas andesites are thought to ultimately derive from melting in the hydrated supra-subduction mantle wedge, TTGs seem to form from wet melting of oceanic basalts at sometimes >50 km depth, and the most popular formation model is melting of subducting oceanic crust (Foley et al. 2002). So the differences between modern and Archean continental crust suggest a secular evolution of the subduction process. But at the same time, it indicates the need for a process to bring fluids to 50–100 km depth throughout the Earth's history. At present, no other mechanism than subduction seems capable of doing that, which is regarded as one of the strong arguments in favor of Archean plate tectonics.

However, although most studies support Archean plate tectonics, perhaps in some modified form, the possibility of other dominant tectonic processes should not be excluded. If indeed plate tectonics were absent in the Archean, such alternative tectonic models were probably essential to provide a mechanism for the observed steady mantle cooling of 50–100 K/Gyr. One popular model is the crustal delamination model (e.g., Zegers and van Keken 2001), in which mantle melting events would thicken the continental crust until its base becomes gravitationally unstable and would cause lithospheric overturn. Such models would explain observations from early Archean rocks such as the ovoid-shaped intrusions in the eastern Pilbara craton.

Applications

The style and vigor of tectonics in the Archean has important consequences for many aspects of the evolution of the Earth. Tectonic style directly influences (a) how and when continents formed

and why cratons remained stable and preserved over much of the Earth's history (Lenardic et al. 2003); (b) how tectonics-related events such as melting, remelting, and fluid-related alteration has changed the composition of the mantle from its primitive composition shortly after core formation to its modern composition (Shirey et al. 2008); and (c) the composition of the atmosphere and oceans through ► **degassing** (during volcanism) and regassing (at subduction zones) of volatiles and surface weathering (Lowe and Tice 2007; Rollinson 2007), and through that the emergence and evolution of life on Earth. Furthermore, if plate tectonics has been operative throughout the changing conditions of the Earth during its history, how does that relate to the viability of plate tectonics on the other terrestrial planets of our solar system, such as on Mars (which has no plate tectonics today, but might have had some during its earliest history) or Venus (which doesn't have plate tectonics, probably because of the lack of liquid water, but perhaps experiences episodic large-scale mantle overturns).

Future Directions

Integrated, four-dimensional lithospheric studies of Archean lithosphere are the key future research directions, particularly in poorly studied regions. Detailed geochronology within a well-established map framework continues to be key to understanding formation processes of ancient crust, particularly when coupled with ongoing reevaluation of uniformitarian assumptions given known aspects of secular change. Hf isotope determination of zircon can help discriminate juvenile crustal growth through subduction from volcanism and crustal recycling during episodes of plume magmatism. Further understanding of crustal growth processes will be aided by more complete knowledge on the origin of subcontinental lithospheric mantle: detailed studies of primary dunite-harzburgite xenoliths are required to determine the age, composition, and history of these more depleted rocks, and their properties tied into detailed regional seismic studies, including physical modeling of their geophysical response.

Additional work is also required on the ► **metamorphism** of granite-greenstone terranes, specifically precise dating of mineral assemblages related to magmatic and deformational events and P-T studies of granitic rocks as a counterpart to greenstones, to test models of cold greenstone diapirs in hot rising granites (partial convective overturn; Smithies et al. 2009). Additional studies are required on the origin of Archean calc-alkaline felsic volcanic rocks and high-Mg diorites to establish whether they are really the products of volcanic arc magmatism over an active subduction zone, as widely assumed, or the products of fractionation and crustal contamination of large tholeiitic magma chambers derived from mantle plumes. Additional research is required across the interval 3.3–2.9 Ga, in order to assess the tantalizing clues that there may have been a global change in crust-formation processes at this time, perhaps due to an increase in plate size and concomitant cooling of oceanic lithosphere and steepening of the angle of subducting oceanic lithosphere. Key open questions include the following: How did subduction initiate, and did plate tectonics remain operative from its first onset until today, or was it once more episodic (Sleep 2000)? Is the onset of plate tectonics related to any atmospheric and oceanic changes in the Archean, to the habitat that provided early life and its evolution, and to the presence of the Earth's magnetic field? How does Archean tectonics relate to the observed peaks in continental crust formation at 3.3, 2.7, 1.9, and 1.2 Ga (Condie 1998; Parman 2007)?

Cross-References

- **Continental Crust**
- **Degassing**
- **Komatiite**
- **Ophiolite**
- **Plate Tectonics**

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Areology

Ralf Jaumann
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Synonyms

[Geology of Mars](#)

Definition

Areology (Greek, *Ares* “Mars” and *logos* “speech, science”) is the science of the planet ► [Mars](#), excluding its atmosphere. It comprises the study of the structure, composition, physical properties,

dynamics, origin, and evolution of Mars as well as the processes that formed and shaped Mars. The term areology is not frequently used because scientifically and methodologically it is synonymous to the term “Geology of Mars.” Thus it is common to use the latter term instead of “areology.”

Cross-References

- [Chronostratigraphy](#)
- [Geological Time Scale, History of](#)
- [Mars](#)
- [Mars Stratigraphy](#)
- [Selenology](#)

Argentina Space Agency

- [CONAE, Argentina](#)

Argillaceous Earth

- [Clay](#)

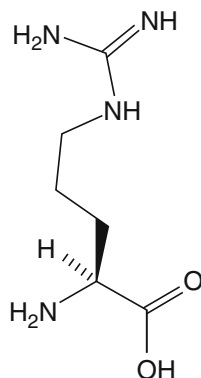
Arginine

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Arginine, shown in Fig. 1, is one of the 20 ► [protein amino acids](#). Its molecular weight is 174.21. Its three-letter symbol is Arg and one-letter symbol is R. It has a guanidinium group ($\text{H}_2\text{NC}(=\text{NH})\text{NH}_2$) in its side chain. The side chain is basic with a pK_a of 12.48. When protonated, the positive charge of the guanidinium ion is delocalized on the three nitrogen atoms. The isoelectric point (pI) of arginine is 10.76, which is the highest among the protein amino acids. Adult humans are able to biosynthesize arginine, but infants cannot. Thus, it is an essential amino acid

Arginine,
Fig. 1 Structural formula
of arginine



only for infants. To date, arginine has not been found in extraterrestrial bodies like carbonaceous chondrites.

Cross-References

- [Amino Acid](#)
- [Protein](#)

Argonium (ArH^+)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

ArH^+

Definition

Argonium is the argon hydride cation, ArH^+ . Argon has three naturally occurring isotopes, with the cosmically most abundant being ^{36}Ar , followed by ^{38}Ar , and then ^{40}Ar . On Earth, in contrast, ^{40}Ar is by far the most abundant isotope, derived primarily from the radioactive decay of ^{40}K . The K-Ar decay is important for geochronology. Argonium is the first noble gas molecule to have been found in space, with both the ^{36}Ar and the ^{38}Ar isotopologs observed by astronomers. Extensive laboratory studies of the rotational spectra and the electric

dipole moment have been carried out for both $^{36}\text{ArH}^+$ and $^{38}\text{ArH}^+$; ArH^+ is quite stable, with a dissociation energy of almost 4 eV.

History

Astronomically, argonium was first reported in the Crab Nebula, the remnant of the supernova observed by Chinese astronomers/astrologers in 1,054 CE (Barlow et al. 2013). The observed ^{36}Ar was presumably produced by ► [explosive nucleosynthesis](#) during the supernova event. Both $^{36}\text{ArH}^+$ and $^{38}\text{ArH}^+$ were more recently reported toward the Galactic Center molecular cloud SgrB2 (Schilke et al. 2014). Because ArH^+ reacts rapidly with molecular hydrogen, H_2 , but not at cold interstellar temperatures with atomic hydrogen, H, Schilke et al. suggest that ArH^+ may well be a useful tracer of the neutral atomic hydrogen in galaxies.

Cross-References

- [Geochronology](#)
- [Isotopolog](#)
- [Molecular Cloud](#)

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ArH^+

- [Argonium \(\$\text{ArH}^+\$ \)](#)

Ariel Space Mission

Theresa Lueftinger¹ and Giovanna Tinetti²

¹Science Division, Directorate of Science, European Space Research and Technology Centre (ESA/ESTEC), Noordwijk, The Netherlands

²Department of Physics & Astronomy, University College London (UCL), London, UK

Synonyms

Atmospheric remote-sensing infrared exoplanet large-survey

Definition

Ariel, the atmospheric remote-sensing infrared exoplanet large-survey, is the fourth medium class mission within ESA's Cosmic Vision science program. Ariel is the first mission dedicated to studying the atmospheres of a statistically large and diverse sample of transiting exoplanets (≥ 500) through a combination of transit photometry and spectroscopy. The Ariel mission has been adopted in November 2020 and is due for launch in 2029 on board an Ariane 6.2 from Europe's Spaceport Kourou.

Overview

The Ariel mission aims to address the fundamental questions on what exoplanets are made of and how planetary systems form and evolve by investigating the atmospheres of many hundreds of diverse planets orbiting different types of stars. This large and unbiased survey will contribute to answering the first of the four ambitious topics listed in the ESA's Cosmic Vision: "What are the conditions for planet formation and the emergence of life?". Thousands of exoplanets have now been discovered with a huge range of masses, sizes, and orbits: from rocky Earth-like planets to large gas giants grazing the surface of their host star. There is no known,

discernible pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star. It is not known to date, whether the chemistry of a planet's surface and atmosphere is linked to its formation environment, or whether the type of host star drives the physics and chemistry of the planet's birth and evolution. Ariel is expected to observe around a thousand transiting planets, including gas giants, Neptunes, super-Earths, and Earth-size planets around a range of host star types. This comprehensive approach will underpin statistical understanding generating robust conclusions which are simply not possible with smaller samples or patchy coverage of the relevant parameter space.

By characterizing exoplanet atmospheres, the Ariel mission will address three fundamental questions:

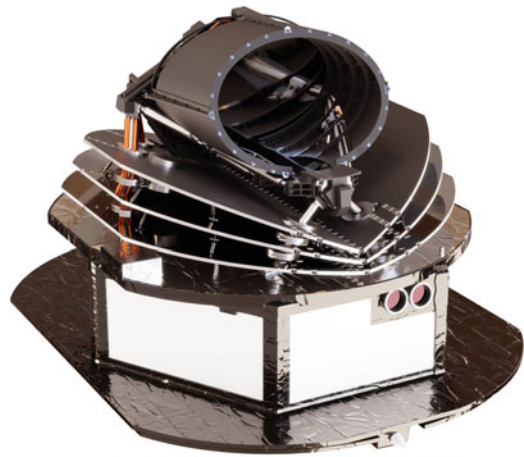
- *What are the physical processes shaping planetary atmospheres?*
- *What are exoplanets made of?*
- *How do planets and planetary systems form and evolve?*

Equipped with an off-axis Cassegrain telescope, 1.1 m $\times$ 0.73 m elliptical in size, Ariel will use transit spectroscopy in the 1.1–7.8 μ m spectral range and photometry in multiple narrow bands covering the optical and near-infrared (NIR). The focus will be on warm and hot planets to take advantage of their presumably well-mixed atmospheres which should show minimal condensation and sequestration of high-Z materials (materials with a high atomic number of protons in the nucleus) and thus have the potential to reveal their bulk elemental composition, especially C, O, N, S, Si). Observations of the upper atmospheres of these warm/hot exoplanets will drive understanding of the early stages of planetary and atmospheric formation during the nebular phase and the following few million years. Ariel will significantly improve the picture of the chemical nature of the exoplanets and relate this directly to the planetary parameters and the type and chemical environment of the host star.

For this ambitious scientific program, Ariel is designed as a dedicated survey mission for transit and eclipse spectroscopy, capable of observing a large and well-defined planet sample within its 4-year mission lifetime. Transit, eclipse, and phase-curve spectroscopy methods allow us to measure atmospheric signals from the planet at levels of 10–50 parts per million (ppm) relative to the star. Given the brightness of the target host stars more sophisticated techniques, such as eclipse mapping, will also be used to give deeper insights. These observations require a specifically designed, stable payload and satellite platform with broad, instantaneous wavelength coverage to detect many molecular species, probe the thermal structure, identify clouds, and monitor the stellar activity. The wavelength range covered by Ariel includes all the expected major atmospheric gases from, for example, H_2O , CO_2 , CH_4 , NH_3 , HCN , H_2S through to the more exotic metallic compounds, such as TiO , VO , and condensed species.

With the exquisite, multi-band, high-speed sampling of Ariel's Core Survey data also a variety of science can be executed in addition to the core scientific objectives of Ariel. It will be possible to gain new insights into stellar variability across the Hertzsprung-Russell Diagram, on phenomena related to stellar activity and stellar flares, exomoons, exorings, exocomets, and exotrojans or on dust clouds in catastrophically disintegrating exoplanets (CDEs), just to name a few.

Humans have been speculating about the cosmos and the possible existence of other worlds throughout recorded history, and probably for longer. Since the discovery of exoplanets in the 1990s this field of astronomy and planetary science has exploded, being one of the most exciting and dynamic. Currently we know over 4300 exoplanets orbiting in excess of 3000 host stars. We know the sizes of about three-fourths of these, and for about one-fifth we have mass information. Only for a few percent of all known exoplanets do we have both, enabling rudimentary conclusions about their bulk compositions, and comparison with models of planetary structure, and for even fewer do we have atmospheric information. We now stand at



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Ariel Space Mission, Fig. 1

the threshold of a revolution in our understanding of our place in the Universe: Ariel is the next step. Only by performing a chemical census of a large, diverse sample of about a thousand exoplanets, studying each as a world in its own right, and as a member of a (sub-)population, can we hope to understand how our own Solar System, and our own planet Earth, fit in the big picture of innumerable other worlds. We are the first generation to know that the ancient hypothesis about planets around other stars is true. We are also the first to be capable of studying these worlds. Ariel will seize this unique opportunity and enable transformative science in this exciting field (Fig. 1).

Cross-References

- [Atmosphere, Temperature Inversion](#)
- [Brown Dwarfs](#)
- [Exoplanet, Detection, and Characterization](#)
- [Habitability, Effect of Eccentricity](#)
- [Habitable Zone, Effect of Tidal Locking](#)
- [Hot Jupiters](#)
- [Hot Neptunes](#)
- [Kepler](#)
- [Planetary Migration](#)
- [Radial Velocity](#)
- [Spectroscopy](#)

- [Stellar Rotation](#)
- [Super-Earths](#)
- [Transit](#)
- [Transiting Planets](#)
- [VLT](#)

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Tinetti G, Eccleston P, Haswell C, Lagage P-O, Leconte J, Lüftinger T, Micela G et al Ariel: enabling planetary science across light-years

Aromatic Hydrocarbon

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

An aromatic hydrocarbon is a cyclic hydrocarbon where the series of saturated and unsaturated carbon-carbon bonds satisfies Hückel's rules, that is, where the number of electrons in double and triple bonds in the ring is $4n + 2$, where $n = 0$ or any positive integer. The name derives from the fact that the first such molecules discovered tended to have an aromatic odor. They are typically somewhat more stable than their hydrogen-saturated analogues. Aromatic hydrocarbons may be monocyclic or polycyclic.

Cross-References

- [Benzene \(C₆H₆\)](#)
- [PAH](#)

Arrhenius Plot

Jeffrey Bada

Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

In 1889, the Swedish chemist Svante Arrhenius showed that the rate of a chemical reaction as a function of temperature could be described by the equation

$$\ln k = \ln A - E_a/RT$$

where k is the reaction rate, R is the universal gas constant, E_a is the ► [activation energy](#) (the energy required in order for the reactants to react), T is the absolute temperature (in degrees K), and A is the so-called pre-exponential factor (associated with collision and transition state theory).

A plot of $\ln k$ versus $1/T$ often yields a straight line, the slope of which is equal to the activation energy of the reaction divided by the universal gas constant (E_a/R) and the y-intercept of which is equal to $\ln A$.

Cross-References

- [Activation Energy](#)

Arrhenius Svante

Gerda Horneck

DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

History

Svante August Arrhenius (1859–1927), Swedish scientist, received the Nobel Prize in Chemistry in 1903 “in recognition of the extraordinary services he has rendered to the advancement of chemistry by

his electrolytic theory of dissociation.” Among other achievements, Arrhenius is famous for the Arrhenius equation, which gives the dependence of the rate constant k of a chemical reaction on the temperature T (in K) and the activation energy of the reaction. For astrobiologists, Arrhenius is famous for his thoughts that microscopic forms of life, for example, ► [spores](#), can be propagated in space, driven by the radiation pressure from the Sun and thereby seeding life from one planet to another or even between planets of different stellar systems. Arrhenius based his considerations on the fact that the space between the planets of our Solar System is teeming with micron-sized cosmic dust particles, which at a critical size below $1.5\ \mu\text{m}$ would be blown away from the Sun with high speed pushed by radiation pressure of the Sun. Herewith Arrhenius provided a scientific rationale for the theory of ► [Panspermia](#), now called Radiopanspermia.

Cross-References

- [Arrhenius Plot](#)
- [Lithopanspermia](#)
- [Panspermia](#)
- [Spore](#)

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Arrokoth

Tanguy Bertrand¹ and Emmanuel Lellouch²

¹LESIA, Observatoire de Paris, Université PSL, CNRS, Observatoire de Paris, Meudon, France

²Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, Meudon, France

Keywords

Trans-Neptunian object · Complex organics · Protoplanetary disk

Definition

Arrokoth is a trans-Neptunian object located in the Kuiper belt. It became the farthest and most primitive object in the Solar System ever visited by a spacecraft when the New Horizons space probe conducted a flyby on 1 January 2019. It was previously named 2014 MU69, then Ultima Thule, and finally Arrokoth. The name Arrokoth means “sky,” in the Powhatan language, and was chosen to represent the Native American living in Maryland, where both New Horizons and the Hubble Space Telescope (which discovered Arrokoth in 2014) are operated.

Discovery

Arrokoth was discovered on 26 June 2014 by the New Horizons team, using the Hubble Space Telescope, as part of a search for a Kuiper belt object reachable by New Horizons after the Pluto flyby in 2015.

Orbit and Classification

Arrokoth orbits the Sun at an average distance of 44.6 astronomical units (AU), taking 297.7 years to complete a full orbit. Arrokoth's orbit is nearly circular (with an eccentricity of only 0.042), with a perihelion at 42.7 AU and an aphelion at 46.4 AU. Its orbital inclination is 2.45° . Arrokoth is classified as a member of the cold classical Kuiper belt (referring to its quasi-circular, near-ecliptic orbit), which represents a relic of the primordial Kuiper Belt.

Shape

Arrokoth's bilobate shape was initially established from stellar occultations in 2017 and 2018, and refined by the New Horizons flyby. Arrokoth is a contact binary 36 km long, consisting of two planetesimals connected by a narrow and bright neck. The two lobes were likely once two objects that merged in a slow collision. The larger lobe ($21 \times 20 \times 9$ km) is relatively

flattened and moderately elongated, whereas the smaller lobe ($15 \times 14 \times 10$ km) is less flattened. The cause of Arrokoth's unexpected flatness is uncertain, with various explanations involving sublimation or centrifugal forces. The longest axes of the two lobes are nearly aligned, suggesting that the lobes were mutually locked, likely due to tidal forces, before merging. From geomorphological analysis, the larger lobe appears to be an aggregate of 8 or so smaller units, each approximately 5 km across.

Mass and Density

In the lack of moons (with upper limits at the 100–180 m diameter out to 8000 km from Arrokoth), the mass and therefore density of Arrokoth remain unknown, though the bulk density is estimated to be very low, similar to that of comets (~ 0.6 g/cm³). A strict upper limit to the density is 1 g/cm³, otherwise the neck would be excessively compressed by the mutual gravity of the two lobes and the entire object would gravitationally collapse into a spheroid.

Rotation and Temperature

Arrokoth's rotation period is 15.938 hours. Its rotational axis is tilted 99° to its orbit. Consequently, as it orbits around the Sun, one pole of Arrokoth faces the Sun continuously while the other pole faces away.

The average surface temperature of Arrokoth at the time of New Horizons encounter is estimated to be around 42 K, with a maximum of around 60 K on the illuminated subsolar point. The mean brightness temperature on the winter night side was measured to be 29 ± 5 K, which implies thermal radiation from the subsurface.

Surface Composition and Appearance

Color and Composition

Preliminary HST observations in 2016 revealed that Arrokoth has a red coloration, similar to the

“ultra red” population of cold classical Kuiper belt objects. The red coloration is attributed to the presence of complex organic compounds, produced from the photolysis of various simple surface compounds by cosmic rays and ultraviolet solar radiation.

Spectral measurements from New Horizons revealed the single signature of methanol ice (noteworthy, water ice was not spectrally identified), a component that was also identified in a handful of other Centaurs/Trans-Neptunian objects, and Arrokoth spectra can be fit with mixtures of methanol with red and neutral materials.

In general, both lobes share the same properties in albedo, color, and composition. The mean 0.6 μ m reflectance of Arrokoth is 0.24 (similar for both lobes). However, at the resolution of the available imagery, the normal reflectance varies across the surface from 0.18 to 0.35 due to various discrete geological units and bright features.

Geology

Arrokoth has a smooth surface, with a general paucity of craters (about ten craters only were detected, and except for one, they are all smaller than 1 km). Craters' densities are smaller than those of most other small bodies. This suggests an ancient surface age (about 4 billion years), a dearth of Kuiper Belt objects <1 km, and a benign collisional environment, associated with the slow orbital speeds of Kuiper belt objects that could potentially have impacted Arrokoth (300 m/s).

Internal Structure

Arrokoth's interior is likely composed of mostly amorphous water ice and rocky material. Trace amounts of gaseous methane and other volatiles may also be present in the interior, trapped in water ice. Assuming that Arrokoth has an internal heat source caused by the radioactive decay of radionuclides and a comet-like porosity, trapped volatile gases would migrate outward and escape from the surface. The escaped gases may subsequently freeze and deposit on the surface.

Formation

As a classical cold Kuiper Belt object, Arrokoth likely formed near its current location and stayed there for the entire Solar System 4.6 Gyr age. As such, it has always been in a cold, weak-radiation environment. The flattened, weakly cratered, and aligned lobes indicate that Arrokoth never experienced a catastrophic collision. Instead, it was likely formed from a gentle (~m/s) collision from two objects born in the same local cloud of bodies, after tidal evolution of a close, co-orbiting binary. This hypothesis gives strong support to pebble cloud gravitational collapse models based on streaming or other instabilities, in which icy pebbles are slowed down due to gas-dust drag. The scenario is further supported by the lack of strong color or composition heterogeneity between the two lobes, as expected to result from the merging of two bodies from the same local cloud. The presence of topography geomorphological units on the larger object indicates that it had likely formed from the coalescence of smaller planetesimals prior to merging with the other object.

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Artificial Cell Division

Petra Schwille
Max Planck Institute of Biochemistry,
Martinsried, Germany

Synonyms

[Protocell Division](#); [Synthetic Cell Division](#)

Cross-References

- ▶ [67P/Churyumov–Gerasimenko](#)
- ▶ [Charon](#)
- ▶ [Pluto](#)
- ▶ [Trans-Neptunian Object](#)

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Definition

Artificial Cell Division is one of the most crucial tasks to be performed by an Artificial Cell in order to be considered alive or life-like. Besides self-assembly, self-organization, morphogenesis by energy dissipation, and the ability of self-sustenance by metabolism, self-replication is one of the necessary requirements for a chemical system to become biological. This usually consists of the two steps, division and regrowth. Division can be symmetric, that is, into equally sized daughters, or asymmetric, although every daughter needs to inherit sufficient resources to be able to regrow autonomously. Division is often considered to be – but is not necessarily – binary. In order to distinguish autonomous division from spontaneous fission induced by internal or external mechanical destabilization of the compartment, it needs to be coupled to energy dissipation within

the artificial cell. In biological systems, cell division is always coupled to information replication and indispensable for the maintenance and evolution of an organism.

History

In the most predominant perception today, artificial cells or protocells are composed of phospholipid or fatty acid membranes that enclose an aqueous compartment, resulting in small to giant vesicles (several 10 nm to several 10 μ m). There are many experimental approaches how to initiate and facilitate the division of such vesicles. Most importantly, the process itself requires sufficiently high forces to drive the mechanical transformation of the vesicle compartment, in particular to overcome surface tension. These forces can be brought about by surface-to-volume growth, for example, through the incorporation of fatty acids or lipids (Zhu and Szostak 2009; Castro et al. 2019), osmotic stress due to enzymatic reactions within (Miele et al. 2020), destabilization of the surface by active membrane-curvature induction (Litschel et al. 2018) or force-inducing elements within, such as active polymers (Kretschmer et al. 2019). Besides these membrane-enclosed artificial cells, it has previously been suggested that cell-like compartments could have formed and acquired functions of life without a membrane boundary (Oparin 1938). Coacervation or liquid-liquid phase separation may have been sufficient to confine reactions with the required properties of self-catalysis and metabolic self-sustenance by energy dissipation which may under certain conditions lead to autonomous growth and division (Zwicker et al. 2017). However, the lack of a selective boundary does not likely support such a system to emerge new functionality, nor protect informational identity as required for Darwinian evolution.

Cross-References

- Artificial Cells
- Self-Assembly
- Self-Replication

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Artificial Cells

- Cell Models
- Protocell

Artificial Chemistries

Pietro Speroni di Fenizio
CISUC, Department of Informatics Engineering,
University of Coimbra, Coimbra, Portugal

Keywords

Artificial chemistries · Artificial life ·
Evolution · Reaction network

Synonyms

Reaction network

Definition

Artificial chemistry (AC) is a field of research that studies systems that are similar to, and commonly a generalization of, chemical networks. Those studies are usually done through computer simulations which are also called artificial chemistries. An AC can be defined as triplet $\{M, R, A\}$, with M being the set of possible molecules (sometimes infinite), R the set of possible reactions, and A the algorithm (Dittrich et al. 2001).

Overview

Artificial chemistry grew as a field from the early 1990s. Different aims converged in producing this field.

One of the aims of artificial chemistry was to investigate evolution and the appearance of life. Some of the main questions that have been investigated deal with biology, proto-biology, and evolution and take a bottom-up approach to ► [artificial life](#):

- Can we generate an artificial chemistry that can generate an artificial life?
- What kind of chemistry can sustain life?
- How does the Darwinian evolutionary process depend upon the chemistry on which it is based?

Of course, as we extrapolate out of chemistry the basic network of relations that can produce life, this would eventually help to recognize life in different contexts.

Another, more general, aim was to study reaction networks. Reaction networks appear in multiple fields, but our ability to study them has generally been limited by a difficulty in solving differential equations where the number of different interacting elements (*diversity*, i.e., number of equations) were too high, and the quantity of each participating element in the reaction network (*population size*) was too low (which could lead to an element disappearing and the set of reactions changing). Some artificial chemistries investigated exactly this problem. As such the aim of

artificial chemistries has often been a qualitative study, looking for *what* sets of molecules would be present in the reactor, more than *how many* elements would be present for each type of element in the system (Fontana and Buss 1996).

Due to the computational difficulty in simulating a chemical system that is both unbounded in the complexity of the molecules involved and that permits a faithful representation of space, the field tends to be divided into two main subfields: Complex Artificial Chemistries and Spatial Artificial Chemistries.

Complex Artificial Chemistries are the most simple type of system and assume a well-mixed reactor. Each molecule is either present or absent, with no information about the position. Pairs of molecules are then randomly selected and reacted. Such a simple algorithm frees the computational resources permitting the presence of complex molecules, with different behaviors. It is not uncommon for artificial chemistries to study the behavior of little program strings with computational capabilities (traditionally lambda terms).

Spatial Artificial Chemistries traditionally study systems made up of many simple elements, floating in a 2D or in a 3D spatial environment. The basic elements (in some systems called *atoms*) can often link together creating long chains (usually called *molecules*). In the first pioneering works of Spatial Artificial Chemistries, the positions of the molecules were imprecise, as each molecule was generally assigned to a position on a lattice. Recent computational progress permitted a more faithful representation of the movement using differential equations (Fellermann 2009).

Basic Methodology

The methodology is slightly different for Spatial Artificial Chemistries and for Complex Artificial Chemistries.

Complex Artificial Chemistries, as mentioned before, are essentially reaction networks with a high diversity and a low population size. Such an AC can be defined as a triplet {molecules, reactions, algorithm}. Reactions are usually binary

(i.e., two molecules reacting and generating a third). Yet not all pair of molecules can react. When two molecules cannot react, they are said to be *elastic*. The basic algorithm is generally very simple:

1. Define a Soup S as a multiset of m molecules out of M .
2. Two molecules are randomly selected.
3. If the two molecules can react, a reaction takes place:
 1. The result of the reaction is inserted in the Soup.
 2. A random molecule is extracted from the Soup and eliminated.
4. Go to 2.

In many Artificial Chemistries, the reactions are catalytic, so when two molecules react, they are *not* taken away from the Soup while their product is added to the Soup (3a). Instead, the molecules catalytically induce the formation of the new molecule out of a substrate of basic material (too vast and ubiquitous to be explicitly modeled), while the disappearance (3b) would model the outflux due to molecules being washed away or breaking apart (Dittrich et al. 2001). This traditional structure has been strongly criticized (e.g., for not considering conservation of mass), and many alternatives have been offered but generally with only partial differences in the observed behavior. Traditionally the standard way to investigate such a system is to run it until no new molecule would be generated, at which point the resulting multiset is studied. Lately, a more advanced method has been to calculate all the possible sets where the system could stop (called organizations) and study the structure of the lattice of organizations and use this to map the movement of the artificial chemistry as time progresses (Kaleta 2009).

Spatial Artificial Chemistries start in general with a set of atoms, to which a position in space is randomly assigned. At each time step all the atoms are randomly moved, and when two atoms end up near each other, they have the possibility of colliding. Unless the system is superimposed on a lattice, the movement of the molecules would

follow a Brownian motion style of movement or a dissipative particle dynamic style, where the forces interacting on a molecule are taken into account in greater detail (Fellermann 2009).

Key Research Findings

The first result in AC is that there are sets of molecules, called *organizations*, which are qualitatively stable, in the sense that each molecule present in the set can be generated by the reactions inside the set and that all reactions inside the cell can only generate molecules that are already inside the cell. Such organizations form an algebraic lattice, and in the absence of external inputs, each experiment eventually leads to the system reaching one of those sets. As artificial chemistries can be represented using ordinary differential equations (ODE), it has been shown that fixed points in the ODE of the system exist only inside organizations. In other words, if we take a fixed point of the system, find the molecules that are present with a quantity higher than 0, and then this set of molecules forms an organization. Those results permit a preliminary study of an artificial chemistry by finding (through algebraic studies) the lattice of organizations and produce a map of the system on which it is possible to track the changes in the system (Dittrich and Speroni di Fenizio 2007).

Spatial Artificial Chemistries have been successfully used to model the lipid bilayer of cell membranes and to investigate the spontaneous emergence of artificial life protocells. More recently, experiments have been carried out generating protocells that are able to reproduce (Rasmussen et al. 2007).

Applications

While the long-term aim of artificial chemistry, to investigate the appearance of life, has not been reached, a number of partial findings were recognized as being useful in different fields. As Complex Artificial Chemistry can investigate reaction network with a high diversity, they are often the

right tool to study ► [biological networks](#). In particular, studies have been done on gene regulatory networks and the internal metabolism of a cell. In this regard, AC has started merging with the other tools inside systems biology and bioinformatics. Other studies have tried to consider social systems, language, and economical systems (Dittrich et al. [2001](#)).

Future Directions

Spatial Artificial Chemistries and Complex Artificial Chemistries are going in separate ways, mostly answering different questions about nature. Spatial Artificial Chemistries try to produce a minimal cell, but have not yet succeeded in generating a spontaneous emergence of a full Darwinian evolutionary system. So we can expect more research to go in this direction. Results in Complex Artificial Chemistries have been more connected with systems biology, and artificial chemistries have been used to explicitly study system biology models, and recent studies show that it is possible to use AC to build programmable systems made up of many interacting components. In the future, we can expect those two trends to merge, as scientists investigate chemistries that can evolve and that can be programmed to evolve.

Cross-References

- [Artificial Life](#)
- [Autopoiesis](#)
- [Biological Networks](#)
- [Chemical Reaction Network](#)
- [Darwin's Conception of the Origins of Life](#)
- [Evolution, Biological](#)

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Artificial Evolution

- [Evolution, In Vitro](#)

Artificial Life

Hugues Bersini
IRIDIA, Université Libre de Bruxelles, Brussels, Belgium

Keywords

Bioinformatics · Genetic algorithms · Networks · Self-replication · Software simulations · Von Neumann

Synonyms

[Life, artificial](#); [Theoretical biology](#)

Definition

Artificial ► [life](#) uses software simulation and, to a lesser degree, robotics in order to abstract and elucidate the fundamental mechanisms common to living organisms. It focuses on the rule-based mechanisms making life possible, supposedly neutral with respect to their underlying material embodiment, and to replicate them in a non-biochemical substrate. In artificial life, the

importance of the substrate is purposefully understated for the benefit of the function. Minimal life begins at the intersection of a series of processes that need to be isolated, differentiated, and duplicated as such in computers. Only software development and running make it possible to understand the way these processes are intimately interconnected in order for life to appear at the crossroads.

Overview

Artificial life obviously relates to astrobiology; this other recent interdisciplinary field of scientific research equally centered on life and the study of its origins, not only on the obvious environment of Earth but also throughout the universe. Astrobiology cannot restrict itself to a mere materialistic view of life, in order to detect it elsewhere, as the material substrate could be something totally different. This substrate could be as much singular on a distant planet as it could be in the RAM memory somewhere in a university computer laboratory. The presence of life might be suspected through its functions, much before scientists are able to dissect it. Artificial life does not attempt to provide an extra thousandth attempt at the definition of life, any more than do most biologists. As a matter of fact, the concept of “life,” as opposed to “gravity” or “electromagnetism” or “quantum reduction of a wave packet,” has already been in widespread existence prior to any scientific reading or reification. The rejection of an authoritative definition of “life” is often compensated for by a list of functional properties that never finds unanimity among its authors. Some demand more properties, and others require fewer of those properties that are often expressed in terms of a vague expression such as “self-maintenance,” “self-organization,” “metabolism,” “autonomy,” ▶ “self-replication,” and “open-ended evolution.” A first determining role of artificial life consists in the writing and implementing of software versions of these properties and of the way they do connect, so as to render them unambiguous, making them algorithmically precise enough that, at the end, the only reason for disagreement on the

definition of life would lie in the length or the composition of this list and on none of its items.

The biologist obviously remains the most important partner; but what may he expect from this “artificial life”? These computer platforms could be useful in several ways, presented in the following in terms of their increasing importance or by force of impact. First of all, they can open the door to a new style of teaching and advocating of the major biological ideas, that is, computer software as pedagogical help, as, for example, Richard Dawkins (1986) who, bearing the Darwinian good news, did so with the help of a computer simulation where sophisticated creatures known as “biomorphs” evolve on a computer screen by means of a genetic algorithm. These same platforms and simulations can, insofar as they are sufficiently flexible, quantifiable, and universal, be used more precisely by the biologist, who will find in them a simplified means of simulating and validating a given biological system under study. Cellular automata, Boolean networks, genetic algorithms, and algorithmic chemistry are excellent examples of software to download, parameterize, and use to produce the natural phenomena required. Their predictive power varies from very qualitative (their results apparently reproduce very general trends of the real world) to very quantitative (the numbers produced by the computer may be precise enough to be compared with those measured in the real world). Although being at first very qualitative, a precise and clear coding is already the guarantee of an advanced understanding accepted by all. Algorithmic writing is an essential stage in formalizing the elements of the model and making them objective. The more the model allows us to integrate what we know about the reality being reproduced, that is, the detailed structures of objects and relationships between them, the more the predictions will move from qualitative to precise and the easier the model will be to validate according to the Karl Popper ideal falsifying process.

Finally, through systematic software experiments, these platforms can lead to the discovery of new natural laws, whose impact will be greater if the simulated abstractions will be present in

many biological realms. In the 1950s, when Alan Turing (1952) discovered that a simple diffusion phenomenon propagating itself at different speeds, depending on whether it is subject to a negative or positive influence, produces zebra or alternating motifs, it had a considerable effect on a whole section of biology studying the genesis of forms (animal skins, shells of sea creatures (Meinhardt 1998)). When some scientists discovered that the number of attractors in a Boolean network or a neural network exhibits a linear dependency on the number of units in these networks (Kauffman 1993, 1995), these results are equally well applied to the number of cells expressed as dynamic attractors in a genetic network or the quantity of information capable of being memorized in a neural network. Entire chapters of biology dedicated to networks (neural, genetic, protein, immune, hormonal) had to be rewritten in the light of these discoveries. When some scientists recently observed a non-uniform connectivity in many networks, whether social, technological, or biological, showing a small number of key nodes with a large number of connections and a greater number of nodes with far fewer, and when, in addition, they explained the way in which these networks are built in time (Barabasi 2002) by preferential attachment, again biology was clearly affected. Artificial life is of course at its apogee when it reveals new biological facts, destabilizing the presuppositions of biologists or generating new knowledge, rather than simply illustrating or refining the old.

In the next section, I shall attempt to set out the history of life as the disciples of artificial life understand it, by placing the different landmark steps on a temporal and causal axis, showing which one is indispensable to the appearance of the next and how it connects to the next. This history will certainly be very incomplete and full of numerous unknowns, but most people involved in artificial life will be in agreement. They will mainly disagree on the number of these functions and on the causal sequence of their appearance, acknowledging, however, that the appearance of any would have been conditioned by the presence and the functioning of the previous ones. The task of artificial life is to set up experimental software

platforms where these different lessons, whether taken in isolation or together, are tested, simulated, and, more systematically, analyzed. I shall sketch some of these existing software platforms whose running delivers interesting take-home messages to open-minded biologists.

The History of Life as Seen by Artificial Life Proponents

Appearance of Chemical Reaction Cycles and Autocatalytic Networks

In order for a system to emerge and maintain itself inside a soup of molecules that are potentially reactive and contain very varied constituents (which could correspond to the initial conditions required for life to appear, i.e., in the primordial soup), this reactive system must form an internally cycled network or a closed organization, in which every molecule is consumed and reproduced by the network. Above all, in order for life to begin, all of the constituent components must have been able to stabilize themselves in time. These closed networks of chemical reactions are thus perfect examples of systems, which, although heterogeneous, are capable of maintaining themselves indefinitely, despite the shocks and impacts that attempt to destabilize them. This comes about through a subtle self-regeneration mechanism, where the molecules end up producing those molecules that have produced them. It may be obtained on a basic level in a perfectly reversible chemical reaction but can be obtained more subtly in the presence of a lot of intermediary molecules and catalysts. By this reaction-based roundabout in which they all participate, all molecules contribute to maintaining themselves at a constant concentration, compensating and reestablishing any disruption in concentration undergone by anyone of them. The bigger the network, the more stable it should be and the more molecules it will maintain in a concentration zone that will vary very little, despite external disruptions.

A network of this kind will be materially closed but energetically open if none of the molecules appears in or disappears from the network as a result of material fluxes, whereas energy,

originating in external sources, is necessary for the reactions to start and take place. The presence of such an energy flux, maintaining the network far from the thermodynamic equilibrium, is needed, since, without it, no reactive flow would be possible circulating through the entire network. A molecular end of the cycle must be reenergized in order to start again the whole circular reaction process. This cycle thus acts as a chemical machine, energetically driven from the outside. As soon as one of the molecules is being produced in the network without, in its turn, producing one of the molecules making up the network, it absorbs and thus destroys the network. In the presence of molecules of this kind, produced but nonproductive (a kind of waste), the only way of maintaining the network becomes to feed it materially and to make it open to material influx. The network acts on the flow of material and energy as an intermediate ongoing stabilization zone, made up of molecules that may be useful to other vital functions (such as the composition of enclosing membranes or catalyzing self-replication), to be described in the following sections. It transforms, as much as it “keeps on,” all the chemical agents that it recruits. Biologists generally agree that a reactive network must exist prior to the appearance of life, at least to catalyze and make possible the other life processes such as genetic reading and coding; it is open to external influences in terms of matter and energy but necessarily contains a series of active cycles. They are most often designated as ► “metabolism” or “proto-metabolism,” the most popular and active advocates of this “metabolism-first” hypothetical scenario of the origin of life being (De Duve 2002; Ganti 2003; Maynard Smith and Szathmary 1999; Kauffman 1993; Shapiro 2007; Dyson 1999).

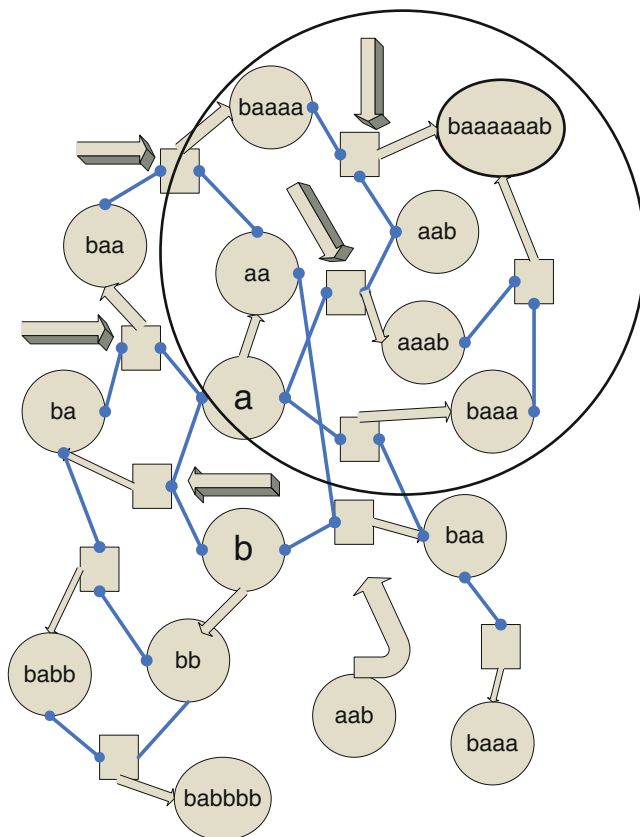
Lenaerts and Bersini (2009) give priority to the study of chemical reaction networks, viewing them as key protagonists in the appearance of life. These chemical reaction networks, where the nodes are the molecules participating in the reactions and the connections are the reactions linking the reacting molecules to the molecules produced, are generally characterized by fixed point dynamics, the chemical balances during which the producers and the products mutually

support each other. The attractors in which these networks fix themselves are as dynamic (the concentrations slowly stabilize) as they are structural (the molecules participating in the network are chosen and “trapped” by the network as a whole). These networks are perfect examples of systems that combine dynamics (the chemical kinetics in this case) and metadynamics (the network topological change), as new molecules may appear as the results of reactions while some of the molecules in the network may disappear if their concentration vanishes in time. Both the structure of the network and the concentration of its constituents tend to stabilize over time. Kauffman (1993, 1995) and Fontana (1992) were the forerunners in the study of the genesis and properties of these networks. Figure 1 illustrates the work of these two artificial life pioneers, dedicated to the study of prebiotic chemistry, limiting the reactions studied to polymerization, such as $aa + bb \rightarrow aabb$, or, inversely, depolymerization or hydrolysis, such as $abaa \rightarrow ab + aa$.

Kauffman showed that provided the probability that a reaction takes place is affected by the presence of a catalyst, which is itself produced by the network (in such a case the whole network is said to be autocatalytic), a phenomenon of percolation or phase transition, characteristic of this type of simulation, is produced. For probabilities that are too low, the network does not pop up because the reactions are too improbable, but as soon as a threshold value is reached for this same probability, the network “percolates,” giving rise to multiple molecules produced by multiple reactions. Kauffman grants a privileged status to this threshold value and to the giant “explosive” network resulting from it (in his scenario of the origin of life), without really arguing the reason why such a status should exist, but passing the immense interest and enthusiasm that the phenomena of phase transitions arouse among physicists onto the world of biology. Fontana for his part is concerned with the inevitable appearance of reaction cycles (such as that illustrated in Fig. 1). All the molecules produced by these cycles in the network in turn produce molecules of the network. He is among those many biologists who see these closed networks or

Artificial Life,

Fig. 1 Representation of a network of chemical reactions of polymerization ($a + b \rightarrow ab$) and depolymerization ($ab \rightarrow a + b$) taking place in a simulated chemical reactor. Molecules are represented by *circles* and reactions by *squares*. Each reaction can be catalyzed, like the *arrows* pointing to the *squares* show, by a molecule of the network (giving rise to an autocatalytic network). Some molecules can appear (like the molecule “aab”) or simply disappear from the network. Reaction cycles can appear, like the one surrounded in the figure ($aa \rightarrow baaaa \rightarrow baaaaaab \rightarrow baaa \rightarrow aa$)

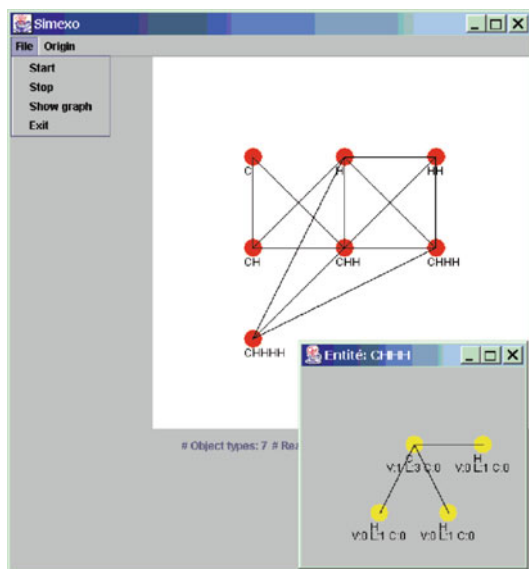


organizations as forming a key stage in the appearance of life, due both to their stability and to the fact that they form structural and dynamic attractors for the system. They cause a stabilization and internal regulation zone together with an energetic motor in a chemical soup, which is continually being crossed by a flow of matter and energy. Fontana goes on to show how these networks are also capable of self-regeneration and self-replication.

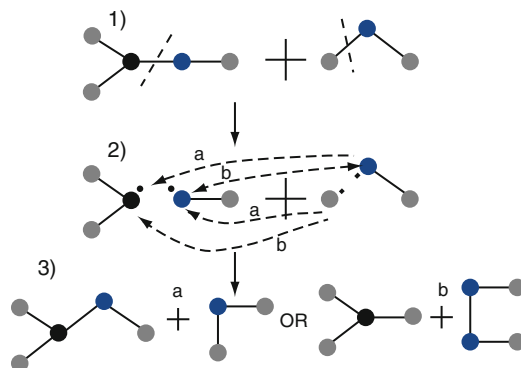
Lenaerts and Bersini (2009) have programmed the genesis of these chemical reaction networks by adopting the object-oriented (OO) programming paradigm. The OO simulator aims to reproduce a chemical reactor and the reaction network that emerges from it (like that shown in Fig. 2). This coevolutionary (dynamics + metadynamics) model incorporates the logical structure of constitutional chemistry and its kinetics on the one hand and the topological evolution of the chemical reaction network on the other hand. The network topology

influences the kinetics and the other way round, since only molecules with a sufficient concentration are allowed to participate in new reactions (to avoid a combinatorial explosion of molecules and reactions). The model is expressed in a syntax that remains as close as possible to real chemistry. Starting with some initial molecular objects and some initial reaction objects, the simulator follows the appearance of new molecules and the reactions in which they participate, as well as the development of their concentration over a period of time. The molecules are coded as canonical graphs. They are made up of atoms and bonds that open, close, or break during the reactions. The result of the simulation consists in various reaction networks, unfolding in time and whose properties can be further studied (for instance, the presence and the properties of reaction cycles or the nature of the network-particular topology such as scale-free or random).

One of these reaction schemes, in addition to just cycling, can also be autocatalytic, when a



Artificial Life, Fig. 2 The OO chemical simulator developed by Lenaerts and Bersini (2009). On the *left*, the molecules are represented as canonical graphs. On the



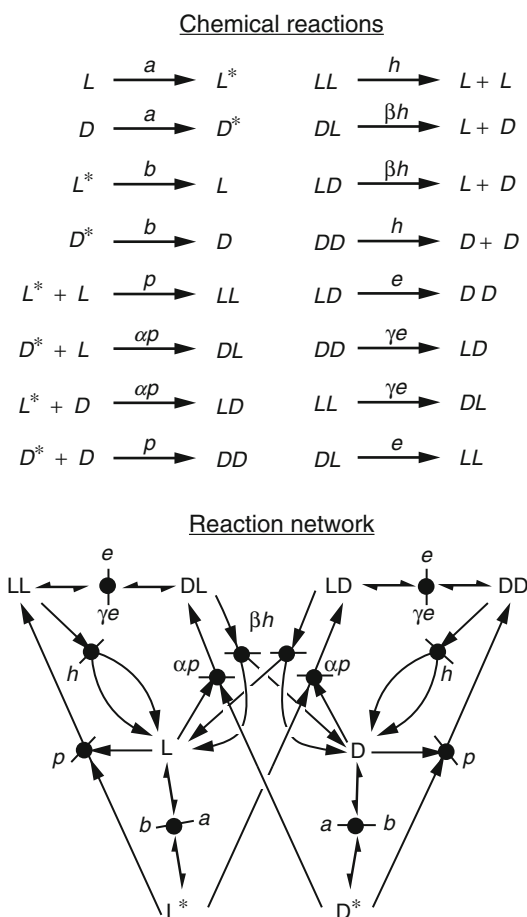
right, the outcome of the simulator is an evolving reaction network, which can be studied in its own right (the presence of cycles, the type of topology)

product of the reaction cycle has twice the concentration of one of the reactant: $a + b \rightarrow a + a$. This is, for instance, the case of the so-called formose reaction (that Ganti and Szatmary have discussed at large in Ganti 2003), during which a two-carbon molecule, reacting twice with a monomer composed of one carbon, leads to a four-carbon molecule, which then splits in order to duplicate the original molecule. This is the chemical variant of genetic self-replication, since in both cases an original molecule is duplicated. As will be discussed later, Ganti has been the first to connect and synchronize these two replication processes, chemical and genetic, in order for the cell to simultaneously duplicate its boundary, its metabolism, and its informational support. In the presence of autocatalysis, the reaction kinetics amounts to an exponential increase and, more interestingly, when various autocatalytic cycles enter in antagonistic interaction, turns out to be responsible for symmetry breaking (one of the cycle, initially favored, wins and takes it all). The early origin of life should not be studied without taking account of the self-organization of chemical networks, the emergence and antagonism of autocatalytic cycles, and how energy flows drive the whole process. Such

chemical networks are, for instance, appealing to the effort to understand the onset of biological homochirality as the destabilization of the racemic state resulting from the competition between enantiomers and from amplification processes concerning both autocatalytic competitors (one left oriented and the other right; see Plasson et al. 2007). The chemical reaction network under study (shown in Fig. 3) is made up of the same type of polymerization and depolymerization reactions as the one studied by Fontana. In the additional presence of epimerization reactions allowing the transformation of a right-hand monomer into a left-hand one and vice versa, the concentration of one family of monomers (for instance, the left one) vanishes in favor of the other. The flux of energy is transferred and efficiently distributed through the system, leading to cycle competitions and to the stabilization of asymmetric states.

Production by This Network of a Membrane Promoting Individualization and Catalyzing Constitutive Reactions

The appearance of a reaction network of this kind undeniably creates the stability necessary for exploiting its constituents in many reactive



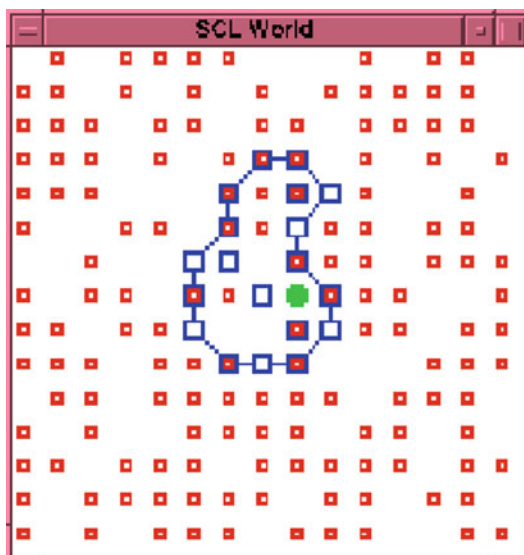
Artificial Life, Fig. 3 The prebiotic chemical reactor system responsible for a homochiral steady state studied by Plasson et al. (2007). The complete set of reactions is indicated, containing activation (the necessary energy source), polymerization and hydrolysis (which together shape the cycles), and epimerization (which induces the competition between the enantiomers)

systems such as the ones dedicated to the construction of ► [membranes](#) or the replication of molecules carrying the ► [genetic code](#). This network also acts as a primary filter as it can accept new molecules within it but can equally well reject other molecules seeking to be incorporated within it. They will be rejected, as they do not participate in any of the reactions making up the network. Can we see a primary form of individualization in this network? No, because by definition, it can only be unique as no spatial frontier allows it to be distinguished from another

network. Although it is roughly possible to conceive of an interpenetration of several chemical networks, establishing a clear separation between these networks would remain a problem.

It would seem fundamental that a living organism of any kind can be differentiated from another. We know that the reproduction of a second organism from a first is a central mechanism of life and can only operate if the “clone” elaborates something to spatially distinguish itself from its “original.” The best way of successfully completing this individualization and to be able to distinguish between these networks is to revert to a spatial divide, which can only be produced by some form of container capable of circumscribing these networks in a given space. Biochemists are well acquainted with an ideal type of molecule, the raw material for these membranes in the form of lipid/amphiphilic molecules or fatty acids, the two extremities of which behave in an antagonistic fashion – the first hydrophilic, attracted to water, and the second hydrophobic, repulsed by it. Quite naturally, these molecules tend to assemble in a double layer (placing the two opposing extremities opposite to each other), formed by the molecules lining up and finally adopting the form of a sphere to protect the hydrophobic extremities from water. Like soap bubbles, these lipid spheres are semipermeable and imprison the many chemical components trapped during its formation. They do, however, actively channel in and out the most appropriate chemicals for maintaining themselves.

In assimilating living organisms to autopoietic systems, Varela et al. (1974) were the first to insist that this membrane should be endogenously produced by the elements and the reactions making up the network (e.g., lipids would come from the reactions of the network itself) and would in return promote the emergence and self-maintenance of the network. The membrane can help with the appearance of the reactive and growing network by the frontiers that it sets up, by the concentration of certain molecules trapped in it, or by acting as a catalyst to some of the reactions due to its geometry or its makeup. Basically, autopoiesis requires a cogeneration of the membrane and of the reactive network that it “walls up.” The



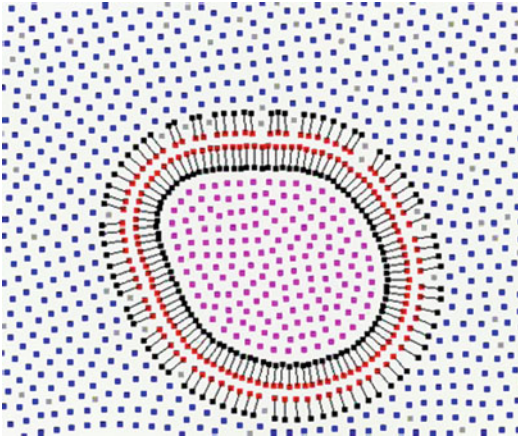
Artificial Life, Fig. 4 Simulation by means of cellular automata of the autopoietic model originally proposed by Varela. The minimal cell can easily be seen, together with the catalysts and the substrates that it encapsulates

network presents a double closure – one chemical, linked to the cycling chain of its reactions, and another physical, due to the frontiers produced by the membrane. In the cellular automata model of Varela (Varela et al. 1974; McMullin and Varela 1994) illustrated in Fig. 4, there are three types of particles capable of moving around a two-dimensional surface: “substrates,” “catalysts,” and “links.” The working and updating rules of these cellular automata go as follows:

- If two substrates are near a catalyst, they disappear to create one single link where one of the two was located.
- If two links are near each other, they link up and attach themselves to each other. Once attached, these links become immobile.
- Each link is only allowed to attach itself to two other links at the most. This allows the links to form chains and to be able to make up a closed membrane.
- The substrates can diffuse through the links and their attachments, while the catalysts and the other links cannot. We can therefore understand how the process of the cogeneration comes about. The membranes shut in the catalysts and the links, which in turn support the membrane by being essential to its formation and regeneration.
- The reactions creating the links are reversible, as the links can recreate the two original substrates (and thus cause the membrane to deteriorate), but at a lower speed. When this happens, the attachment between the links also disappears.

Continuous updating and execution of these rules produces minimal versions of reactive systems, physically closed and confined by means of a membrane, which is itself produced by the reactive system. For Varela and the others following him, this turns out to be an essential stage in the road to life. Running the software, many difficulties are encountered such as the simple attainment of a closed cell on account of the many more possibilities for the membranes to unfold in a straight way. Only software simulations can interconnect the physical compartment played by the membrane with the generating metabolism and further show how far from obvious it is for these two systems to mutually sustain each other.

The whole, interactive “metabolism and membrane” prefigures a minimal elementary ► **cell**, which already seems capable both of maintaining itself and detaching itself from its environment and from cells similar to it. It is at this stage on the way to establishing a better and more exact characterization of life that the definition given by Luigi Luisi (2002) takes on its full meaning (restating the idea of autopoiesis in more biological terms). “Life is a system which can be self-maintaining by using external energy and nutritional sources to the production of its internal constituents. This system is spatially circumscribed by a semipermeable membrane of its composition.” In the footsteps of Varela, considering life impossible without a way for individualization and compartmentalization, the constitution of the membrane by simple self-organization or self-assembly processes of bipolar molecules (hydrophilic and hydrophobic) has become a very popular field of artificial life. It is indeed rather simple to reproduce this



Artificial Life, Fig. 5 Simulation of a minimal cell based on A-B (A is hydrophobic and B hydrophilic) and water molecules. All molecules move in reaction to repulsive forces of different intensities and thermal agitations. The *pink dots* are the A; the *gray dots* are the B that do connect to give A-B (represented in *red and black*) by a simple chemical reaction. The *blue dots* are the water molecules

phenomenon in software (as illustrated in Fig. 5). You need water molecules that just randomly move, in *blue* in the figure. You need two kinds of submolecules (call then A and B), which when they meet – through the only authorized additive chemical reaction – form an A-B molecule (A is hydrophobic and B hydrophilic) whose two poles are connected by a small string. You need also to adjust the degree of repulsion between A and water and between B and water, the strength of the string of the A-B molecule, and the random component (akin to the thermal noise) to add on each of the intermolecular forces. Nevertheless, the final outcome turns out to be rather robust. The bilayer of B-A/A-B molecules will very naturally and spontaneously form just as for real cells.

Again, as for Varela's minimal cell, the closure turns out to be quite delicate to obtain. One very simple way to obtain it is to locate the source of A submolecules (the *pink dots* in the figure) in a singular point, so that the closed membrane will simply surround that source, the circular shape being the local minimal of the mechanical energy connecting all A-B together. Like in Varela's model, and somewhat paradoxically, the source needs to be circumscribed by the membrane for that same membrane to close on itself. However,

in contrast with this autopoietic model, once in place, the membrane cannot deteriorate, and thus, no further internal chemistry is required to endogenously produce what would be needed to fix it. Ultimately, this membrane should exhibit some selective channeling in and channeling out (akin, for some authors (Luisi 2002), to a very primitive form of cognition) providing its internal metabolism with the right nutrients and the right evacuating way out so as to facilitate the cell's self-maintenance. These two software models raise interesting questions for the biologists like: how are the molecular parts of the membrane generated (endogenously or exogenously) and is this cogeneration of the membrane and the internal metabolism the signature of minimal life?

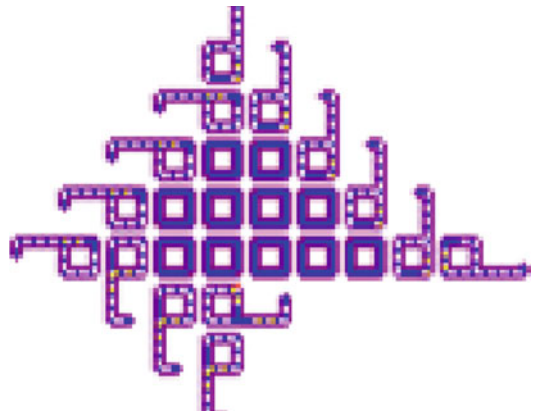
Self-Replication of This Elementary Cell

Self-replication, or the ability of a system to produce a copy of itself on its own, is one of the essential characteristics that has most intrigued and impassioned disciples of artificial life, beginning with John Von Neumann. Biology, and in particular this faculty of self-replication, fascinated Von Neumann. For if we want to compare a cell to a computer and a genome to a code, we need to explain how the computer itself was able to be created out of this code. Let us follow the reasoning of this genius step by step, as it is the perfect illustration of an "artificial life" type of approach: no material realization but just pure functions or rules. Through a sequence of purely functional questions and showing an almost complete ignorance of actual biology, his reasoning led to a logical solution, the content of which retraces astonishingly closely those lessons we have since learned about the way biology functions. Von Neumann begins from the principle that a universal constructor C must exist, which, based on the plan of some kind of machine P_M (P the plan, M the machine), must be capable of constructing the machine M^P . This idea may be simply translated by $C(P_M) = M^P$. The question of self-replication that is then raised is, "Is this universal constructor capable of constructing itself?" In order to do so, it must, following the example of other construction products, have a plan of what it wants to construct; in this specific case, it is the

constructor's plan P_C . The problem is then expressed as follows: can $C(P_C)$ give $C(P_C)$ in order for there to be a perfect replication of the original? Von Neumann therefore realized that the question at issue is that of the fate of the construction plan, because if the constructor constructs itself, it has to add the plan itself to the product of the construction. Von Neumann proposed then allotting two tasks to the universal constructor: constructing the machine according to the given plan and thus adding the original plan to this construction. The constructor's new formula then becomes $C(P_M) = M^P(P_M)$. If the constructor applies itself to its own plan, this time the replication will be perfect: $C^P(P_C) = C^P(P_C)$.

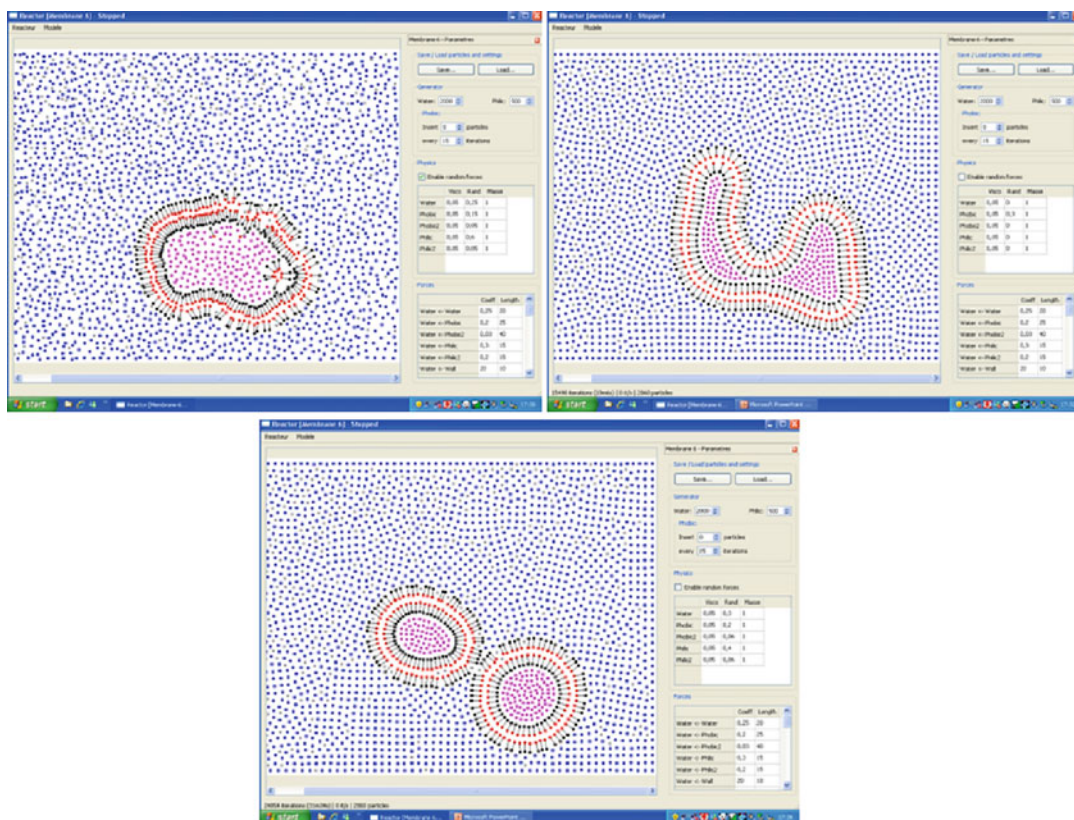
The fascinating aspect of Von Neumann's solution is that it anticipated the two essential functions that, as we have since discovered, are the main attributions of the protein tools constituting the cell: constructing and maintaining this cell and also duplicating the code in order for this construction to be able to prolong itself for further generations. Starting with the ► [DNA](#), the whole ► [protein](#) machinery first of all builds the cell and then, by an additional procedure, duplicates this same DNA. Von Neumann did not stop at duplication, because, at the same time, he imagined how this same machinery could evolve and become gradually more complex as a result of random mutations taking place while the plan recopies itself. Von Neumann gave also a cellular automata solution of the problem in which each cell of the automata possessed 5 neighbors and 29 states, and around 200,000 cells were necessary for the phenomenon of self-replication to take place. Many years later, Chris Langton (Langton 1984, 1989), the organizer of the first conference on artificial life in 1989, proposed an extremely simplified version of this (8 states, but 219 rules remain necessary), although it still follows the pattern mapped out by Von Neumann. This automaton, shown in Fig. 6, incessantly reproduces a little motif shaped as a loop.

For many biologists, as opposed to Varela, Luisi, Ganti, and Maynard-Smith, life is not simply indissociable from but also essentially reducible to this capacity for self-replication. Nevertheless, they still need to explain how life



Artificial Life, Fig. 6 Langton's self-replicating cellular automata

can actually reproduce without an entire preexistent metabolic chemical machinery. Departing from the elementary cell introduced in the preceding section and in the interest of an unbroken narrative, let us imagine a simpler scenario leading to self-replication. The closed circuit of chemical reactions could be destabilized by some kind of disturbance, causing a growth in concentration of some of its constituents, including those involved in the formation of membranes. This would also be the case provided all the reactions of the metabolism turn out to be autocatalytic, entailing the exponential growth in the concentration of all its molecular elements (including again the membrane constituents). The membrane and the elements that it captures begin to grow (as illustrated in Fig. 7) until they reach the fatal point where the balance is upset. This is followed by the production of a new cell produced by and from the old one. When the new one comes, it quickly grows fast enough to catch up with the "generator" and "nursing" cell, as a chemical network is capable of some degree of self-regeneration due to its intrinsic stability; each molecule looks around for another that it can couple up to. This reconstitutes the natural chain reaction of the whole. The new membrane and the new chemical network reconstitute on their own by helping each other. Again, obtaining such duplication is far from obvious since, any cell being intrinsically stable, only a thermal but quite unnatural agitation would do the job.

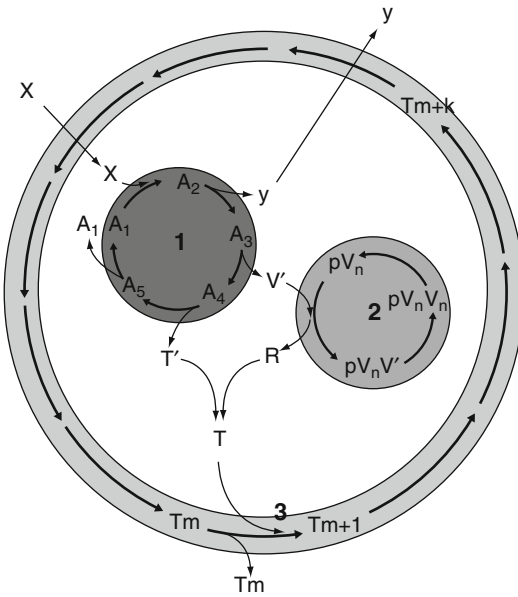


Artificial Life, Fig. 7 The elementary minimal cell of Fig. 5 in a process of self-replication induced by the growing and the division of the chemical metabolic network

together with the membrane enclosing it. A lot of random thermal noise is here indispensable to destabilize the initial cell

Rather than this elementary form of chemical self-replication coupled to the physical self-replication induced by the growth and division of the membrane, life has opted for a more sophisticated physicochemical version of it, more promising for the evolution to come: self-replication by the interposing of an “information template.” Each element of the template can only couple itself with one complementary element. The new elements will as a whole naturally reconstitute the template they were attracted to, causing then the replication of the entire template. In biology, it is the extraordinarily emblematic double helix of DNA that acts as a template, shouldering the major role in the history of life—that of the first known replicator. Our elementary cell must now be internally equipped with this information template. Since the 1950s, Timor Ganti (2003) proposed the first minimum mathematical system,

named “chemoton,” represented in the Fig. 8. This is the first abstract computational protocell that we know, constructed by Ganti as the original ancestor of living organisms. It possesses three autocatalytic chemically linked subsystems: a metabolic network, a membrane, and an information template responsible for scheduling and regulating self-replication. All three grow exponentially until they are able to reproduce, and they depend on each other for their existence and stability. The metabolism feeds the membrane and the template, the membrane concentrates the metabolites, and the template mechanism dictates the reproduction of the whole. The triad ensemble is indeed capable of a whole synchronous self-replication and tries to computationally answer questions about the three subsystems and their interdependency, such as “how does the self-replication of the template automatically



Artificial Life, Fig. 8 The schematic representation of Ganti's chemoton. One can easily see the three autocatalytic subsystems: the metabolism, the membrane, and the information template, chemically coupled

accompany the self-replication of the whole.” This complex software object, the “chemoton,” has also become the topic of many software developments and experimentations and is emblematic of artificial life at its best.

Genetic Coding and Evolution by Mutation, Recombination, and Selection

In the information template introduced in the last section, each letter constituting it contributes to the code of a functional component essential to the cell and designed on the basis of that code – a protein. As soon as he hears anyone talking about code, the software specialist has, quite legitimately, to put his head in through the window, because it is to him and him alone that we in fact owe the metaphor of the genetic code. Since ► [Darwin](#) and thereafter throughout all evolutionary science, we have a good idea of what the last chapter of the history of life is. Doubtless what has stimulated most developments in “artificial life” (primarily from the point of view of engineering) is the fact that the genetic code can evolve through ► [mutation](#) and sexual crossing between the old

machines, evolving so as to produce new machines that are more and more efficient. Over the past 20 years, many of those developments into artificial life have been eager to show how beneficial this idea is for the research and the automated discovery of sophisticated solutions to complex problems. As illustrated in Fig. 9, this research can take place through a succession of mutations and recombinations operating at the level of the code, with the best solutions proposed being preserved in the next generation in order to be used for a new cycle of these same operations. The brute force of the computer is used to its full effect.

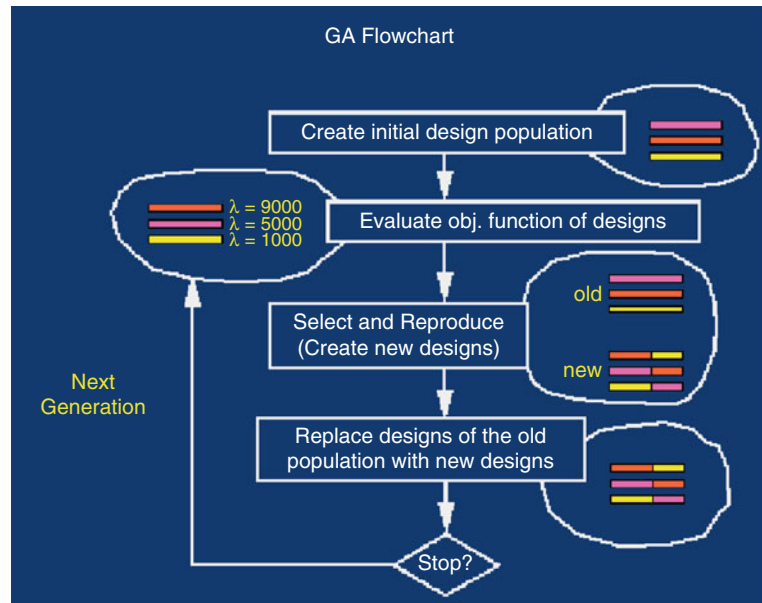
These are the same genetic algorithms that Dawkins used in his Darwinian crusade, when he developed his biomorphs. It should also be stressed that another element in Dawkins' program is that, when it is finally evaluated, the phenotype is not directly obtained from the genotype, as would be the case for classical optimization in a real or combinatorial space. In his work, the biomorphs are the product of a recursive sophisticated program, which is carried out starting from a given ► [genotype](#) to give a ► [phenotype](#). A great “semantic distance” is maintained between these genotypes and phenotypes, which reflect the long process of cell construction from the genetic code and the need for a sophisticated metabolism building the machine out of the code. In brief, this constant program, able to interpret the evolving genotype, is much more important for the complexity of the final outcome than the genotype itself. Similarly, a very prized derivative of these algorithms is genetic programming (Koza 1992), where the individuals now to be optimized are software codes.

Conclusions

Parallelism, functional emergence, and adaptability are the conditions necessary to allow these new biologically inspired artifacts to emerge, to “face the world.” We are jumping straight into the robotics branch of artificial life (Brooks 1991). The interfacing with the real world required by these robots needs a parallel information reception mechanism, because the environment subjects it to a constant bombardment of stimuli. They have

Artificial Life,

Fig. 9 Illustration of the genetic algorithms: the recurrent iterated sequence of selection, mutation, and recombination easily leads to an interesting solution of a complex optimization problem



to learn to organize and master this avalanche falling on their perceptions. They have to learn to build their own concepts, fed and stimulated by this environment, which, in turn, allows them to master it. The conceptual high-level cognitive processes are born out of motor-sensory interactions and serve to support them. Cognitive systems extend at new levels what the minimal cell in the primitive soup does, with a flow of matter and energy crossing straight through, maintaining itself by selectively integrating this influx to form a closed reactor network and the membrane enclosing it.

My conclusions are addressed to the three partners: the biologist, the engineer, and the philosopher. To the first, the outcomes of artificial life consist in bringing out what the computer and biology share intimately: an elementary way of working at the ultimate lowest level, but, which by the brute force of parallelism and incessantly repeated iterations, can make unknown and sophisticated phenomena to emerge at higher levels. The qualitative aspect of these simulations can give them new roles in the vast scientific register: use it for education, illustrate biological principles that are already understood, open up possible experiences of thought, play and replay multiple biological scenarios very quickly, titillate

the imagination by on-screen representations, call into question some of the ambiguously interpreted but commonly accepted facts, and, when detailed at most, be able to predict experimental measurements.

The second partner, the engineer, is vigorously encouraged to use the computer for what it is best at doing – this infinite possibility of trial and error. There is a perfect synergy, where both participants complement each other ideally: the engineer must bow to the computer in terms of calculating power, but this is compensated for by his judgment. Genetic algorithms, ant colonies, neural networks, and reinforced learning have enriched the engineer's toolbox.

Finally, for the philosopher, for each attempt at a definition of life, artificial life makes a real attempt to achieve a computerized version in conformity with this definition. For the skeptic, unhappy with this computerized "lining," the question now becomes how to refine his definition, to complete it, or to renounce the possibility that there is no definition that cannot be computerized. The other possibility, doubtlessly more logical but more difficult for many philosophers to accept, would be that life poses no problem for a computer snapshot since it is computational at its roots.

Cross-References

- [Autocatalysis](#)
- [Bioinformatics](#)
- [Biological Networks](#)
- [Cellular Automata](#)
- [Code](#)
- [Complexity](#)
- [Emergence of Life](#)
- [Life](#)
- [Membrane](#)
- [Self-Replication](#)

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Artificial Meteorite

- [Stone](#)

Artificial Organelles

Friedrich C. Simmel
Technical University Munich, Garching, Bavaria, Germany

Synonyms

[Synthetic organelles](#)

Definition

An artificial organelle is a distinct functional sub-unit or sub-compartment of an artificial cell.

Artificial organelles serve to localize and spatially organize cellular components, separate competing chemical processes from each other, enhance the efficiency or specificity of chemical reactions, or perform other dedicated functions. Similar to biological organelles, artificial organelles may be generated through membrane encapsulation, phase separation, organization on, and association with membranes or other types of scaffolding. Artificial organelles improve and expand the capabilities of artificial cells and enable the realization of larger and more complex cellular structures.

History

In biology, organelles refer to specialized functional subunits of cells. In eukaryotic cells, organelles often specifically denote membranous compartments such as the nucleus, the endoplasmic reticulum, the Golgi network, mitochondria, and intracellular vesicle structures. In recent years, it has become clear, however, that liquid-liquid phase separation inside the cell can also give rise to organelles not bounded by membranes. With few exceptions, prokaryotes do not have internal membrane systems, but they also have distinct functional subunits or structures, which are referred to as prokaryotic organelles – for example, the nucleoid, flagella, carboxysomes, and other protein nano-compartments (Yeates et al. 2008; Agapakis et al. 2012).

Much work on artificial cells has initially focused on the encapsulation of biochemical reaction networks within membranous compartments, but did not consider sub-compartmentalization. The complex internal structure of extant cells shows, however, that cells are not simple “bags of enzymes,” and that their internal structure is important for their function. More recent artificial cell structures, therefore, involved the inclusion of artificial organelles (Göpprich et al. 2018), which were designed to perform a variety of different functions:

- 1) Compartmentalization of enzymatic pathways: Multienzyme pathways involve the interconversion of a substrate into a product over

multiple intermediate steps. Pathway intermediates may be lost by diffusion, via competing enzymatic reactions, or through reactions caused by unfavorable chemical conditions (Schoonen and Van Hest 2016). Compartmentalization of enzymes into artificial organelles has been used to address these issues: co-encapsulation of enzymes belonging to a pathway can protect intermediates from competitors, prevent diffusion, and ideally also provide the appropriate chemical environment (e.g., pH, ionic conditions). A variety of artificial organelle systems based on lipid vesicles and also polymersomes have been realized so far that demonstrate the benefit of sub-compartmentalization for several model enzyme pathways (Peters et al. 2013; Elani et al. 2014; Hindley et al. 2018; Reifenrath et al. 2020). There is also a considerable body of work on the creation of synthetic protein organelles that enable the localization of enzymatic pathways (Jordan et al. 2016; Sigmund et al. 2018).

- 2) Spatial separation of transcription and translation processes: In eukaryotes, transcription processes are localized to the nucleus, while translation takes place in the cytosol and the rough endoplasmic reticulum. In attempts to mimic the separation of these processes in the context of artificial cells, dedicated transcription, and translation organelles have been developed by several groups (Thiele et al. 2014; Aufinger and Simmel 2018; Niederholtmeyer et al. 2018). In biology, the emergence of a nucleus appears to be a consequence of the endosymbiotic origin of eukaryotes. Separation of transcription and translation by the nucleus enables splicing of eukaryotic transcripts before translation and facilitates fine-tuned gene regulation by localizing specific transcription factors to the nucleus. The nucleus is also the site of genome replication and plays an important role in eukaryotic cell division. Potentially, similar functional roles could be important for the development of more complex artificial cells.
- 3) Bioenergetic organelles for the generation of chemical fuels: One of the major tasks for the

realization of autonomous artificial cells is the establishment of energy harvesting processes. Extant cells generate chemical fuels by converting the energy stored in an electrochemical membrane potential into energy stored in chemical bonds. These processes require membranes for the establishment of an electrochemical gradient and membrane-bound enzymes such as ATP synthase that can perform the conversion. While in prokaryotes these processes are localized to the cell membrane, eukaryotes harbor bioenergetic organelles such as mitochondria for respiration and chloroplasts for photosynthesis. These organelles are presumed to have enabled eukaryotic genomes and cell sizes to grow far beyond those of prokaryotes and are thus made responsible for the complexity of eukaryotic life forms (Lane and Martin 2012). Several artificial cell systems have been realized so far that contain bioenergetic organelles and were thus capable of a limited form of autonomous energy harvesting and ATP generation (Lee et al. 2018; Pavan Kumar et al. 2018; Göpflich et al. 2019).

Cross-References

- ▶ Artificial Cell Division
- ▶ Cell Membrane
- ▶ Chemical Reaction Network
- ▶ Enzyme
- ▶ Membrane
- ▶ Organelle
- ▶ Protocell

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ASA, Austria

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Aeronautics and Space Agency of FFG; Agentur für Luft-und Raumfahrt der FFG; Austrian Space Agency, Austria](#)

Definition

The Aeronautics and Space Agency (ASA) of the FFG (Forschungsförderungsgesellschaft) is the gateway to the international aerospace industry for Austria's industry and science sectors and aims to strengthen their international standing in these key technologies. The agency supports the participation of Austrian researchers in international and bilateral aerospace collaborations and fosters the creation and development of international networks. It implements Austrian aeronautical space policy and represents Austria's interests in international aeronautical and space organizations.

The FFG's main focus is on managing the contributions of the Republic of Austria to the programs of the ► [European Space Agency](#)

([ESA](#)), and FFG is responsible for the management of the Austrian Space Applications Programme (ASAP), a bottom-up program targeted to space science, technology, space technology transfer, direct applications of space technology, and international cooperation.

History

The Space Research Institute of the Austrian Academy of Sciences was founded in 1970, and the Austrian Space Agency in 1972 (which was merged into FFG in 2004). Austria has been participating in ESA programs since 1975 and became a full member in 1987.

Bilateral cooperative projects have been undertaken in particular with the former Soviet Union, such as the development of Austrian instruments for space probes and missions. These projects include, for example, the two Venus probes, Venera 13 and 14 (1981–1982), the Vega 1 and 2 (1984–1986) missions to Halley's Comet, and the PHOBOS Mars probes (1988–1989). The highlight of bilateral cooperation with the former Soviet Union was the AUSTROMIR-91 mission – the flight of the first Austrian cosmonaut, Franz Viehböck, to the MIR space station. Other bilateral projects were, and still are, run in partnership with Norway, Sweden, France, Switzerland, and Germany.

Among other activities, FFG organizes annually since 1975 the well-known Alpbach Summer School that has a long tradition in providing in-depth teaching on aspects of space science and space technology with the aim of advancing the training and working experience of European graduates, postgraduate students, young scientists, and engineers.

ASB

► [Astrobiology Society of Britain](#)

Aseptic Process

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Synonyms

[Aseptic processing](#)

Definition

A process carried out under conditions that limit the potential for contamination of an article, by microorganisms, to below a specified probability level that (post-process) the article has one or more microorganisms present.

Cross-References

► [Terminal Sterilization](#)

Aseptic Processing

► [Aseptic Process](#)

Asgard, Archaea

Ricardo Amils
Departamento de Biología Molecular, Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Asgardarchaeota](#)

Definition

Asgard archaea also known as Asgardarchaeota is a superphylum of archaea which includes the closest prokaryotic relatives to eukaryotes. Lokiarchaeota, Thorarchaeota, Odinararchaeota, and Heimdallarchaeota phyla were the first members of the group, and new phyla have recently been incorporated. The general property of Asgard archaea is that their genomes contain genes that encode proteins detected previously only in eukaryotes: (GTPases, ubiquitin, profilin, gelsolin, regulated actin cytoskeleton, and membrane-remodeling proteins of the ESCRT type). Ecologically, they have been identified in very diverse environments: hydrothermal vents, rivers, and marine bays. The described Asgard archaea are generally obligate anaerobes, although some members can grow in the presence of O₂. In relation to their carbon source, some are autotrophs, others are heterotrophs, and some members are even phototrophs using a rhodopsin-like pigment to generate a proton gradient. The origin of the cellular complexity of eukaryotes is one of the major enigmas in biology. A favored scenario for eukaryogenesis is a syntrophic relationship between an Asgard archaea and unknown bacteria generating the nucleus and a posterior endosymbiotic incorporation of an Alphaproteobacteria to become the energy-generating system (mitochondria). This hypothesis was Lynn Margulis' most important contribution to evolution, and even though it was challenged by neo-Darwinists, the use of molecular biology techniques has proved its merit.

Cross-References

► [Anaerobe](#)
► [Archaea](#)
► [Autotroph](#)
► [Eukaryote](#)
► [Heterotroph](#)

- Margulis, Lynn
- Phototroph
- Prokaryote

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Asgardarchaeota

- Asgard, Archaea

ASI

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Agenzia Spaziale Italiana](#); [Italian Space Agency](#)

Definition

The Italian Space Agency was established in 1988 to coordinate all of Italy's efforts and investments in the space sector that had begun in the 1960s. Today, ASI has a key role at the European level

where Italy is the third contributing country to the ► [European Space Agency](#).

Italy is directly involved in major European and international programs. It provides several elements for the International Space Station like the multipurpose logistic module (MPLM) used to transfer cargo with the US space shuttle, Nodes 2 and 3, and is participating within ESA in the European Automated Transfer Vehicle activities. ASI selected five astronauts flying either through bilateral cooperation or through ESA. Franco Malerba was the first Italian in space in 1992 onboard the STS 46 flight. Italy is involved also in many missions dedicated to planetology, astronomy, and exploration. It is playing a major role in the Cassini-Huygens mission, the ► [ExoMars](#) ESA mission, and many others. Italy is taking also a major share (65%) in the medium launcher program (Vega rocket) of ESA.

Beyond the headquarters in Rome, ASI has three bases and one center. “Luigi Broglio” Space Centre of Malindi, Kenya, was used to launch US Scout rockets with Italian satellites from oceanic platforms (the marine segment) up to 1988. Nowadays this base (the ground segment) is dedicated to receive data from satellites and launchers.

A stratospheric balloon launch base is located on a former airport in Trapani (since 1975). This base is, in particular, actively involved in trans-Mediterranean flights of research balloons.

In Matera, in collaboration with several institutions, ASI opened in 1983 a Space Geodesy Center dedicated to this discipline. Now this base is diverting its activities welcoming some technical activities required for robotic exploration.

Finally, an ASI Science Data Center (ASDC) was established in September 2000 for the management and analysis of scientific data collected by scientific satellites. This center is located in the ESA facility (European Space Research Institute-ESRIN) in Frascati, which is dedicated to the Earth observation.

Askja Caldera, Lunar Natural Analog

Daniele L. Pinti¹ and Océane Rocher²

¹GEOTOP Research Center for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

²Faculté des Sciences et Technologies, GeoRessources – UMR 7359, Université de Lorraine, Vandoeuvre-Les-Nancy, France

Definition

Askja (Google Earth coordinates: 65° 00' 41" N; 16° 44' 54"; and 1510 m elevation) is an active volcano situated in the remote center of Iceland, in the region called *Highlands of Iceland*. Askja consists of three nested calderas (depressions created by the collapse of volcanic edifices by emptying the magma chamber during paroxysmal eruptions) which cover a total surface of 45 km². Askja volcanic complex is located just 35 km north of the northern edge of the *Vatnajökull*, the largest ice cap of Iceland and of Europe, and today is part of the *Vatnajökulsþjóðgarður* (the Vatnajökull National Park). Since the 1960s, NASA selected this site for training the ► [Apollo mission](#) crews. Recently, there was a renewed interest for Askja as a Moon and Mars natural analog, for its spectacular exposure of regolith, subsurface ice deposits, and lava flows.

Overview

The Askja central volcano belongs to the Askja volcanic system (Trippanera et al. 2017). This site is located within the so-called North Volcanic Zone of Iceland which corresponds to the north-eastern branch of the north-Atlantic ► [midocean ridge](#) that crosscuts Iceland with a general NE-SW trend. The midocean ridge is here characterized by *oblique extension*, i.e., the direction of spreading

is oblique to the regional trend of the deformation. This created five *en echelon* spreading segments, each having a fissure swarm and an associated central volcano, from north to south: Theistareykir, Krafla, Fremrinámar, Kverkfjöll, and Askja.

The Askja central volcano is thought to have been active for the last 300,000 years and hosts three nested calderas within the basaltic *Dyngjufjöll* massif (e.g., Trippanera et al. 2017). The older one is the *Kollur* caldera which rim is partly obliterated by the largest 8-km diameter *Askja* caldera, which in turn contains the younger 5-km diameter *Öskjuvatn* caldera, which hosts today *Lake Öskjuvatn*. More than 175 eruptions (both effusive and explosive) during the last 7000 years have been identified on the field, more than 50 of which occurred in historical times, with the last ones occurring at the end of the 1920s. The most impressive eruption is the 29–30 March 1875 rhyolitic Plinian eruption that initiated the formation of the *Öskjuvatn* caldera. The explosive products were dispersed through Europe. Today, only a little fumarolic activity within the Askja caldera is observed, but the volcano is still active. This volcanic activity – which extended for 200–300 ka – created the *Dyngjufjöll* massif, which is the product of numerous interglacial, ice-confined subaqueous, subglacial, and emergent basaltic eruptions that produced an 800-m-thick sequence of tuffs, lapilli tuffs, hyaloclastite, lava breccia, and ► [pillow lava](#).

Askja location was selected by NASA in the 1960s to train its Apollo mission astronauts to “lunar analog geology.” The site was selected for two main reasons: the presence of large basaltic regolith deposits with an impressive similarity to the lunar landscapes (Fig. 1) and the remoteness of the place, which allowed the US army to easily control the place and avoid worried espionage activity by the Soviets. Still today, there are only two roads to access the site (open from June to October because of the adverse climatic conditions) with several rivers to cross, requiring specially equipped 4 × 4 trucks. NASA organized



Askja Caldera, Lunar Natural Analog, Fig. 1 Lunar-like regolith landscape at the summit of Askja caldera, August 2019. (Photo credit: O. Rocher)

two geological field trips in 1965 and 1967 with a total of 23 Apollo astronauts participating to various activities (Fig. 2), including Neil Armstrong, the first man on the Moon of Apollo 11, and Harrison Schmitt of Apollo 17, the only scientist (geologist) trained as an astronaut by the program.

More recently, there was a renewed interest in Askja local geology as a lunar and Mars natural analog. The site offers a wide range of opportunities for planetary analog research and operations in the context of lunar and Mars exploration. The *Holuhraun* lava flow field erupted in 2014 south of Askja, which is the largest fissural eruption in the last 230 years in Iceland, is now the privileged playground for testing new technologies of future Martian rovers and drones by The University of Arizona-funded RAVEN team (Rover–Aerial Vehicle Exploration Network).

As an environmental analog, the poorly consolidated, locally ice-rich pyroclastic deposits

of the *Dyngjufjöll* massif constitute proxies for understanding the lunar regolith composition and stratigraphy (Williamson et al. 2013). The channelized basalt flows at Askja are also a morphologic analog for the long and thick lava flows of *Mare Imbrium* on the Moon (Garry 2014), the landing site of several lunar past missions such as Apollo 15, 17 and more recently in 2013 of the Chinese *Chang’e 3* lander and lunar rover *Yutu*. The newest *Holuhraun* lava field appears as a platy-ridged terrain analog of those observed in *Athabasca Valles* and *Marte Vallis* on Mars (Tolometti et al. 2020; Voigt et al. 2020). Finally, the geomorphology of subglacial hyaloclastites (a volcanoclastic accumulation or breccia consisting of glass fragments formed by quench fragmentation of lava flow surfaces during subglacial extrusion) and Aeolian deposits at Askja provides clues to the interpretation of volcanic

Askja Caldera, Lunar Natural Analog,

Fig. 2 Astronaut David R. Scott (Gemini 8, Apollo 9 and 15) indicating some geological feature to colleagues on the ridge of the Askja Caldera, November 1965. Far behind, Lake Öskjuvatn occupying the homonymous caldera. (Photo credit: NASA)



landforms in the north polar regions of Mars and of subglacial deposits and chaotic terrain located at the periphery of Martian volcanoes (Williamson et al. 2013; Baker et al. 2021).

Finally, volcanic subsoils of Askja have been also studied to determine microenvironment variability and its impact in the diversity of microbial life (Rader et al. 2020). A maximum of diversity and abundance of microbial life in ash layers buried under surface pumices has been observed. This suggests a sampling strategy for Mars search of ancient life, by looking for undisturbed explosive volcanic ash that could maximize diversity and abundance of different bioindicators.

Cross-References

- [Apollo Mission](#)
- [Mars](#)

- [Mid-Ocean Ridge](#)
- [Moon, The](#)
- [Regolith, Planetary](#)
- [Regolith, Terrestrial](#)
- [Volcano, Planetary](#)

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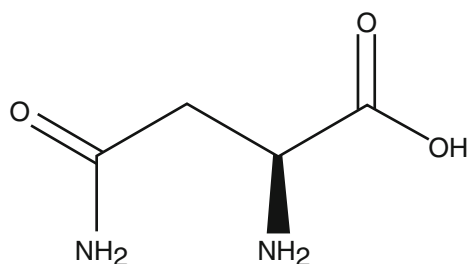
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Asparagine

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Asparagine, shown in Fig. 1, is one of the 20 ► [protein amino acids](#). Its three-letter symbol is Asn and one-letter symbol is N. It has a molecular weight of 132.12. It has an amide group ($-\text{CONH}_2$) in its side chain, and it is easily hydrolyzed to give ► [aspartic acid](#), another protein amino acid (Asp), and ammonia. In the hydrolysis of proteins, both aspartic acid and asparagine are determined as aspartic acid (noted Asx as the origin cannot be determined unambiguously). It



Asparagine, Fig. 1 Structural formula of asparagine

is classified as a neutral amino acid with an isoelectric point (pI) of 5.41.

Cross-References

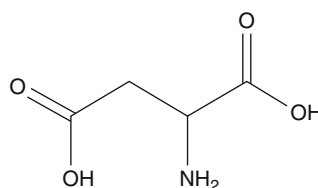
- [Amino Acid](#)
- [Aspartic Acid](#)
- [Protein](#)

Aspartic Acid

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Aspartic acid, shown in Fig. 1, is one of the 20 protein ► [amino acids](#). Its three-letter symbol is Asp and one letter symbol is D. It is a mono-aminodicarboxylic acid, and it is classified as an acidic amino acid. Aspartic acid has the lowest isoelectric point (pI) 2.77 of the protein amino acids. It is among the five amino acids that were detected in Miller's electric discharge experiment in 1953 and is found in extracts from carbonaceous chondrites. Since it has two carboxyl groups (α - and β -carboxyl group), it can make both α - and β -peptide bonds with other amino acids. In biosynthesis of ► [proteins](#), only α -peptide bonds are formed. As the ► [racemization](#) of aspartic acid is relatively rapid, the D/L ratio of aspartic acid can be used for dating biological materials such as bone.



Aspartic Acid, Fig. 1 Structural formula of aspartic acid

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Miller, Stanley](#)
- ▶ [Protein](#)
- ▶ [Racemization](#)

ASPAST, Peru

Octavio A. Chon-Torres
Programa de Estudios Generales, Universidad de
Lima, Lima, Perú

Acronyms

ASPAST

Definition

The Peruvian Association of Astrobiology, ASPAST (Asociación Peruana de Astrobiología in Spanish), is the first Peruvian institution dedicated to astrobiology. Founded in 2013, it includes researchers, students, and disseminators of astrobiology from all over the country. ASPAST is proud to count among its members with very committed people from different disciplines with a transdisciplinary perspective, from natural sciences to social sciences. ASPAST is a nonprofit organization that works constantly to integrate astrobiology's goals with scientific dissemination like workshops organized in schools, the launch of stratospheric balloons for experimental purposes, as well as conducting conferences, online courses, and participation in scientific meetings.

Further information: www.astrobiologia.pe

ASPERA-4

- ▶ [Venus Express](#)

Assay

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

A collection of activities performed to obtain an estimate of the biological cleanliness of spacecraft (or other) surfaces, involving collection and quantitation of microorganisms according to a standard protocol. In ▶ [Planetary Protection](#) application, often the NASA ▶ [Spore](#) Assay is used, with spore enumeration as the target for the assay. Such assays may be performed by a spacecraft project team for purposes of end-to-end bioburden accounting, or by the space agency planetary protection responsible official as a verification of the project bioburden accounting approach.

Cross-References

- ▶ [Bioburden](#)
- ▶ [Planetary Protection](#)
- ▶ [Spore](#)

Assimilative Metabolism

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Assimilative ▶ [metabolism](#) is the process by which an inorganic compound (NO_3^- , SO_4^{2-} , CO_2) is reduced for use as a cell nutrient source. Assimilative metabolism is conceptually different from the ▶ [reduction](#) reactions that take place when the same inorganic compounds are used as electron acceptors to obtain energy by ▶ [anaerobic](#)

respiration (► **dissimilative metabolism**). There are important differences between both types of ► **metabolism**. In the assimilative metabolism, only enough of the compound is reduced to satisfy the needs for cell growth, and the products are normally converted into cell material, while in the dissimilative metabolism, a large amount of ► **electron acceptor** must be reduced to guaranty the generation of sufficient energy and the product is excreted into the environment.

Cross-References

- **Anaerobic Respiration**
- **Dissimilative Metabolism**
- **Electron Acceptor**
- **Metabolism, Prebiotic**
- **Reduction**
- **Sulfate Reducers**

Association Constant

- **Affinity Constant**

Asteroid

Alan W. Harris
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Keywords

Dynamical and physical properties ·
Taxonomy · Mineralogy · Impact hazard ·
Mitigation

Synonyms

Minor planet; Planetoid; Small Solar System body

Definition

An asteroid is an irregularly shaped rocky body orbiting the Sun that does not qualify as a planet or

a dwarf planet under the International Astronomical Union's (IAU) definitions of those terms introduced in 2006. In contrast to planets and dwarf planets, asteroids do not have sufficient mass for their self-gravity to overcome rigid body forces and assume a hydrostatic equilibrium (nearly round) shape. In contrast to comets, asteroids are inert bodies that do not display a coma of gas and dust (although a few objects originally classed as asteroids have subsequently been found to display cometary activity). Very small objects with a size of less than about 10 m are normally referred to as meteoroids.

Overview

The first asteroid, 1 Ceres, was discovered in 1801 by the Italian astronomer Giuseppe Piazzi, quickly followed in succeeding years by the discovery of 2 Pallas, 3 Juno, and 4 Vesta. Ironically, Ceres is now classed as a dwarf planet under IAU Resolution B5 of 2006, and Pallas and Vesta are candidates for transfer to this new category of dwarf planets. Since about 1850, the discovery rate has increased dramatically, especially in recent years, leading to the current tally (September 2021) of over 585,000 numbered asteroids. An asteroid is assigned a permanent designation, i.e., a sequential number, once its orbit has become accurately established through a sufficient number of astrometric observations.

Asteroids and comets are considered to be remnant bodies from the epoch of planet formation. Planet embryos, roughly lunar-sized bodies, formed in the protoplanetary disk about 4.5 billion years ago via the accretion of dust grains and collisions with smaller bodies (kilometer-sized planetesimals). A number of planet embryos succeeded in developing into the planets we observe today; the growth of other planet embryos and planetesimals was terminated by catastrophic collisions or a lack of material in their orbital zones to accrete. Most asteroids are thought to be the fragments of bodies that formed in the inner Solar System and were subsequently broken up in collisions. Comets and related icy bodies are thought to have accreted in the cold, outer regions of the protoplanetary disk where volatile

materials, such as water and carbon dioxide, were abundant as ices.

Most numbered asteroids are in the main asteroid belt between the orbits of Mars and Jupiter. The existence of the main belt is thought to be due to the collisional fragmentation of remnant planet embryos and planetesimals that were prevented from accreting into planets by the gravitational perturbations of the nearby massive planet Jupiter.

Main-belt asteroids (here we include Ceres, which has been reclassified as a dwarf planet – see above) consist largely of silicates and metals and come in all shapes and sizes up to about 1,000 km in diameter. Table 1 lists physical data for the first ten asteroids discovered. Large asteroids with diameters of several hundred km tend to be roughly ellipsoidal, but smaller objects generally have very irregular shapes. Asteroid surfaces appear to consist of loose dust mixed with gravel and boulders (regolith), whereby there is evidence that the regolith of km-sized bodies is coarser and less dusty than that of large main-belt asteroids.

Asteroid Dynamical Groupings

Asteroids are classified dynamically according to their orbital elements (semimajor axis, period, inclination, eccentricity, etc.). The most significant grouping of asteroids is the main belt, between about 2.0 and 3.5 astronomical units (au, the mean Sun-Earth distance) from the Sun. The main belt is populated by millions of asteroids, some 585,000 of which have been assigned sequential numbers to date.

A number of asteroid families exist in the main belt. Family members have very similar dynamical characteristics and may be fragments from relatively recent (relative to the history of the Solar System) collisions. For example, there are large families associated with the main-belt asteroids 4 Vesta, 8 Flora, and 10 Hygiea (Table 1). In these cases, the families presumably arose as the result of cratering events that gave rise to ejecta from the surfaces of the large asteroids. In other cases, precursor asteroids were apparently completely broken up. In both scenarios, the result

Asteroid, Table 1 The first ten numbered asteroids

Number and name	Discovery: year, site, and discoverer	Diameter (km)	Taxonomic class (see below) [4]	Bulk density (g cm^{-3}) [1]	Rotation period (h) [5]
1 Ceres	1801, Palermo, G. Piazzi	939 ± 0.2	G, C	2.16 ± 0.008	9.074
2 Pallas	1802, Bremen, H. W. Olbers	533 ± 6 [1]	B	2.71 ± 0.11	7.813
3 Juno	1804, Lilienthal, K. Harding	234 ± 11 [2]	S	–	7.210
4 Vesta	1807, Bremen, H. W. Olbers	525 ± 0.2	V	3.46 ± 0.03	5.342
5 Astraea	1845, Driesen, K. L. Hencke	119 ± 7 [2]	S	–	16.81
6 Hebe	1847, Driesen, K. L. Hencke	185 ± 3 [2]	S	–	7.274
7 Iris	1847, London, J. R. Hind	200 ± 10 [2]	S	–	7.139
8 Flora	1847, London, J. R. Hind	136 ± 3 [2]	S	–	12.86
9 Metis	1848, Markree, A. Graham	172 ± 13 [3]	S	–	5.079
10 Hygiea	1849, Naples, A. de Gasparis	434 ± 14 [6]	C	1.94 ± 0.25 [6]	13.8[6]

References: Data for Ceres and Vesta are from the results of the Dawn rendezvous mission (Park et al. 2016 and Russell et al. 2012, respectively). References for the remaining objects are: [1] Britt et al. (2002); [2] Tedesco et al. (2002); [3] Müller and Barnes (2007); [4] Bus and Binzel (2002); [5] Warner et al. (2019); [6] Vernazza et al. (2020). (Updates to the data given here can be found at: <https://ssd.jpl.nasa.gov/sbdb.cgi>)

Asteroid, Table 2 Selected asteroid dynamical groups

Dynamical category	Semimajor axis [au]	Approx. no. known ^a	Notes
Trans-Neptunian objects (TNOs) ^b	>30	2,600	
Centaurs ^b	5.2–30	1,000	Possibly TNOs whose orbits have been perturbed by Neptune
Jupiter Trojans	5.05–5.4	10,000	Associated with the Lagrangian points of Jupiter's orbit
Main belt	2.0–3.5	1.1×10^6	5.85×10^5 <i>numbered</i> asteroids
Amors ^c	>1	11,000	$1.017 < \text{perihelion} \leq 1.3$ au
Apollos ^c	≥ 1	13,400	Perihelion ≤ 1.017 au
Atens ^c	<1	2,100	Aphelion ≥ 0.983 au
Inner-Earth objects (Atiras) ^c	<1	26	Aphelion <0.983 au

^aThe listed approximate numbers of known objects are valid as of September 2021; these numbers increase rapidly with time as new objects are discovered. For more details and updates, see the Minor Planet Center web site <https://www.minorplanetcenter.net/iau/lists/MPLists.html>

^bTNOs and Centaurs are distant icy bodies that may have much in common with comet nuclei

^cThe orbital characteristics of the different classes of NEAs are defined with respect to the Earth's perihelion (0.983 au) and aphelion (1.017 au) distances

is a family of fragments with similar orbits (and dust particles that probably contribute to the cloud of dust associated with the ecliptic plane and give rise to the zodiacal light). In most cases, the family members have very similar compositions.

Other major dynamical groups are described below and listed in Table 2.

Jupiter Trojans are asteroids that are trapped in dynamically stable zones 60° ahead of and behind Jupiter in its orbit. The stable zones are associated with the L4 and L5 Lagrangian points of Jupiter's orbit. There are some 10,000 known Jupiter Trojans orbiting between about 5.0 and 5.4 au from the Sun.

Trans-Neptunian Objects (TNOs) are very distant, presumably icy, bodies with semimajor axes larger than 30 au. Most TNOs are classed as asteroids according to the formal definition of an asteroid given above, but in terms of their physical characteristics, they may have more in common with comets. The first TNO was discovered in August 1992; some 2,600 have been discovered since.

The Centaurs have orbits between that of Jupiter and the TNOs. Centaurs are possibly objects that originated as TNOs but due to perturbations by Neptune are now in orbits that bring them

closer to the Sun. The number of known Centaurs is currently around 1,000. A few Centaurs have been observed to display comae and are classed as both asteroids and comets. TNOs and Centaurs are of particular scientific interest because they have been subject to less thermal alteration and processing than main-belt asteroids and may contain well-preserved primordial material from the epoch of formation of the Solar System.

Near-Earth asteroids (NEAs) are asteroids that are thought to originate in the main belt but which now have highly evolved orbits with perihelion distances of less than 1.3 au. NEAs are further categorized dynamically as Amors, Apollos, Atens, or Atiras (also referred to as inner-Earth objects – IEOs), according to the semimajor axes, aphelion and perihelion distances of their orbits (Table 2). The orbits of NEAs may evolve to intersect that of the Earth. Interest in the population of NEAs is focused mainly on the associated impact hazard (see below), but close approaches of NEAs to the Earth facilitate detailed telescope observations, including radar investigations, which provide insight into the characteristics of asteroids in general. Furthermore, the rendezvous missions, NEAR-Shoemaker, Hayabusa, Hayabusa 2, and OSIRIS-Rex, have provided a wealth of data on

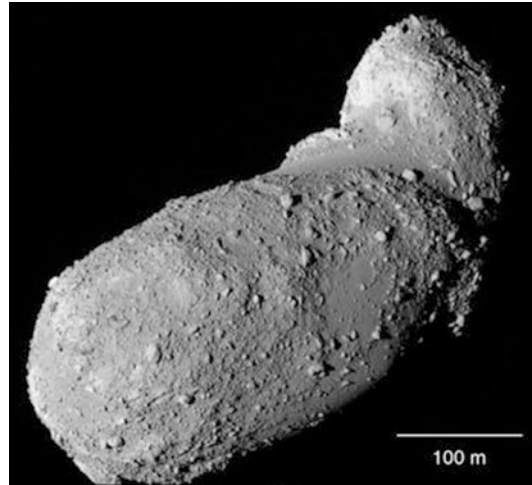


Asteroid, Fig. 1 Near-Earth asteroid 433 Eros was the target of the NASA NEAR-Shoemaker spacecraft in 2000–2001. Eros is 34 km in length and of taxonomic type S. The large number of impact craters indicates an age of 1–2 Gyr. (Credit: JHUAPL, NASA)

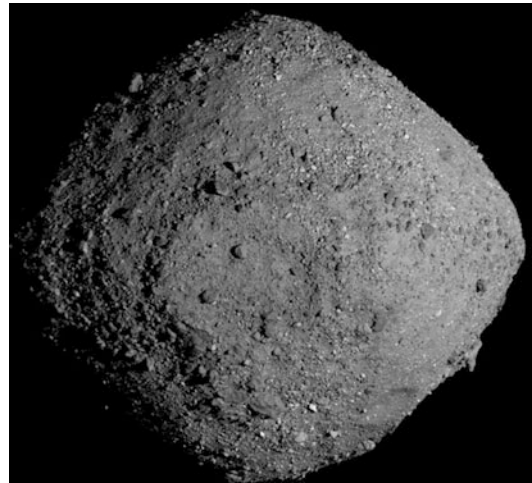
the NEAs 433 Eros (Fig. 1), 25143 Itokawa (Fig. 2), 162173 Ryugu, and 101955 Benu (Fig. 3), respectively.

The Taxonomic Classification and Mineralogy of Asteroids

Sunlight incident on the surface of an asteroid suffers absorption in particular wavelength bands depending on the minerals present; reflected light therefore carries a spectral signature of the mineralogical composition of the asteroid's surface. Attempts have been made to classify asteroids according to details of the absorption features in their optical reflection spectra observed with astronomical telescopes. A number of classification schemes have been devised based on letters of the alphabet (e.g., Bus and Binzel 2002; DeMeo et al. 2009; Tholen and Barucci 1989). For example, a very common spectral or taxonomic type is S, originally intended to signify a stony or “siliceous” object. Another common type is C,



Asteroid, Fig. 2 Near-Earth asteroid 25143 Itokawa was the target of the Japanese Hayabusa spacecraft in 2005–2006. Itokawa is 535 m in length and of type S. Itokawa, which lacks craters, is much younger than Eros and may be an aggregate of components weakly bound by gravity or “rubble pile.” (Courtesy of JAXA)



Asteroid, Fig. 3 Near-Earth asteroid 101955 Benu was the target of the NASA OSIRIS-REx spacecraft launched in September 2016, which reached Benu in August 2018. Benu is surprisingly spheroidal in shape and has a diameter of some 500 m. It is a B-type asteroid and has a much rougher surface than anticipated from ground-based observations. (Credit: NASA)

originally signifying carbon rich or “carbonaceous.” Other letters, which are in common use, are M for metallic and V for Vesta-like. As the inventory of asteroid spectral data grew, and more

distinct spectral types were discovered, the taxonomic alphabet had to expand to incorporate more letters. Thanks to the improved sensitivity of modern astronomical instrumentation, it has become possible to identify subtle differences in spectral features within the classical taxonomic types, leading in some cases to the addition of small letters after the class letter to signify subclasses, e.g., Cb, Sq, etc.

Basic Methodology

Our knowledge of the physical properties of asteroids derives primarily from astronomical observations in various spectral ranges, using both ground-based and space-based telescopes. Information on rotation rates and shapes can be obtained from observing the variation of the brightness of reflected sunlight from an asteroid’s surface as it rotates. Information on mineralogy can be derived from spectroscopic observations, primarily in the visible and infrared regions of the spectrum. Observations in the mid-infrared, or thermal-infrared, spectral region provide information on surface temperatures and allow sizes to be calculated. A powerful method for the derivation of asteroid physical properties is radar. Analysis of radar echoes from asteroids provides precise information on position and velocity and therefore orbital parameters, and in some cases radar

imaging can reveal details of surface structure, and provide information on size, shape, rotation rate, and composition. Unfortunately, the use of radar is restricted to objects that make close approaches to the Earth or are relatively large.

Increasingly, rendezvous and fly-by space missions are contributing detailed information on selected asteroids. The data from such missions provide far more accurate information on the physical characteristics of the target objects than can be obtained from remote astronomical observations. On the other hand, although astronomical observations provide less detailed information, they have done so to date for many thousands of asteroids, while only a handful of asteroids have been visited by spacecraft. Astronomical observations and space missions are complementary approaches in asteroid research, with space missions providing “ground-truth” data that help to calibrate the results obtained from astronomical observations.

Key Research Findings

Water and Organic Material in Asteroids

The mineralogical associations listed in Table 3 include hydrated (water-bearing) silicates and organics. There is considerable evidence that hydrated minerals are also present on a number of M-type asteroids. Furthermore, water ice and

Asteroid, Table 3 Important asteroid taxonomic (spectral) classes

Class	Probable mineralogy	Associated geometric albedo ^a (p_v) range	Approx. % of all classified asteroids ^b
D, P	Carbon, organic-rich silicates	0.03–0.06	2
C, B	Carbon, organics, and hydrated silicates	0.03–0.1	30
M	Fe, Ni, and enstatite	0.1–0.2	2
S	Olivine, pyroxene, and metals	0.1–0.3	40
Q	Olivine, pyroxene, and metals	0.2–0.5	1
V	Pyroxene, feldspar	0.2–0.5	3
E	Enstatite, other Fe-poor silicates	0.3–0.6	1
X	Unknown (signifies otherwise unclassifiable featureless spectrum)	0.03–0.6	15

^aThe geometric albedo p_v is the ratio of a body’s (V-band) brightness at zero-phase angle to the brightness of a perfectly diffusing (Lambertian) disk with the same apparent size as the body

^bEstimated from the data of Bus and Binzel (2002) and Tholen and Barucci (1989). Note that discovery and observation bias against objects with dark surfaces implies that the distribution of taxonomic classes in the known population may not be representative of the entire asteroid population

organic material have been detected on the surface of the main-belt C-type asteroid 24 Themis (Campins et al. 2010; Rivkin and Emery 2010) and since on many other asteroids (Rivkin et al. 2015). The fact that many asteroids evidently carry significant amounts of water and organic materials may be relevant to questions concerning the origin of water and life on Earth. It is widely believed that bodies similar to asteroids and comets contributed to the early Earth's inventory of water and organics, but there is currently no consensus as to when or how.

A point of current debate is whether Earth's water was provided primarily by asteroidal material from the outer main belt at the time of formation of the Earth or whether comets and asteroids contributed water-bearing material at a later stage after the Earth had formed and cooled. Measurements indicate that the hydrogen isotopic ratio D/H in most of the comets for which such measurements have been made is an order of magnitude higher than that of protosolar material, but this significantly exceeds the factor of 6 enrichment of the Earth's oceans. On the other hand, the D/H ratio of carbonaceous chondritic asteroidal material is compatible with that of the Earth's oceans. Therefore, at face value, the D/H evidence appears to argue against a dominant post-formation water contribution from comets.

Investigations of the composition of meteorites, which are thought to originate in asteroids, indicate that carbonaceous chondritic asteroidal material contains up to 10% by mass of water (Drake and Righter 2002; Morbidelli et al. 2000). Therefore, asteroidal material, in the form of planet embryos from the outer main belt incorporated into the forming Earth (Morbidelli et al. 2000), may have contributed much of the Earth's water. Alternatively, hydrogen present in material similar to enstatite chondrite meteorites, incorporated into the growing proto-Earth, could account for most of its present-day water (Piani et al. 2020). While on the basis of current knowledge, e.g., comparisons of isotope ratios and noble gas ratios, it appears unlikely that comets or known asteroid types bombarding the Earth after the formation phase could have contributed significant water (Drake and Righter 2002), the debate

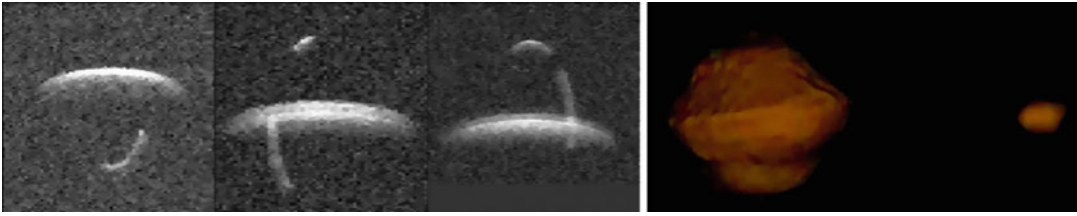
continues to the present day. For example, Lis et al. (2019) present evidence that hyperactive comets, such as 46P/Wirtanen, may have D/H ratios similar to that of the Earth's oceans.

In the case of organic material, a postformation source is required because it seems significant quantities of organics could not have survived on the Earth until formation was complete and the Earth had cooled. The most plausible source of organic material is therefore the flux of asteroids and comets that deposited material on the Earth after the formation phase. Some 100 amino acids have been detected in meteorites (e.g., the Murchison meteorite), and it is widely believed that many comets and asteroids carry amino acids and other organic molecules.

The Densities and Structure of Asteroids

Reliable estimates of density are difficult to obtain, since techniques for obtaining accurate masses and sizes of asteroids are complex and subject to large uncertainties. There are various methods of determining asteroids masses (see Britt et al. 2002 for a review), which all require measurement of the asteroid's gravity field by means of, for example, a spacecraft, observations of the perturbations of the orbits of other asteroids or Mars (applicable to large asteroids only), or observations of a satellite or companion asteroid by means of precision optical or radar observations. Asteroid sizes can be determined from, for example, spacecraft, thermal-infrared measurements (see Harris and Lagerros 2002 and Delbo' et al. 2015 for reviews, and the section on asteroid physical properties below), radar observations (see Fig. 4), polarimetry (e.g., Delbo' et al. 2007), and occultation observations.

Density estimates for just a few hundred asteroids are available to date. An important finding is that asteroid bulk densities tend to be significantly lower in general than expected from measurements of meteorites and terrestrial analogues of asteroid material ($2\text{--}8\text{ g cm}^{-3}$). In fact the bulk densities of some asteroids appear to be similar to that of water (1 g cm^{-3}), implying that these bodies must be highly porous. Such results and those from rendezvous missions provide convincing evidence that some asteroids, e.g., 25143



Asteroid, Fig. 4 Radar images of binary near-Earth asteroid 1999 KW₄ (left-hand row of three frames) received at the Goldstone 70-m antenna in May 2001. Each image has a resolution of 19 m/pixel and is a time exposure spanning several hours, showing the motion of the secondary relative to the primary. Due to the complexities of radar

imaging, these three images do not show true relative sizes or shapes of the components. The right-hand frame shows a computer model of the system in which the two components are seen to scale. The diameters of the primary and secondary bodies are 1.5 km and 0.5 km, respectively. (Images courtesy of L. A. M. Benner, NASA/JPL)

Itokawa (Fig. 2), 162173 Ryugu, and 101955 Benu (Fig. 3), are aggregates of components of various sizes weakly bound by gravity, or “rubble piles.” An asteroid that has been shattered by collisions with other objects may survive under the collective weak gravitational attraction of the resulting fragments as a cohesionless, consolidated rubble pile.

The rubble-pile idea leads to a natural explanation for the existence of the many binary asteroid systems or asteroids with natural satellites (moons) that have been discovered (see Fig. 4 for an example). The spin rates of asteroids can be modified by dynamical phenomena, such as the close approach to a planet, or the reflection and/or absorption and thermal reradiation of sunlight. If a loosely bound rubble pile is spun up sufficiently, it can shed mass that may form a companion body or moon gravitationally bound to it. Computer simulations have demonstrated the credibility of binary asteroid production via the spin-up and rotational breakup of a rubble pile (Walsh et al. 2008).

Near-Earth Asteroids and the Impact Hazard

As a result of subtle thermal effects and the very strong gravitational field of Jupiter, small main-belt asteroids can drift into certain orbital zones from which they may be ejected under the influence of Jupiter into the inner Solar System. As a result, there exists a population of near-Earth asteroids with orbits that can cross that of the Earth. Comets can also collide with the Earth, but the risk of a comet impact is thought to be

much lower than that of a NEA impact (although given the potentially high relative velocity, the effects in the case of a comet impact could be much more devastating).

The phenomenon of collisions in the history of our Solar System is very fundamental, having played the major role in forming the planets we observe today. Asteroids and comets may have contributed to the delivery of water and organic materials to the early Earth necessary for the development of life, but later impacts probably played a role in mass extinctions, and they currently pose a small but significant threat to the future of our civilization. Collisions of objects with the Earth have taken place frequently over geological history, and it is an irrefutable scientific fact that major collisions with the Earth will continue to occur at irregular, unpredictable intervals in the future.

Collisions of asteroids and comets with the Earth can have dramatic effects on the biosphere. A well-known example is the so-called Cretaceous–Paleogene (K–Pg) event, formerly known as the Cretaceous–Tertiary event, 65 million years ago, which is thought to have been caused by the impact of an object with a diameter of 10–15 km, bringing about the extinction of not only the dinosaurs but also more than 70% of all species living at the time. The idea that the K–Pg mass extinctions observed in the paleontological record were caused by the impact of a near-Earth asteroid was proposed by Alvarez et al. (1980), and given a great deal of credibility by the discovery of a 65-million-year-old circular impact structure

nearly 200 km in diameter centered near the town of Chicxulub on the Yucatan Peninsula, Mexico (Pope et al. 1991). The impactor must have had a diameter of at least 10 km and may have hit the Earth with a velocity of some 15–25 km s^{−1}. The results of such an event would have included the deposition of billions of tons of dust and aerosols into the stratosphere that would have spread around the world, dimming sunlight, and cooling the surface for many months. The ensuing climatic effects could have created a very stressful environment for life on the Earth’s surface for many years.

While past impacts have probably altered the evolutionary course of life on Earth, and paved the way for the dominance of mankind, we would now rather not remain at the mercy of this natural process. Can we protect our civilization from the next major impact? Various initiatives are being taken by space agencies, including ESA and NASA, and research groups around the world to identify potential future impactors, investigate their physical characteristics, and develop strategies to mitigate against impacts.

A number of observatories are operated specifically to discover near-Earth objects and establish their orbits. The main currently active asteroid search programs, such as Pan-STARRS, the Catalina Sky Survey, and ATLAS, are based in the USA (for a summary, see Melosh et al. 2019).

Many observers, including amateur astronomers, around the world contribute to the tracking of asteroids and submit their astrometric data to the Minor Planet Center in Cambridge, Massachusetts, which acts as a clearing house for asteroid position data and maintains databases of orbits.

As of September 2021, the number of known near-Earth objects is approaching 27,000, of which some 900 have diameters of 1 km or more; the total number of the latter, including as yet undiscovered objects, is thought to be about 1,000 (see below). A special term, “potentially hazardous asteroids” (PHAs), is reserved for those with diameters above a critical size and orbits that bring them within 0.05 au of the Earth’s orbit. PHAs are large enough to survive passage through the Earth’s atmosphere and cause extensive damage on impact. The diameter threshold qualifying an object as a PHA is traditionally set at 140 m for historical reasons but is currently under debate.

The estimated impact frequency of NEAs on the Earth depends on size. The impact frequency increases with decreasing size due to the size distribution of the asteroid population: There are many more small objects than large ones. The impact risk to the Earth from NEAs based on recent assessments (e.g., Harris et al. 2015; Harris and D’Abramo 2015) is summarized in Table 4.

Asteroid, Table 4 Estimated frequency and effects of asteroid impacts on the Earth

Impactor size (m) larger than	Mean impact interval (year)	Energy released (megatons TNT)	Crater diameter (km)	Possible effects/comparable event
30	150	2	–	Fireball, shock wave, and minor damage
50	1,000	10	≤1	Tunguska-type explosion or small crater
100	10,000	80	2	Largest H-bomb detonation
200	40,000	600	4	Destruction on national scale
500	140,000	10,000	10	Destruction on continental scale
1,000	500,000	80,000	20	Many millions dead, global effects
5,000	20 million	10 million	100	Billions dead, global climate change
10,000	100 million	80 million	200	Extinction of human civilization

The energy release estimates assume a density of 3500 kg m^{-3} (stony body) and an impact velocity of 20 km s^{-1} . The given impact intervals are statistical, for example, the probability of a 100-m or larger object impacting in the next 100 years is 1%, which is the same as the probability of such an object *not* impacting in 46,000 years.

Asteroid Physical Properties Relevant to the Impact Hazard

Accurate assessment of the impact hazard depends on knowledge of the size distribution and orbits of the NEA population. Which physical parameters are most relevant for mitigation considerations? Preventing a collision with a NEA on course for the Earth would require either total destruction of the object, to the extent that the resulting debris poses no hazard to the Earth or, perhaps more realistically, deflecting it slightly from its catastrophic course. In either case, accurate knowledge of the object's mass would be of prime importance. In order to mount an effective mission to destroy the object, knowledge of its density, internal structure, and strength would also be required. Deflection of the object from its course would require the application of an impulse or continuous or periodic thrust, the magnitude and positioning of which may depend on the mass and its distribution throughout the (irregularly shaped) body, the surface characteristics, and the spin vector, depending on the strategy deployed. Mitigation planning takes on a higher level of complexity if the Earth-threatening object is a rubble pile or binary system.

Since the observed brightness of an asteroid is proportional to its surface albedo and cross-sectional area, a very rough size estimate can be obtained from the observed brightness and knowledge of the asteroid's orbit. However, the albedo can have any value between 3% and 60% (Table 3), so the assumption of a typical albedo of, say, 15%, can lead to errors in diameter and mass of a factor of 2 and 8, respectively. While current estimates of the overall impact hazard are necessarily based on the assumption of a typical or mean albedo for NEAs, more accurate methods of

size determination are clearly necessary for accurate hazard estimation and mitigation purposes.

Telescope observations in the thermal infrared combined with knowledge of an asteroid's optical brightness offer a means of obtaining more accurate information on size and albedo (Delbo' et al. 2015; Harris and Lagerros 2002). Darker, low albedo, asteroids are less reflective in the visible spectral region and absorb more solar radiation; they are therefore warmer and brighter in the thermal-infrared spectral range. The opposite is true for high-albedo asteroids. The two different physical relationships governing visible and thermal-infrared brightness enable simultaneous solutions for size and albedo to be obtained. While the number of asteroids observed in the thermal infrared is still only a very minor fraction of the total known, this technique has provided the vast majority of size and albedo determinations to date. For example, surveys of the sizes and albedos of thousands of NEAs have been carried out by the NASA WISE (Wide-field Infrared Survey Explorer) and Spitzer infrared space telescopes. WISE was launched to Earth orbit in December 2009 carrying a 40-cm-diameter telescope and infrared detectors. WISE surveyed the sky for nearly 12 months in its cryogenic phase and observed a total of at least 584 NEAs, of which more than 130 were new discoveries. The NEO-WISE project, funded by NASA, continues to use the WISE spacecraft (albeit without cryogen and therefore with warm and less sensitive detectors) to discover and characterize NEOs. Before the Spitzer Space Telescope ceased operations in 2020, it enabled the diameters and albedos of over 2000 NEAs to be estimated. See Trilling et al. (2020) for a review of Spitzer's contributions to asteroid science.

Applications

Apart from the contributions that asteroid research provides to our understanding of the evolution of the Solar System, the formation of the planets and the origin of life on Earth, and the hazard posed by near-Earth objects, an area of interest inspired by the recent rapid development of the field is that of

asteroids as potential providers of raw materials for future space-faring generations. As described above, some asteroids carry significant amounts of water that could be extracted and used to sustain human activities in space. The constituents of water, hydrogen, and oxygen could be used as rocket fuel. Other asteroids contain large amounts of metals, e.g., platinum group metals, that are used in many applications in industry and for which there is an ever-increasing demand.

Future Directions

The rate of discovery of NEAs is now seriously outstripping the rate at which the population can be physically characterized. The NEA population is still largely unexplored. Telescope observations will continue to provide valuable information about the NEA population as a whole, but rendezvous missions are vital for probing the detailed characteristics of individual objects. To date only four NEAs have been visited by spacecraft (see above), but many more rendezvous missions to NEAs of different taxonomic types will be necessary before we can start to understand the diverse compositions, structure, and origins of NEAs and their relation to meteorites.

Mitigation of Hazardous Asteroids

At present, there is no general agreement on the most effective strategy to adopt in the case of a predicted impact. In the case of an object with a diameter below 50 m, the best course of action may be to simply evacuate the region around the predicted impact point (see Table 4), assuming there would be sufficient advance warning (only a small fraction of the asteroids in this size category have been discovered to date). For larger objects, a number of mitigation strategies may be considered, depending on circumstances. In 2004, ESA established the Near-Earth Object Mission Advisory Panel (NEOMAP) to study and prioritize proposals for planetary defense missions. NEOMAP concluded that a dual-spacecraft mission called Don Quijote, based on the kinetic-impactor method, should be given highest priority as the basis for ESA's participation in

NEO impact-risk assessment and reduction (NEOMAP report to ESA 2004). The kinetic-impactor method involves applying an impulsive force to the asteroid by means of a large mass in the form of a spacecraft accurately guided to the target at a high relative velocity. The change of momentum of the target asteroid depends on the porosity and the amount of ejecta produced in the impact (Fig. 5), predictions of which would require some prior knowledge of the asteroid's physical properties. To facilitate effective mission planning, the kinetic-impactor approach would require an initial reconnaissance mission to gather relevant physical data.

The NASA report to Congress (2007) on the surveying and deflection of near-Earth objects concluded that nuclear devices offer the most effective means of applying a deflecting force to



Asteroid, Fig. 5 Artist's impression of a kinetic-impactor spacecraft deployed to modify the orbit of a near-Earth asteroid. The second spacecraft at the bottom of the picture is orbiting the asteroid or "hovering" near it to observe the effects of the impact and monitor the altered trajectory of the asteroid. The scenario depicted derives from the Don Quijote mission, studies of which were commissioned by ESA in 2006. The European-led NEOShield project carried out detailed investigations of this and other promising deflection techniques. (Credit: ESA-AOES Medialab)

an asteroid. While they may offer the only feasible solution in desperate circumstances, e.g., in the case of very little advance warning, it is widely felt that the obvious political problems associated with launching nuclear devices and testing them in space seriously compromise the practicability of this technique. The NASA report concluded that the most effective nonnuclear option is the kinetic impactor.

Alternative approaches include the “gravity tractor” and “space tug.” The gravity tractor relies on the force of gravity between the target asteroid and a spacecraft hovering under power in close proximity to gradually modify the asteroid’s orbit. A significant advantage of the gravity tractor is that no contact with the target is required. The principle of the space tug is similar, but in this case, the spacecraft is physically attached to the asteroid’s surface and prior knowledge of surface characteristics would be necessary for effective mission planning. The gravity tractor and space tug are examples of “slow-push-pull” approaches that require sustained, reliable propulsion and sophisticated autonomous control systems to achieve the required amount of deflection, but may be promising techniques in cases in which there is sufficient advance warning (e.g., decades), the target is relatively small, and/or a very slight, precise deflection is required to prevent an impact on the Earth.

A unique research program funded by the European Commission and involving 13 partner organizations in six countries, including Russia and the USA, was established in 2012 to investigate deflection techniques in detail. The project, called NEOShield (Drube et al. 2015; Harris et al. 2013), investigated the feasibility of promising deflection options and carried out research into the mitigation-relevant physical properties of NEOs. A follow-on project, NEOShield-2, was funded from 2015 until 2017.

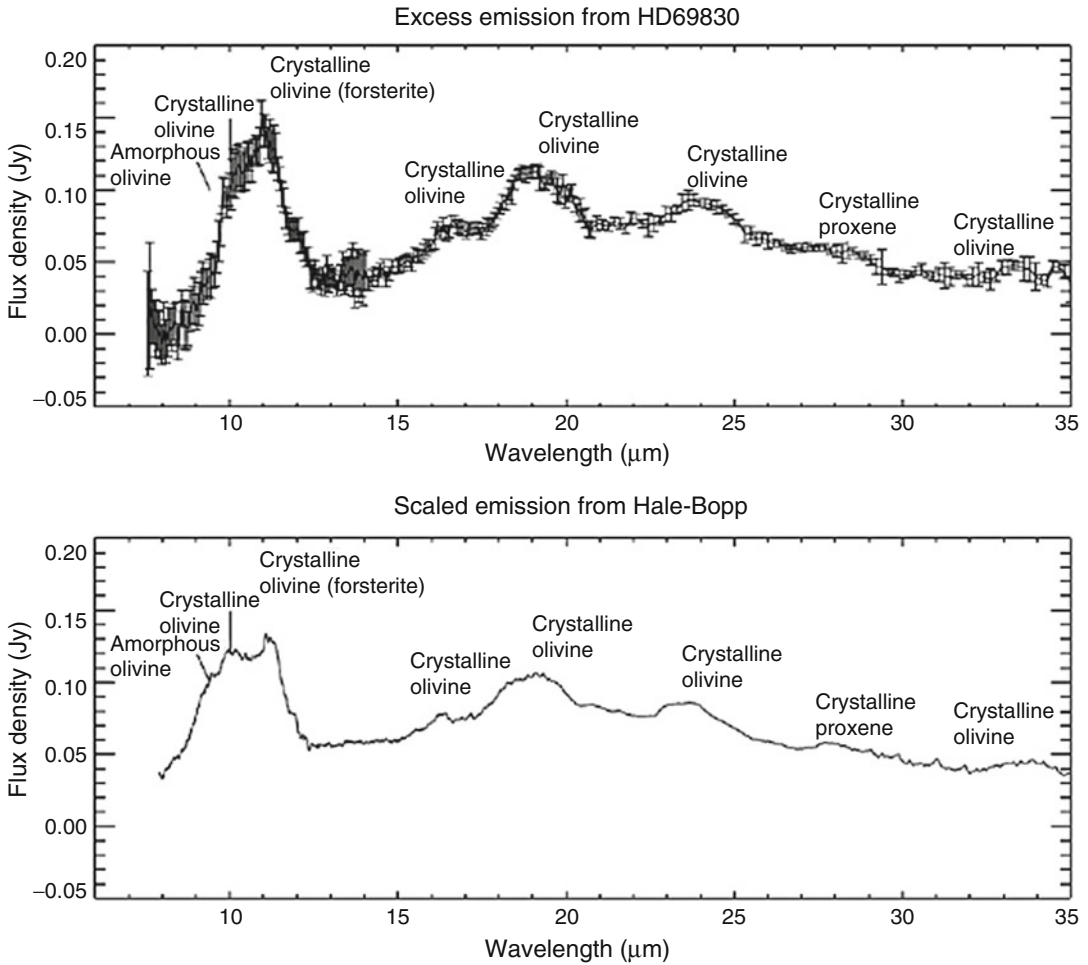
Endeavors such as those described above paved the way for two missions: the NASA Double Asteroid Redirect Test (DART: Cheng et al. 2018), a kinetic impactor, due for launch at the end of 2021 to the binary asteroid 65803 Didymos, and the ESA mission Hera (Michel et al. 2018), a

reconnaissance mission with the aim of carrying out a survey a few years later of the effects of the impact on the Didymos system. The aim of DART is to deflect the small secondary of the binary asteroid Didymos (primary diameter = 780 m), chosen so that the perturbation of the orbit of the secondary (diameter = 160 m) can be observed from ground-based facilities in 2022. DART will be the first mission to measurably alter the motion of an asteroid, and the first realistic demonstration of the kinetic-impactor deflection technique. Hera will obtain information needed for an accurate assessment of the feasibility and efficiency of the technique. At the time of writing, the European Commission is funding two research programs, NEO-MAPP and NEOROCKS, in which research relevant to the interpretation of DART and Hera data is being carried out.

Asteroids in Extrasolar Planetary Systems

The presence of asteroids and comets outside our Solar System cannot be confirmed by direct observation, but there is considerable evidence that such objects play a role in the formation and development of extrasolar planetary systems. Infrared observations have shown that many stars exhibit thermal emission in excess of that predicted for their stellar types. The excess thermal emission can be modeled in terms of surrounding dust disks heated by the star that may be the debris of asteroids and comets destroyed by collisions or close approaches to planets or the central star.

Data obtained with the Spitzer Space Telescope in the mid-infrared spectral region suggest that some extrasolar systems have multiple debris disks: warm disks analogous to the main asteroid belt and cooler outer disks possibly containing bodies analogous to the distant TNOs in the Solar System (for a review, see Chen et al. 2020). Attempts have been made to match the infrared spectra of extrasolar debris disks with spectra obtained from observations of comets and asteroids. In the case of the star HD 69830, which exhibits unusually intense emission from dust (Fig. 6), the best match appears to be materials found in P- or D-type asteroids (Lisse et al.



Asteroid, Fig. 6 Comparison of features in the spectra of the excess thermal emission from the star HD 69830 and the comet Hale Bopp. The similarity of the spectra strongly suggests that the dust in the debris disk around HD 69830 has a very similar composition to dust in the Solar System. Despite the similarities to the spectrum of Hale Bopp,

detailed analysis of the spectral signature of the dust around HD 69830 indicates that it probably originates from the breakup of asteroids (Lisse et al. 2007). (The figure is taken from Beichman et al. (2005) and is reproduced by permission of the AAS)

2007), which are very numerous in the outer main belt. The production of dust would follow the collisional breakup of asteroids, as invoked to explain the existence of asteroid families and zodiacal dust in the Solar System (see section on “Asteroidal Dynamical Groupings” above).

The discovery of extrasolar planets and debris disks strongly suggests that planet formation is a common phenomenon in the Galaxy. Knowledge gained from investigations into the processes of planet formation and development in our Solar

System will continue to stimulate and guide future research into similar processes taking place elsewhere in the Galaxy.

Cross-References

- [Carbonaceous Chondrite](#)
- [Centaur \(Asteroids\)](#)
- [Chondrite](#)
- [Dwarf Planet](#)

- [Meteorite, Murchison](#)
- [Near-Earth Objects](#)
- [Planet](#)

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Asteroid (433) Eros

- [Eros Asteroid](#)

Asteroid 101955

- [Bennu Asteroid](#)

Asteroid 162173

- [Ryugu Asteroid](#)

Asteroid 25143

- [Itokawa Asteroid](#)

Asteroid Belt, Main

Alan W. Harris

Institute of Planetary Research, DLR, Berlin, Germany

Synonyms

[Main asteroid belt](#)

Definition

The ► [asteroid](#) belt is a region of the ► [Solar System](#) between the orbits of ► [Mars](#) and ► [Jupiter](#) that contains the orbits of most of the known asteroids (over 1.1 million to date). The reason for the existence of the asteroid belt is thought to be gravitational perturbations of the orbits of ► [planetesimals](#) and planetary embryos (planetary building blocks) in the region by the massive ► [planet](#) Jupiter that have prevented these objects from combining to form a planet. Collisions between objects in the asteroid belt cause them to be ground down into an ever-increasing number of smaller bodies.

Cross-References

- [Asteroid](#)
- [Jupiter](#)
- [Mars](#)
- [Planet](#)
- [Planetesimals](#)
- [Solar System, Inner](#)

AsteroSeismology

Patrick Eggenberger
Geneva Observatory, University of Geneva,
Geneva, Switzerland

Synonyms

[Stellar seismology](#)

Definition

AsteroSeismology is the study of stellar oscillations aiming at determining the internal structure and global properties of stars. The oscillation patterns observed on the stellar surface result from waves that propagate into the interior of the star. The observation of these oscillations, done either by monitoring the variation of the star's brightness or of its radial velocity, offers therefore a unique means to probe the otherwise unobservable internal layers of stars and to help us in our understanding of the complex physical processes at work in stellar interiors.

Cross-References

► [Stellar Pulsation](#)

Asthenosphere

Daniele L. Pinti
Geotop, Research Centre on the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Following the rheological subdivisions of the Earth, the asthenosphere is the viscous mechanically weak-ductile layer of the mantle. It lies

below the lithosphere, at depths between 100 and 200 km down to the transition zone (670 km). The asthenosphere plays a key role in plate tectonic movements and isostatic adjustments. The heat is transmitted by convection, and the thickness and viscosity of this layer controls the stress applied at the base of the lithosphere. This, in turn, influences the global tectonic style of the Earth and of any other terrestrial planet. The viscosity and the convective regime of the asthenosphere has also a control on the degassing history of a terrestrial planet and the evolution of its atmosphere.

Cross-References

► [Mantle](#)
► [Plate Tectonics](#)

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Astrobiocentrism

Octavio A. Chon-Torres
Programa de Estudios Generales, Universidad de Lima, Lima, Peru

Definition

According to Chon-Torres (2020, 2021), astrobiocentrism is the way of understanding the place of human beings in the universe from an astrobiological perspective, overcoming the limitations of biogeocentrism, where the latter focuses on the understanding of life in an Earth-centric, carbon-based way (Chela-Flores 2001, 2009; Arétxaga 2004). (Note that the term “bio” is at the beginning of the word because that is how it appears in the original. In the specific case of astrobiocentrism, the word “astrobio” is

composed and at the beginning to evoke the astrobiological meaning to be expressed.) Some of the conceptual astrobiocentric pillars would be found in telompathy (Cockell 2005a, b, 2011) and the development of astroethics (Chon-Torres 2018). In it the debates on what we understand by a planetary, interplanetary, and multiplanetary ethics take place. It is an opportunity to put terrestrial ethics in context in an astrobiological landscape. In this concept, we would not only see ourselves as planetary citizens, but as citizens who share a moral community that despite having differences on how to manage or conduct an off-Earth society promotes dialogue and consensus for peaceful coexistence (Chon-Torres and Murga-Moreno 2021).

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Astroethics

Erik Persson
Department of Philosophy, Lund University,
Lund, Sweden

Keywords

Astroethics · Ethics · Applied ethics · Moral status · Interstellar communication

Synonyms

[Astroethics](#); [Ethics of astrobiology](#)

Definition

Astroethics is the study of ethical questions in connection with astrobiology.

Overview

In addition to being concerned with the same ethical issues as science and academia in general, for instance research ethics, discrimination, etc., astroethics also includes questions that are particular to astrobiology or have an added twist or dimension when applied to astrobiology. Among the key issues, we find the following:

- The moral for status of extraterrestrial life and its implications, for example, planetary protection and experimentation.
- How to interact with extraterrestrial life, including a wide range of issues ranging from what kind of experiments would be acceptable on different types of extraterrestrial life-forms,

to who should speak for Earth when interacting with extraterrestrial intelligent life.

- How to handle risks to humanity and other Earth life when interacting with extraterrestrial life, including risks of contamination in connection with Earth return missions and the retrieval of extraterrestrial material to Earth, and risks in connection with interstellar communication.
- How to balance conflicting interests, including conflicting interests regarding planetary protection between astrobiology, commercial interests, and groups who perceive space as a frontier that needs to be conquered, conflicting interests regarding the protection of space analogue sites on Earth between astrobiology and commercial and political interests; conflicting interests regarding the placement of telescopes between astrobiology, environmental concerns, and indigenous culture; and conflicting interest regarding public funding between astrobiology and other scientific as well as nonscientific competing projects.
- How to communicate with and involve the general public, including how to communicate results and possible interpretations of results to the public in a way that is transparent, but also accurate and that minimizes the risk of misinterpretation and inflated expectations while maintaining public trust in astrobiology and in science in general and avoid fuelling conspiracy theories (Almár and Race 2011; Chon-Torres 2018; Gartrelle 2015; Neal 2014).

Here follows short descriptions of the current most intensely debated issues in astrobioethics:

The Moral Status of Extraterrestrial Life

The moral status of extraterrestrial life is a question that is very much debated, both as a general question and, in particular, in connection with planetary protection. Here follows a short description of the main contestant theories regarding who or what has status as moral objects (i.e., who's interests have to be considered by a moral agent),

together with their implications for astrobiology (see also Persson 2012).

Anthropocentrism is the idea that only humans can be moral objects (e.g., Carruthers 1994; Descartes 1960; Kant 1998; Smith 2009). Historically, this has been the dominating answer to the question of moral status on Earth, though presently it is losing ground due to advances in both ethics and biology. Its implications for astrobiology depend primarily on the grounds for the theory. If only humans are considered moral objects on Earth due to us belonging to the same species, then no extraterrestrial life will count since independently of what other properties they have, they will not belong to the human species. If humans are considered the only moral objects on Earth because we are assumed to be the only species on our planet that possess a particular property (other than just belonging to a particular species), for example, a certain level of intelligence, then it is at least in theory possible that we will at some point encounter extraterrestrial life that has to count as moral objects according to anthropocentrism. As long as we do not expect to find intelligent extraterrestrial life in our solar system, this theory will only be relevant in connection with SETI and METI and in connection with the possibility that Earth in the future will visit or be visited by intelligent entities from other solar systems. Whether nonbiological intelligence counts according to this theory, depends on its exact basis for moral status. If intelligence is used as the sole basis, they will count.

Biocentrism is the idea that all living organisms count as moral objects (e.g., Goodpaster 1978; Schweitzer 1989; Taylor 1986). For astrobiology, this means we might have to consider what kinds of studies we can perform on extraterrestrial organisms, as well as on extremophiles on Earth. A particular challenge when applying biocentrism to extraterrestrial life is to determine what counts as life. For planetary protection, a biocentric perspective would create an interesting dilemma, since, on one hand, it means that all extraterrestrial life, including microbes, need protection that goes beyond their value as study objects, while on the other hand, it might be difficult to motivate mass killing of Earth microbes (i.e., cleaning and

sterilization of spacecraft, landers and equipment) in order to protect merely possible extraterrestrial life. Nonbiological intelligent entities will not count according to biocentrism.

Sentientism is the idea that all and only sentient life has moral standing (e.g., Regan 1983, 2001; Singer 1993, 1995). “Sentient” in this context is often defined as being able to feel pleasure and displeasure, and to have conscious experiences. It is sometimes explained as having a subjective perspective from which things can go better or worse, or as experiencing sensory data contrary to just receiving and acting on them. Sentientism is often considered the most philosophically plausible of the contestant theories and it is increasingly gaining influence in human-animal relations on Earth. When applied to extraterrestrial life, it may be difficult to determine whether an extraterrestrial entity is sentient, however, especially if it differs considerably from sentient life-forms as we know them on Earth. As long as we do not expect to find sentient life in our own solar system, and as long as we do not plan to travel to other solar systems, this theory will only be relevant for questions of back contamination, where sentient Earth life could be affected by alien biological material, or in connection with interstellar communication, that according to some critics may put the entire Earth biome at risk. For sentientism, nonbiological sentient entities will count exactly in the same way as biological sentient organisms.

Ecocentrism is the idea that not only individual organisms, but also holistic entities such as species, ecosystems, or entire biospheres have moral standing (e.g., Callicott 1986, 1999; Johnson 1991, 1992; Rolston 1986, 1999). The impact of this theory on astrobiology depends on which version of the theory one considers. According to one common interpretation, all environments have moral status, even if they do not contain life (Rolston 1986). According to another interpretation, called Land Ethics, extraterrestrial entities, including living organisms, cannot count at all since they are not part of the same living community as life and environments on Earth (Callicott 1986). Nonbiological intelligence will not count according to any of these interpretations of the theory.

Interstellar Communication

Another center of attention within astroethics is how we should react to messages from extraterrestrial civilizations and whether we should risk revealing our existence to extraterrestrial civilizations by active messaging, either as a response to their messages or on our own initiative.

The question of what to do if we receive a message from an extraterrestrial intelligence is rather complicated, not least due to the great uncertainties involved in the decision. It has been pointed out that decoding, or even receiving such a message may be dangerous (Neal 2014). It may contain harmful code that can infect our computers (Musso 2012), or information or misinformation that might (intentionally or unintentionally) disrupt human society by creating unrest or conflicts among the population of Earth, or it may (intentionally or unintentionally) lead us to self-destruction by containing instructions for how to construct very potent technology that we are not ready to handle in a safe way (Musso 2012). In addition to these concerns, there are also concerns about who should get access to the information (Wisian and Traphagan 2020). The possibility that the information is very valuable, maybe of a kind that would provide the reader with a strategic military or economic advantage on Earth, may lead to conflicts about who has the right to the information.

The next question regards whether we should actively transmit messages to outer space, either on our own initiative or as an answer to a message from an extraterrestrial civilization. If we do, we also need to discuss who should get to speak for Earth (Wisian and Traphagan 2020), and what to say. What kind of impression do we want to give of Earth and its human population? Do we want to be completely open about the conditions on Earth and what is going on here, or do we want to look more powerful or more peaceful than we are?

The issue that has gained the most attention in connection with interstellar communication is whether we should do it at all and risk revealing our existence, our location, and possibly other information about ourselves, when we do not

know if the potential receivers are friendly or not (e.g., Atri et al. 2011; Neal 2014). Critics argue that it is both imprudent and immoral to expose humanity and other Earth life to such a risk.

Those in favor of messaging extraterrestrial intelligence (METI), on the other hand, like to point out that the probability that the signals will be detected is very small (Zaitsev 2011), that we already transmit radio signals and have done so for some time, and that some of these signals are even stronger than those used by METI initiatives (Atri et al. 2011; Shostak 2013; Vakoch 2016; Zaitsev 2011), that an alien civilization that is so advanced that it can easily destroy us, can easily find us through other means (Zaitsev 2011), and that if a civilization is so technologically advanced that they can detect us and destroy us if they want, they will probably also be correspondingly more ethically mature and thus not be a threat (Musso 2012). Some of the proponents of active messaging also argue that we need to weigh the risks against possible advantages (de Vladar 2013) and against the risks we run by isolating ourselves (Vakoch 2016). The relevance and plausibility of these defenses are contested by those who argue for a low profile.

There are also a number of suggestions for how to handle the risk associated with messaging to potential extraterrestrial civilizations. Shuch and Almér (2007) recommend a cost-benefit analysis and input from international expert groups. Atri et al. (2011) suggest a protocol for messaging and input from outside the METI community and from different cultures.

Some criticize METI for being anthropocentric (e.g., Atri et al. 2011). Traphagan (2019) argues that METI is a form of scientific study that involves sentient beings as subjects and therefore should need approval from an ethical review board.

Cross-References

- [Astrobiology as Science](#)
- [Geoethics](#)
- [Planetary Protection](#)
- [SETI](#)

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Astrobiology

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Synonyms

[Bioastronomy](#); [Exobiology](#)

Definition

This encyclopedia defines astrobiology as the study of the origin, evolution, and distribution of life in the universe (see Preface). Such studies, or some part of them, have also been referred to as exobiology or bioastronomy, and at the present time, these terms can be considered synonymous. Although it has been stated that astrobiology is a science without a subject (since life outside the Earth remains undiscovered), in fact there is a vast and growing volume of research in fields included in the present encyclopedia.

Overview

Thus, although the physical and chemical processes that led to the origin of life on Earth are still far from understood, they clearly involve,

inter alia, the nucleosynthesis of chemical elements including carbon that are essential for life; the formation and evolution of the Sun and ► [Planets](#), including the delivery of water and organic material to the ► [Earth](#); prebiotic chemical processes; and the nature and evolution of the early Earth's atmosphere, crust, and interior. Furthermore, the study of the evolution of life and ultimately the development of ► [Intelligence](#) on our planet requires research, for example, in biochemistry, biophysics, microbiology (including life in environments that seem extreme by human standards), and ► [Genetics](#).

There is also the question of whether life exists elsewhere in the solar system or at other locations in the universe. These issues are addressed in the Encyclopedia of Astrobiology through entries characterizing various bodies in the solar system (particularly the existence of water, the universal solvent of terrestrial life), current knowledge concerning planets around other stars (extrasolar or exoplanets), how life might be identified beyond the Earth (biosignatures or ► [Biomarkers](#)), and space missions to investigate these topics.

Moreover, many questions relevant to astrobiology have in fact been asked by humanity throughout recorded history and certainly before that. In consequence, the Encyclopedia includes a section on History of Science, which includes theories on the origin and evolution of life and on the possible multiplicity of habitable worlds from classical Greek and Roman times, from the Islamic world, from ancient Asia, and from pre-Columbian America.

Lastly, what is the future of life, at least on Earth? Entries concerning ► [Artificial Life](#) are included which address some of these questions.

Cross-References

- [Enceladus](#)
- [Europa](#)
- [Evolution, Biological](#)
- [Exoplanets, Discovery](#)
- [Mars](#)
- [Planetary Theories and Cosmology, Islamic Theories](#)

- [Prebiotic Chemistry](#)
- [Solar System, Inner](#)
- [Solar System, Outer](#)
- [Titan](#)
- [Water in the Solar System](#)
- [Water in the Universe](#)

Astrobiology (IAU Commission)

William M. Irvine
 Department of Astronomy, University of
 Massachusetts Amherst, Amherst, MA, USA

Definition

The activities of the International Astronomical Union (► [IAU](#)) are mostly carried out within Commissions, grouped in turn into Divisions. The scope of the IAU Astrobiology Commission, within Division F (Planetary Systems and Astrobiology), is the study of the origin, evolution, and distribution of life in the universe. In this context, astrobiology encompasses the search for extant life, evidence of past life, or evidence of prebiotic chemistry on solar system bodies, including Mars, Europa, Titan, and Enceladus; the search for planets around other stars and potential spectroscopic evidence for habitability and biological activity; the origin of the biogenic chemical elements and the study of biologically relevant molecules in the interstellar medium and in primitive solar system objects such as comets, undifferentiated asteroids, and some meteorites; the search for intelligent signals of extraterrestrial origin (► [SETI](#)); and the study of the origin, early evolution, and environmental conditions for life on Earth. The coordination of efforts in all these areas at the international level and the establishment of collaborative programs with other international scientific societies with related interests are among the duties of this IAU Commission.

History

The International Astronomical Union established the Commission 51, “Bioastronomy: Search for

Extraterrestrial Life,” in 1982. The Commission was renamed simply “Bioastronomy” in 2006 and renamed again “Astrobiology” in 2015, when it was also renumbered as Commission F3. From an early concentration on ► [SETI](#), the Astrobiology Commission has expanded its interests as described in the previous paragraph. In most current usage, bioastronomy and astrobiology are synonyms.

Cross-References

- [Bioastronomy](#)
- [IAU](#)
- [SETI](#)

Astrobiology as Science

Erik Persson
 Department of Philosophy, Lund University,
 Lund, Sweden

Keywords

Discipline · Interdisciplinary · Metadiscipline ·
 Philosophy of science · Science ·
 Multidisciplinary

Definition

“Astrobiology as science” refers to how astrobiology is characterized and discussed in the philosophy of science.

Overview

The name “astrobiology” could be interpreted to imply that astrobiological research is limited to the search for, and eventual study of, extraterrestrial life (as was the case with astrobiology’s predecessor, exobiology). This interpretation of the term “astrobiology” would be misleading, however. “Astrobiology” is commonly defined as “the study of the origin, evolution, distribution, and future of life in the universe” (e.g.,

Blumberg 2011; Dunér et al. 2018). In the latest edition of the *Astrobiology Primer* (Domagal-Goldman and Katherine 2016), “astrobiology” is defined as “the science that seeks to understand the story of life in our universe.” Both these definitions, as well as a look at the research published in journals and presented at conferences dedicated to astrobiology, tells us that the focus of astrobiology is rather on the universal aspects of biology. If biology primarily studies living organisms, relations between living organisms, and relations between living organisms and their environments, it can be said that the focus of astrobiology is on the phenomenon of life as such, including eventual universal properties of life, its boundaries, and its boundary conditions. This means, for instance, that though many astrobiologists do study organisms in the form of extremophiles and the relation between these organisms and their environments, astrobiologists are not (in their role as astrobiologists) focused on the particular organism they study, but on properties that can inform our understanding of life as a phenomenon, general properties of life and life’s boundaries and boundary conditions.

Taxonomy

Whether astrobiology should count as a discipline, a research field, or something else entirely, is a matter of ongoing discussion (Dick 2020; Michaud 2007). Astrobiology does fulfill some commonly accepted criteria for being a discipline, such as having its own questions and its own journals, conferences, and professional societies. A number of universities have centers that focus entirely or partly on astrobiology, though it is still uncommon for universities to have astrobiology departments. An increasing number of universities also offer courses and programs in astrobiology. On the other hand, there is no particular astrobiological method. Instead, astrobiology uses a multitude of methods borrowed from (other) disciplines. It has therefore been suggested that astrobiology is best characterized as an interdisciplinary (e.g., Grinspoon 2003; International Journal of Astrobiology 2002; Michaud 2007) or

multidisciplinary (e.g., Dick and Strick 2004) science. It has also been referred to as a meta-discipline by Grinspoon (2003) and Michaud (2007).

Czyżewska (2013) uses both “multidisciplinary” and “interdisciplinary” when talking about astrobiology, which may in fact be the most correct way to characterize astrobiology. Many studies in astrobiology are performed strictly within the borders of a traditional discipline, but it takes many such studies from different disciplines to answer some of the questions of astrobiology. In this sense, astrobiology is multidisciplinary. On the other hand, some of astrobiology’s questions call for genuinely interdisciplinary studies. It is also often insufficient to just add together results from different disciplines to answer the bigger questions of astrobiology. Instead, the work of synthesizing results from different intra- and interdisciplinary studies into answers to astrobiological questions needs to be interdisciplinary in itself. So, astrobiology is also interdisciplinary.

The term “metadiscipline” used by Grinspoon (2003) and Michaud (2007) is less well established and defined than the terms “multidisciplinary” and “interdisciplinary.” Michaud (2007) uses the term to emphasize astrobiology’s ambition to formulate universal laws and a universal theory of biology. This ambition is echoed by Blumberg (2011), though without using the term “metadiscipline.” Grinspoon (2003) uses the term in connection with describing astrobiology as being “potentially revolutionary in its attempt to reverse the slide toward increasing scientific specialization and isolation,” adding a will to “blur the borders and tear down the walls that modern academia has erected.” Lynn Rothschild reasoned along the same lines by declaring that astrobiology “liberates us from disciplinary boundaries” (Dick and Strick 2004).

If it is correct to say that astrobiology, in addition to its explicit research goals, also has the ambition to transform (another) discipline and/or to transcend or abolish the borders of (other) disciplines, it may make sense to describe astrobiology as metadisciplinary, in addition to being multi- and interdisciplinary.

Is Astrobiology a Science Without a Subject?

In 1964, biologist George Gaylord Simpson criticized exobiology for being a science that has yet to show that its subject matter exists (Simpson 1964). From a philosophy of science perspective, Simpson's critique was misinformed since the aim of exobiology was not merely to study extraterrestrial life but also, and primarily, to find it – an aim that is perfectly consistent with extraterrestrial life not yet having been found or shown to exist. Looking for something that is not yet known for sure to exist is in fact, not an unusual scientific aim. It is an aim that exobiology has in common with, for instance, the search for the Higgs Boson, the search for exoplanets (Dick 2020), the search for black holes, and the search for Neptune and Pluto, all of which have now succeeded. Simpson's words are sometimes also used about astrobiology where they are misguided for the same reason, but also because the scope of astrobiology is different from that of exobiology through astrobiology's focus on life as a phenomenon, where finding and studying extraterrestrial life would be important milestones but not the only or the ultimate goals.

Astrobiology as an Empirical Science

Even though the characterization of astrobiology as a science without a subject is incorrect, the fact that we so far only have one example of life (namely Earth life), means the empirical basis for astrobiology is still relatively weak. This is presently handled in two ways. One is to continue to collect data about the life we know on Earth, as well as about its living conditions on Earth and the physical and chemical conditions on other worlds. The other is to continue searching for a second data point (that is, extraterrestrial life).

Given, however, that we will (presumably) never be able to find every life-form in the universe or travel in time, the main aim of astrobiology cannot be to find the ultimate truth about how life actually started on Earth or in the universe, exactly how life is distributed in the universe, or

be absolutely certain that the laws and theories we formulate about life are truly universal. On the other hand, this does not mean in any way that the field is completely open for speculation. The space for speculation is circumscribed by logic and mathematics, but also by existing data. As an empirical science, astrobiology also moves forward by continuing to formulate explanations that are possible given the current state of knowledge, while at the same time keep narrowing down the number of possible explanations by formulating testable hypotheses and figuring out new and better ways of testing these hypotheses. Through this general method, the room for speculation will successively shrink.

SETI

Another controversy regards whether the search for extraterrestrial intelligence (SETI) is a proper part of astrobiology (Almár and Race 2011). This controversy is not in a strict sense a matter of philosophy of science, however, but rather a matter of the politics and sociology of science (Dick and Strick 2004; Michaud 2007). From a strictly scientific and philosophy of science perspective, neither the scientific status of SETI, nor its fit within the broader area of astrobiology can be considered controversial.

Cross-References

- [Astrobiology](#)
- [Ethics of Astrobiology](#)
- [Evidence in Astrobiology](#)
- [Exobiology](#)
- [Life, Definition of](#)
- [SETI](#)

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Astrobiology Graduates in Europe

► [AbGradE](#)

Astrobiology Society of Britain

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[ASB](#)

Definition

The Astrobiology Society of Britain was founded in 2003 “to assist those who research or study subjects related to astrobiology.” Membership is

international and is open to all professional scientists and students interested in this field. The ASB publishes regular newsletters and holds annual workshops and biennial conferences. The ASB is an Affiliated Partner of the NASA Astrobiology Institute (NAI, USA), an Associated Group of the Royal Astronomical Society (UK), and an Organization Member of the European Astrobiology Network Association (EANA).

Cross-References

- [Astrobiology](#)
- [EANA](#)
- [NAI](#)

Astroethics

► [Astrobioethics](#)

Astrometric Orbit

David W. Latham¹ and Nader Haghighipour²
¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA
²Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, Hawaii, HI, USA

Definition

When two bodies are in ► [Keplerian orbits](#) around a common center of mass, the apparent motion projected onto the plane of the sky defines an astrometric orbit. In some cases, such as the famous example of Sirius A and its white dwarf companion Sirius B, both objects can be spatially resolved, and their absolute positions and motions can be determined. This allows the ratio of the two masses to be determined, which can be combined with the total mass, if the distance is known, to derive individual masses. More often, only a single photocenter can be resolved, and only motions relative to nearby stars can be determined. In this

case an orbital solution requires additional information about the relative brightness of the components. In the case of a planetary companion, the contribution of the planet to the total light can almost always be neglected, and the mass of the planet can be estimated from the observed wobble of the parent star if the mass of the star and its distance can be estimated. In common with a spectroscopic orbit determined from radial velocities along the line of sight, an astrometric orbit also yields the ► [period](#), ► [eccentricity](#), and time of ► [periastron](#) passage. Astrometry has the advantage over radial velocity of measuring motions in two dimensions on the plane of the sky instead of just one motion along the line of sight, and this allows the orbital inclination to be determined. Thus, astrometric orbits can eliminate the ambiguity of the unknown orbital inclination and can yield actual masses under certain circumstances, for example, when applied to minimum masses determined by spectroscopic orbits.

Cross-References

- [Astrometric Planets](#)
- [Eccentricity](#)
- [Exoplanets, Discovery](#)
- [Inclination \(Astronomy\)](#)
- [Keplerian Orbits](#)
- [Periastron](#)
- [Period](#)

Astrometric Planets

G. Fritz Benedict¹ and Nader Haghighipour²

¹McDonald Observatory, The University of Texas, Austin, TX, USA

²Institute for Astronomy, University of Hawaii, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Astrometry · Coplanar orbits · Orbital inclination · Perturbation · Planetary mass · *HST* FGS

Definition

Astrometry is a discipline of astronomy that is concerned with the measurements of stellar positions. As applied to exoplanets, a series of astrometric measurements over time is analyzed to obtain an estimate of the size of the reflex motion of the host star caused by the gravitational pull of its unseen planet. The planet and its host star orbit a common center of mass. Given an estimate of the mass of the host star, normally from the mass-luminosity relation, one can determine the mass of the planet. Astrometry also provides the orbital inclination of exoplanets. The knowledge of the orbital inclination of a planet will enable us to determine the true value of its mass (see “► [Inclination \(Astronomy\)](#)”) and can also be used to constrain models of planet formation.

History

The history of astrometric planets is littered with past failures. A notable example was the reported discovery of a planetary system associated with Barnard’s star by van de Kamp (1969), which was subsequently disproven through reanalysis of the data by Ianna (1995) and re-observation of the same system by Benedict et al. (1999). Astrometry has yet to *discover* an independently verified exoplanet; although as a technique to further characterize the companions to stars discovered by precision Doppler measurements (radial velocities), it has enjoyed some recent successes. Future successes (both discovery and characterization) are expected from the astrometric satellite Gaia.

Overview

We describe some of the astrometric planet results obtained using one of the Fine Guidance Sensors (FGS) aboard the *Hubble Space Telescope* (*HST*). The techniques employed are illustrative of both past astrometric approaches and future astrometric investigations. Exoplanetary

astrometry relates the time-varying position of a target to positions of stars defining a reference frame. To obtain the orbital elements of the perturbation due to the companion, one must first characterize motions extrinsic to the system: parallax and proper motion (defined below). Anyone attempting to measure a perturbation will find (to either their delight or horror) that the Earth orbits the ► [barycenter](#) of the Solar System. The corresponding apparent motion of the host star evidences itself as an ellipse, which for nearby stars can exceed 100 milli-arcsec (mas) in size. Added to that parallactic motion is the apparent motion of the host star across the line of sight due to the transverse component of the star's space velocity relative to our Sun. This proper motion often exceeds 50 mas/year. We use the determination of the mass of the planetary companion HD 38529 c (Benedict et al. 2010) as an example of the methodology. The star HD 38529 (= HIP 27253 = HR 1988 = PLX 1320) hosts two known companions b and c, discovered by high-precision ► [radial velocity](#) (RV) monitoring (see Wright et al. 2009). Previously published minimum masses of HD 38529b and c were 0.85 and 13.1 Jupiter masses, respectively. The latter lies just above the official definition of the transition between planets and brown dwarfs. A predicted minimum perturbation of the semimajor axis = 0.8 mas for the outermost companion, HD 38529 c, motivated us to obtain astrometric observations with mas precision using *HST* FGS, to determine the

orbital inclination and thus the true mass of this planet. These astrometric data span 3.25 years of the complete 5.85-year period.

Basic Methodology

Our approach depends on the discovery and orbital characterization results from radial velocity studies. Specifically, the period, eccentricity, time of periastron passage, and position angle of periastron (P, e, T, ω) of the perturbing body are initially known. As can be seen from Table 1, most of our target systems have periods far in excess of 2 years. The data from the astrometry and radial velocity are combined through the constraint (Pourbaix and Jorissen 2000), $\alpha \sin i / \pi_{\text{abs}} = P K (1 - e^2)^{1/2} / (2\pi \times 4.7405)$, where quantities derived only from astrometry (parallax, π_{abs} ; apparent semimajor axis of the elliptical perturbation, α ; and inclination, i) appear on the left, and quantities derivable from both the period P and eccentricity e , or from radial velocity only (the RV amplitude of the primary K), appear on the right. In most cases such as the one here, given the fractional orbital coverage of the HD 38529 c perturbation afforded by the astrometry, all the quantities on the right-hand side are dominated by the radial velocities (Table 1).

Before analysis, all astrometric measurements from the FGS are corrected for optical field angle distortion. Like the part of an iceberg below the

Astrometric Planets, Table 1 *HST* FGS astrometric results. Fe/H measures the abundance of iron relative to hydrogen on a logarithmic scale normalized to the Sun. Sp.T. is the spectral type of the host star

Companion	M_* ($M_{\odot}$)	[Fe/H]	Sp.T.	d(pc)	ecc	M (M_{Jup})	α (mas)	Inc ($^{\circ}$)	P(d)
GJ 876 b	0.32	-0.12^2	M4 V	4.7	0.1	1.9 ± 0.5	0.25	84 ± 6	61
55 Cnc d	1.21	+0.32	G8 V	12.5	0.33	4.9 ± 1.1	1.9	53 ± 7	4517
ϵ Eri b	0.83	-0.03	K2 V	3.2	0.7	1.6 ± 0.2	1.9	30 ± 4	2502
HD 33636 B	1.02	-0.13	G0 V	28.1	0.48	142 ± 11	14.2	4.0 ± 0.1	2117
HD 136118 b	1.24	-0.01	F9 V	52.3	0.35	42 ± 15	1.5	163.1 ± 3	1191
HD 38529 c	1.48	+0.27	G4 IV	40.0	0.36	17.6 ± 1.4	1.1	48.3 ± 3.7	2136
v and c	1.31	+0.15	F8 V	13.5	0.25	14 ± 4	0.62	8 ± 1	240.94
v and d	1.31	+0.15	F8 V	13.5	0.32	10 ± 2	1.4	24 ± 1	1281.51
HD 128311 C	0.84	0.02	K0 V	16.5	0.16	3.8 ± 0.7	0.46	56 ± 14	921.5d

water, this correction, while typically “out of sight” (McArthur et al. 2003), is an essential part of our process. Actual FGS distortions with amplitudes in excess of 1 arcsec are reduced to 1 mas or less over the FGS field of regard.

We are able to relate the position of the bright host star to the far fainter reference frame stars through the use of a neutral density filter. The astrometric reference frame for HD 38529 consists of four stars. Any prior knowledge concerning these four stars eventually enters our modeling as observations with errors, which helps improve the values of the parallax and proper motion for the prime target, HD 38529. Distances to the reference stars are estimated from (BVIJHK) photometry and stellar classification spectroscopy. Of particular value are independently measured proper motions from the UCAC3 catalog (Zacharias et al. 2010). All these periodic and nonperiodic motions must be removed as accurately and precisely as possible to obtain the orbital inclination, i , and perturbation size, α , caused by HD 38529 c.

Key Research Findings

Results from *HST* astrometry are presented in the table above. HD 38529 c is clearly more massive than 13 Jupiter masses, the threshold above which deuterium fuses to helium. This threshold has been adopted by the International Astronomical Union as the official transition between planets and brown dwarfs.

Other results: McArthur et al. (2010) determined the inclinations of components c and d in the ν Andromeda system, indicating non-coplanarity. Whether this architecture is a result of the migration of component b (with $M_{\text{sin}i} = 0.69 M_{\text{Jup}}$) now in a $P = 4.6$ -day orbit, or the past passage of the M star companion, ν Andromeda B, is as yet unknown (Barnes et al. 2011). A recent attempt to determine the degree of coplanarity for HD 128311 was unsuccessful, but did yield a planetary mass for component c (McArthur et al. 2014). A review of the results

made with HST can be found in Benedict et al. (2017).

Applications

These techniques have been applied to determine masses for 14 Her b, HD 47536 b, and HD 168443 c. There now exist sufficient FGS astrometric measurements to attempt to determine orbital inclinations for b and c, HD 202206 b and c, μ Ara b and c, and γ Cep A and b. The latter two host stars may be too bright for Gaia. If the degree of orbital coplanarity can be established for those systems, astronomers will have valuable data to probe the architectural uniqueness (or not) of our own Solar System, complementing analogous results from the recent Kepler transit discoveries and the study of ► [radial velocity planets](#).

Note that other instruments have also contributed to achieving astrometric constraints of the masses and inclinations of the planets of various systems, like VLT/SPHERE (e.g., for the system HR8799, Wertz et al. 2017) and the interferometric instrument VLTI/GRAVITY (e.g., for the system β Pictoris b, Gravity Collaboration et al. 2020).

Future Directions

Major progress will result from two improvements to past practice as exemplified by *HST* FGS astrometry. First, future missions will employ global (as opposed to local) reference frames, removing the correction to absolute parallax required when using a local reference frame. Second, the astrometric precision will improve by two orders of magnitude, from millisecond of arc to micro-arcseconds (μas). Future success is expected from *Gaia*, an astrometric satellite launched on December 2013 by the ► [European Space Agency \(ESA\)](#). The expected 10 μas mission accuracy

should permit the discovery of 21,000 massive planets (mass higher than Jupiter's) on long-period orbits (Perryman et al. 2014). This number can go as high as 70,000 if the nominal 5-year mission is extended to 10 years. However, the unambiguous astrometric identification of an Earth-mass exoplanet, orbiting a nearby Sunlike star at a star-planet separation allowing surface liquid water, remains a difficult goal, one requiring 1 μ as/observation precision.

Cross-References

- ▶ [Aeronautics and Space Agency of FFG](#)
- ▶ [Barycenter](#)
- ▶ [Doppler Shift](#)
- ▶ [European Space Agency](#)
- ▶ [Exoplanets, Discovery](#)
- ▶ [Gaia Mission](#)
- ▶ [Radial-Velocity Planets](#)
- ▶ [Spectral Type](#)

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Astrometry

François Mignard

Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France

Keywords

Coordinate systems · Fundamental astronomy · Gaia · Hipparcos · Reference frame

Synonyms

[Positional astronomy](#)

Definition

Astrometry is that part of astronomy dealing with the determination of the position, distance, and motion of celestial bodies and by extension their size and shape. This is by far the oldest branch of astronomy, and until the mid-1800s, the word did not even exist. It was only coined at that time to make the distinction from the new field of astrophysics.

Overview

Taken as a broad subject, *astrometry* covers the definition and realization of the astronomical ► [coordinate systems](#) and the construction and maintenance of positional star catalogues, but also the techniques for the computation of astronomical events, like eclipses, passages of inner planets across the Sun's disk, orbits of ► [binary stars](#), stellar ► [occultation](#) by the Moon, or the minor planets. Classical astrometry is undergoing a true revolution with the access to radio interferometry and above all the possibility to carry out accurate measurements from space, thanks to the Hipparcos mission (1989–1996) and the ongoing Gaia mission (launched in

2013 and expected to continue operations to 2025). The main benefit of doing astrometry in space is the measurement of absolute parallaxes of stars, that is to say their distances, just from the geometric method without any assumptions on the physics of the sources or on the absorption of the light during its journey to the telescope.

Given the fundamental nature of its investigations, it is fair to state that astrometric data, leading to the realization of an accessible ► [reference frame](#) or giving the distances and the masses of the stars, provide the foundation of stellar physics and of the cosmic distance ladder. Stellar distances are the key to determining stellar luminosities and then for calibrating further methods to determine distances up to the most remote galaxies.

Based on the tools employed and on the objectives, astrometry can be further divided up into three broad categories:

- Small-angle astrometry, measuring the position or the motion of stars in a very small field (less than 1°) with respect to local references. This was typical of astronomical photography until the advent of charged coupled device (► [CCDs](#)) and is still used for solar system astrometry or to determine the relative motion within a binary system. Its accuracy can reach 1 mas (0.001 arc sec) in relative positions.
- Wide-angle astrometry was the basis for the construction of the fundamental catalogues and their extension to fainter magnitudes. The classical instruments were the meridian circles and the astrolabes. Stars over the whole celestial sphere were tied together, thanks to the rotation of the Earth or by overlapping frames in photographic or ► [CCD](#) astrometry. The accuracy, including zonal errors, is of the order of 20 mas for the bright stars (visual ► [magnitude](#) $V < 8$) and 50–70 mas at around $V = 15$.
- Space astrometry is the only way to do absolute measurements over the whole sky with a single instrument able to connect widely separated directions ($>60^\circ$) and perform repeated observations over several years. This method leads to an absolute catalogue of positions and

► [proper motions](#), independent of any pre-existing reference frame. Accuracy was 1 mas with ► [Hipparcos](#) (~120,000 sources) and has already reached 0.025 mas at $V = 15$ in the early releases of ► [Gaia](#) which delivers accurate position, parallaxes, and proper motions for nearly two billion sources. Radio ► [interferometry](#) and Gaia perform absolute astrometry of quasars on the whole celestial sphere, respectively in the radio and visible domain of wavelengths. The associated catalogues are currently the basis of the astronomical reference frame (ICRF: International Celestial Reference Frame) with a similar accuracy of about 0.1 mas over a few thousands radio sources in the radio domain and about 500,000 in the visible domain. The solutions are so constructed to have the same fundamental plane and the same origin of right ascension in this plane, by using sources observed by both techniques.

Cross-References

- [Coordinate Systems](#)
- [Gaia](#)
- [Hipparcos](#)
- [Magnitude](#)
- [Parallax](#)
- [Proper Motion](#)

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Astronomical Unit

- [AU](#)

Astronomy Using Radio Waves

- [Radio Astronomy](#)

Astrophysical Ice Spectroscopy

- [Interstellar Ice Spectroscopy Experiments](#)

Asymmetric Reaction, Absolute

Kazumichi Nakagawa
Sanken, Osaka University, Ibaraki City, Osaka, Japan

Keywords

Asymmetric decomposition · Asymmetric synthesis · Circularly polarized light · Origin of homochirality · Induction of chirality

Definition

An absolute asymmetric chemical reaction is one induced by asymmetric physical conditions such as circularly polarized light (CPL) instead of by chemical reagents or catalysts. They can be divided into two categories: One is asymmetric synthesis, and the other is asymmetric decomposition.

Overview

Asymmetric synthesis is driven by the introduction of chirality into an achiral system, a process

known as asymmetric induction. One example of absolute asymmetric synthesis is the introduction of optical activity into helicenes (twisted polycyclic aromatic hydrocarbons with six rings) studied by Kagan et al. (1974) in 1971, in which the optical yield was lower than 1%. Enantiomeric enrichment of racemic compound such as amino acids by irradiation with circularly polarized light (CPL) is one of the well-known examples of asymmetric decomposition. The first experimental evidence of CPL-induced asymmetric decomposition was reported by Kuhn and Knopf (1930).

Various light sources such as lasers and synchrotron radiation are now available as powerful tools to study asymmetric reactions. Several studies have examined the role of asymmetric reactions on the origin of ► [homochirality](#) in biological molecules: Flores et al. (1977), Nishino et al. (2001), and Meierhenrich et al. (2005).

Polarized radiation from pulsars and interstellar masers has been known for several decades. Natural sources of circularly polarized light were found in space and reported by Bailey et al. (1998). Mie scattering and synchrotron radiation are thought to be the natural sources of circularly polarized light.

Other mechanisms of absolute asymmetric reactions have been discussed by Bonner et al. (1974), Bonner (2000), and Goldanskii and Kuzmin (1989).

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Asymptotic Giant Branch Star

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Synonyms

[AGB](#)

Definition

An asymptotic giant branch (AGB) star is a low- or intermediate-mass star (of mass $M < 8 M_{\odot}$) at a late evolutionary phase in its life, during which it appears as a red giant in the ► [Hertzsprung-Russell diagram](#). After the star has exhausted the supply of He for fusion in its core, it draws energy from He fusion in a shell around the inert carbon-oxygen core, in the *early AGB* (E-AGB) phase. Later, the star enters the *thermally pulsing* (TP-AGB) phase,

Cross-References

- [Chirality](#)
- [Homochirality](#)
- [Polarized Electron](#)
- [Polarized Light and Homochirality](#)

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with intermittent burning (fusion) of the hydrogen and He shells. In the He shell, neutrons are released through (α , n) reactions and are captured on pre-existing nuclei of the Fe peak to produce heavier elements (s-process). The thermal pulses occur in timescales of 10^4 – 10^5 years. They mix material from the burning shells to the convective envelope (the *3d dredge up*), and they also induce heavy mass loss from the star (more than 50 % of its mass), creating a ► [planetary nebula](#).

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Planetary Nebula](#)
- [S-process](#)
- [Stellar Evolution](#)

Atacama Desert

Richard Léveillé
Natural Resource Sciences, McGill University,
St. Anne de Bellevue, QC, Canada

Definition

The Atacama is a hyperarid desert located in northern Chile. It is considered to be one of the driest places on Earth with average annual rainfall of less than 1 mm in some locations. It is a useful analogue to the arid surface of Mars and for analog studies of hydrology, mineralogy, and microbiology. Features that may be analogous to Mars also include caves, salt deposits, water-derived mudflows, and gully-type deposits. Field tests of prototype instruments and rovers have also been conducted there.

Cross-References

- [Desiccation](#)
- [Extreme Environment](#)

- [Extremophiles](#)
- [Mars Analogue Sites](#)
- [Terrestrial Analog](#)

Atacama Desert, Natural Analog

Daniele L. Pinti
GEOTOP Research Center for the Dynamics of
the Earth System, Université du Québec à
Montréal, QC, Canada

Definition

The ► [Atacama Desert](#) is a desert plateau situated along the western coast of South America, west of the Andes, and occupying a surface of 104,741 km². The Atacama Desert is the driest nonpolar desert on Earth, only the Antarctica dry valleys are drier, even if the Atacama receives fewer annual precipitations (maximum 39 mm per year) than the polar deserts (average of 250 mm per year). The Atacama Desert has been extensively used as experimentation site for Mars expedition simulations and as natural analog of the Red Planet past climatic and geological conditions. Morphological aspects of the desertic terrains and the presence of large alluvial fans were compared with those of Mars to understand their conditions of formation. Finally, the extreme conditions of survival of microbial (mainly extremophiles) communities have been also studied to determine the habitability threshold which could be found on other arid planetary surfaces.

Overview

The Atacama Desert owes its extreme aridity to a constant temperature inversion (the warmer humid air is maintained above a cooler drier air mass) caused by the encounter between the Humboldt oceanic current (a cold, low-salinity ocean current that flows north along the western coast of South America) and by the presence of the semi-

permanent Pacific anticyclone, which creates an area of constant high atmospheric pressure. The Atacama Desert is composed mainly of stony terrain, salt lakes (*salares* such as the *Salar of Atacama*, owing one of the more important Lithium reserves on Earth), sand, and felsic lava flowing from the Andean volcanoes.

In the last three decades, the Atacama Desert has been used for testing exploration rovers (e.g., Cabrol et al. 2001) and life detection systems (Good 2017); numerous geological and morphological aspects of the terrains were studied and compared to those found on Mars to understand their formation (e.g., Levy et al. 2010; Morgan et al. 2014; Sager et al. 2021); and finally subsurface microbial habitats investigated to determine minimal environmental conditions to support life in arid conditions, such as those of Mars subsoil (e.g., Azua-Bustos et al. 2020).

Between June and July 1997, 3 months after the arrival of the first-ever rover on Mars (Mars Pathfinder, March 1997), Carnegie Mellon University deployed the robotic rover Nomad to traverse the Atacama Desert (Cabrol et al. 2001). Nomad traveled an unprecedented 215 km in 45 days, and it was remotely driven from the Ames research center and the Carnegie Science Center in Pittsburgh, PA. The Atacama trek of the Nomad rover allowed to test technologies critical to planetary exploration such as remote communication systems and the use of panospheric 360° view camera, which was the ancestor of the more sophisticated 360° cameras now embarked on Mars rovers. The robot also had three pairs of conventional stereo cameras and a laser telemeter for 3D visualization. Among the most important lessons learned from the Nomad trek through the Atacama Desert was that the selection of appropriate targets could even more critical than the time spent in an area, to reconstruct the history of the selected site (Cabrol et al. 2001). Devices for detection of life forms were also tested such as the NASA-funded *Chemical Laptop*, a subcritical water extractor able to analyze water bounded in minerals to detect the presence of amino acids (Good 2017) and which could be used to search for biosignatures in solid samples on rocky or icy worlds.

Several geological and morphological features found on Mars have their equivalent in the Atacama Desert. Among them, the presence of polygonal grounds in salt-cemented soils of the Yungai area (Sager et al. 2021) which resemble to polygonal surfaces found in the northern and southern hemisphere of Mars, between 30° and 80° latitude (Levy et al. 2010). On Earth polygonal grounds are landscape features commonly associated with periglacial environments originating from freeze-thawing cycles or frost-related processes. However, such a mechanism cannot be applied to the hyperarid Atacama Desert. Conclusions of Sager et al. (2021) study is that cyclic thermal contraction cracking is the dominant formation mechanism rather than desiccation cracking, though presence of gypsum salt cannot exclude a minor role of desiccation. This mechanism is likely the one dominating on Mars, where arid climate and salt surface are present (Levy et al. 2010; Sager et al. 2021).

Alluvial fans in arid climates are another common geological feature of Mars and the Atacama Desert. Alluvial fans are sedimentary landforms formed at the base of mountain fronts where a fluvial channel emerges onto a valley floor, and the drastic reduction in the slope forces the deposition of large amounts of sediments. The presence of alluvial fans on Earth is an index of presence of water (fluvial activity) and run-off. On Mars, large alluvial fans offer compelling evidence that surface runoff persisted, at least episodically, into the Hesperian or Amazonian periods (Moore and Howard 2005). This era has generally been thought to be cold and dry, and characterizing the climatic environment that permitted the formation of those fans can give clues into past Mars potential habitability (Morgan et al. 2014). The Martian and Atacama Desert alluvial fans share numerous similarities: they are very large (up to 200 km² in the Atacama); gently sloped (5°); dominantly fine-grained composition; with reworking of inactive fan surfaces by aeolian processes. For both, the dominant flow regime is bimodal, with channels transporting cobble- to boulder-size bedload and fine-grained mudflows that extend laterally from the channel (Morgan et al. 2014). Thus, the study of formation

mechanisms of large alluvial fans on the front of Andes in the Atacama Desert might give clues on the amount of water and climatic conditions of past Mars.

Finally, the presence of microbial communities in the arid soils of the Atacama Desert, where humidity is generally close to zero, has amazed biologists and pushed the scientific community to study the environmental condition of survival of those communities, which could give clues on habitability threshold in similar arid planetary surfaces (Navarro-González et al. 2003). Several microbial communities are halophilic Archaea living in the salt-enriched arid soils of Atacama. Very recently, Azua-Bustos et al. (2020) have discovered a layer of smectite (a clay mineral formed by water-rock interactions) just 30 cm below the arid soils of the Yungai region. This smectite creates a micro-environment completely isolated from the surface, maintaining an exceptionally high degree of humidity for the region (78%), where at least 30 ► [halophile](#) species of metabolically active bacteria and archaea live. The discovery of microbial communities in those smectite-rich subsurface layers of the Atacama soils suggest that similar shallow clay deposits on Mars may contain biosignatures easily reachable by future rovers, such as in 2023 by the ESA's *Rosalind Franklin* rover which will land in the smectite-rich surfaces of *Oxia Planum*.

Cross-References

- [Atacama Desert](#)
- [Mars](#)
- [Mars Analogues](#)

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Atmosphere, Organic Synthesis

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

It is widely thought that the origin of life on a planet may depend on the availability of abiotically synthesized organic compounds. Various potential sources for these exist, including extraterrestrial delivery and submarine hydrothermal synthesis. However, one of the first suggested means of producing these compounds was via synthesis in the gas phase in planetary atmospheres, as shown by the results of the now famous experiment published by Stanley Miller in 1953. It has now been amply demonstrated that the action of various forms of energy, including shock waves, electricity, and

ionizing and UV radiation acting on various simulated planetary atmospheres can result in the synthesis of a variety of organic compounds. In general, more reduced gas mixture atmospheres appear to give more favorable yields of organic compounds; however, even relatively oxidized gas mixtures still produce organics to some extent.

Cross-References

- [Electric Discharge](#)
- [Miller, Stanley](#)
- [Proton Irradiation](#)
- [UV Radiation](#)

Atmosphere, Primitive Envelope

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Synonyms

[Primary atmosphere](#); [Primitive atmosphere](#)

Definition

An atmosphere (or an atmospheric envelope) typically refers to the gas that is gravitationally bound to a planet or another planetary object. In relation to planet formation, atmospheres composed of hydrogen and helium are thought to form as a result of gas accretion by a growing planet embedded in a ► [protoplanetary disk](#). For low-mass planets or even Moon- to Mars-sized planetary embryos, a relatively small amount of gas may be gravitationally captured into a primitive atmosphere. The atmospheres of full-size terrestrial planets are then made up of a combination of atmospheres from their constituent planetary embryos, as well as volatiles that may be degassed from the planetary interior or delivered to the planet via impacts of

small bodies during final stages of accretion (► [late veneer](#)). In that case a large range of atmospheric compositions is possible, and the atmospheres can consist of water and other volatile materials.

Cross-References

- [Earth's Atmosphere, Origin and Evolution of](#)
- [Late Veneer](#)
- [Protoplanetary Disk](#)

Atmosphere, Structure

John Lee Grenfell¹ and Sébastien Lebonnois²

¹Institut für Planetenforschung, Extrasolare Planeten und Atmosphären, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany

²Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, CNRS, Paris, France

Definition

Atmospheric structure usually refers to changes in physical quantities such as temperature, density, etc., in the vertical. Atmospheres can be classified into regions (troposphere, stratosphere, mesosphere, etc.) depending upon the variation of temperature and physical processes in the vertical.

Overview

The vertical structure of an atmosphere is mostly controlled by gravity on one side, and stellar energy absorption on the other side. Gravity controls this vertical structure through the hydrostatic equilibrium, that states that the weight of one given gas element is balanced by the vertical pressure gradient. According to the corresponding equation, pressure is decreasing quasi-exponentially when altitude increases. The scale height, corresponding to a decrease of pressure of a factor e , depends on temperature, and therefore varies with altitude.

A first level of structure in a given atmosphere is related to the atmospheric composition. When pressure is high enough, eddy diffusion is the dominant mixing process and atmospheric composition is uniform (at least with the dominant atmospheric components). This region is called the “homosphere.” When pressure decreases and molecular diffusion becomes dominant over eddy diffusion, each dominant constituent follows its own atmospheric scale height and lighter constituents separate from heavier, with the mean molecular weight varying with altitude. This region is the “heterosphere.” The limit between homosphere and heterosphere is called the “homopause” (on Earth, it is located around 90 km of altitude). The heterosphere is limited at its top by the “exobase,” where the atmospheric scale height equals the molecular mean free path. Above this transition, it is the “exosphere” – the uppermost atmosphere region before space. The top of the exosphere can be defined to occur where the stellar pressure equals the planetary gravitational pull on a hydrogen atom.

In terms of temperature structure, the atmosphere is organized in layers, depending on the energy transfer and balance mechanisms. Energy sources are the solar (or stellar) input flux, and in some cases an internal energy flux (radioactive decay or gravitational contraction). The energy

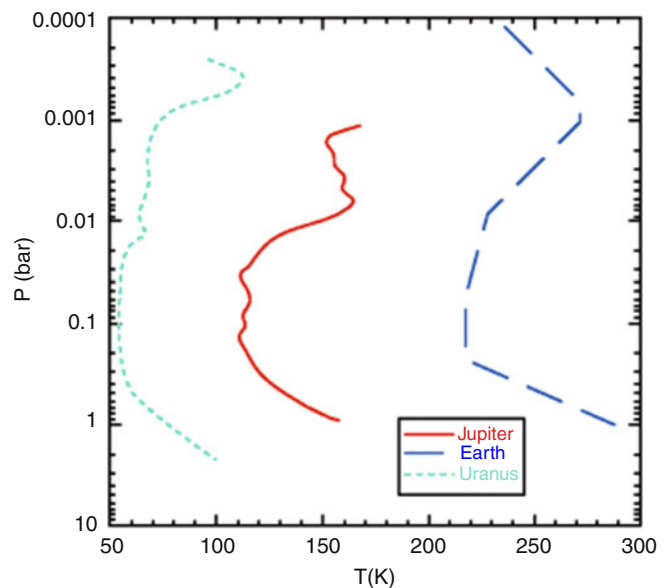
balance is also controlled by the way the absorbed stellar energy is reemitted in the infrared toward space.

In lower regions, with stellar energy absorbed by the surface or internal energy flux, convection is important. Warm air lies below cool air and vertical mixing is strong – this is the “troposphere” region, which is characterized by a decrease of temperature with altitude, up to the “tropopause” (Fig. 1). In the troposphere, since energy transfer is dominated by convection, the average temperature gradient is close to the adiabatic lapse rate, that can be dry, or moist when latent heat exchanges are involved during convective motions. Near pressures lower than about 0.1 bar (on Earth, Jupiter, Uranus) radiative transfer starts to dominate over convection. On Earth, the tropopause is located around 12 km altitude.

At higher altitudes, temperature may increase with altitude due to absorption of some of the incoming UV energy. This is the case on Earth with UV absorption by ozone. Cool air lies below warm air and vertical mixing is weak – this is the “stratosphere” region, a highly stable, stratified region where temperature increases with altitude. The energy transfer is done through radiation, and this radiative equilibrium is controlled, at each level, by the opacity sources and the

Atmosphere, Structure,

Fig. 1 Temperature structure of Earth, Jupiter, and Uranus, showing the presence in similar pressure ranges of a troposphere, a stratosphere, and a mesosphere



balance between the total energy absorbed, and the energy reemitted in infrared. It is strongly dependent on the spectroscopic properties of the atmospheric constituents. Above the maximum of temperature named the “stratopause,” temperature decreases again with altitude in a region called the “mesosphere.” On Earth, the stratopause is located around 50 km altitude, where ozone concentrations are small. Depending on the atmospheric composition, on the presence of haze or clouds, a stratosphere is not always present. As an example, Venus or Mars, both CO₂-dominated atmospheres, do not have a stratosphere. On Venus, the tropopause region is located in the upper cloud, and despite the strong UV absorption in this region, infrared cooling is also large and the region stays roughly isothermal. Above the clouds, infrared cooling dominates and the radiative balance leads to temperature decreasing again with altitude, transitioning directly from troposphere to mesosphere. On Mars, the tropopause merges in a roughly isothermal mesosphere.

In the stratosphere and mesosphere, local thermodynamic equilibrium (LTE) is valid. This means that at every frequency, a given atmospheric level with temperature T emits as a black body. But when pressure decreases again, after reaching a minimum (“mesopause”), temperature rises again with altitude due to the absorption of high energy radiation. This is the “thermosphere,” where non-LTE processes need to be taken into account. Thermosphere reaches up to the exobase. Though not defined on the same physical criteria, thermosphere and heterosphere are approximately overlapping.

Finally, another layer usually overlaps with the thermosphere: the ionosphere, a region where ions and electrons are present, due to photoionization of molecules and atoms.

Cross-References

- ▶ [Atmospheric Modeling, Gray Gas Model](#)
- ▶ [Atmospheric Modeling, Non-gray Gas Model](#)

- ▶ [Mesosphere](#)
- ▶ [Scale Height](#)
- ▶ [Stratosphere](#)
- ▶ [Thermosphere](#)
- ▶ [Troposphere](#)

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Atmosphere, Temperature Inversion

Lisa Kaltenegger

Cornell University, Ithaca, NY, USA

Keywords

Atmosphere structure · Biomarkers · Habitability · Habitable zone · Temperature inversion

Definition

A temperature inversion refers to a reversal in the normal decrease of atmospheric temperature with altitude in the lower portion (▶ [troposphere](#)) of a planetary atmosphere (atmosphere, Structure). Temperature inversions inhibit vertical motion, because the warmer, less dense air is at a higher altitude and tends to remain there. The net result of a temperature inversion is a long time constant for exchange between a stratosphere and a troposphere. It exists due to the heating produced by absorption of sunlight by molecules or aerosols that are chemically produced. There exists a highly non-linear positive feedback between chemistry, radiation, and dynamics, such that absorbers will remain longer, hence lead to a larger thermal inversion, resulting in the trapping of even more absorbers (Pierrehumbert 2011).

Overview

In the troposphere, convection dominates and the temperature decreases according to the so-called wet lapse rate, about 6.5 K/km for Earth (which includes the latent heat released by the condensation of water). Mixing is generally rapid in a troposphere, as the warm, lighter air at the bottom tends to rise and the colder air at the top tends to sink down. The thermal inversion in the stratosphere on Earth is due to absorption of ultraviolet radiation by Ozone (O₃) but can be generated by other molecules on different planets. Above Earth's stratosphere where O₃ is no longer strongly produced, the temperature decreases with height due to cooling in the infrared, mainly by CO₂. In the outermost atmosphere, Earth's hot thermosphere is related to absorption of extreme ultraviolet radiation by O₂, N₂, and O.

In contrast to the Earth, Mars has a thin and Venus a thick atmosphere, which is reflected in their surface temperatures. The tropospheric temperatures of Mars and Venus follow their respective lapse rates (atmospheric thermal gradient). There are no well defined stratospheric inversions, except during dust storms on Mars. The thermospheres of both planets are relatively cold compared to Earth's, because the major atmospheric gas (CO₂) is a very effective radiator of thermal energy. In contrast, the primarily apolar constituents of Earth's atmosphere (N₂, O₂) have virtually no bands in the infrared and are poor radiators.

Cross-References

- [Adiabatic Processes](#)
- [Albedo](#)
- [Apolar Molecule](#)
- [Atmosphere, Structure](#)
- [Clouds](#)
- [Greenhouse Effect](#)
- [Latent Heat](#)
- [Scale Height](#)

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Atmosphere-Ocean General Circulation Model

- [AOGCM](#)

Atmospheric Circulation

Agustín Sánchez-Lavega

Escuela de Ingeniería de Bilbao, Universidad del País Vasco UPV/EHU, Bilbao, Spain

Keywords

Planetary atmospheres · Planetary rotation · Atmospheric dynamics · Meteorology

Acronyms

GCM General circulation models

Synonyms

[General circulation](#); [Global circulation](#)

Definition

The atmospheric circulation is the study of the global, large-scale motions, averaged over a time period, of the atmospheres surrounding the planets and satellites.

Overview

The atmospheric circulation is the study of the global, large-scale motions, averaged over a certain periods of time, of the gases (atmospheres) surrounding planets and satellites. The mass motions are represented by three components of

the velocity on the sphere or ellipsoid that represents the planet figure, relative to planet rotation reference frame. Spatial and temporal averages of the winds show the global trends of the general circulation of the atmosphere. Other ways of representing the atmospheric circulation are by means of the mass stream-function (in particular when referring to meridional motions) and the temperature field (because of its relationship to velocity).

The comparative study of planetary atmospheres shows that their circulation is determined by the energy sources, the rotation angular velocity, the size of the planet, and its structure (presence of a solid surface or fluid planet). The energy sources can be the solar radiation deposited in the atmosphere that produces spatially and temporally variable heating and cooling rates, and the internal energy source important on giant and icy planets. The planetary rotation varies widely from days to few hours in solar system bodies and is the key parameter in shaping the atmospheric motions. According to their structure, the planets are divided in two large groups, on one hand the terrestrial or telluric type, with small size and a solid surface as the lower boundary to the atmospheric motions (Venus, Earth, Mars, and Saturn’s satellite Titan). On the other hand, the giant gaseous (Jupiter and Saturn) and the intermediate size ice giants (Uranus and Neptune) all them with deep atmospheres and no solid surface. Accordingly, the comparative view of the atmospheric circulations of the planets can be grouped in the following couples: slowly rotating

terrestrial bodies (Venus and Titan), rapidly rotating terrestrial planets (Earth and Mars), the gas giants (Jupiter and Saturn) and the icy giants (Uranus and Neptune).

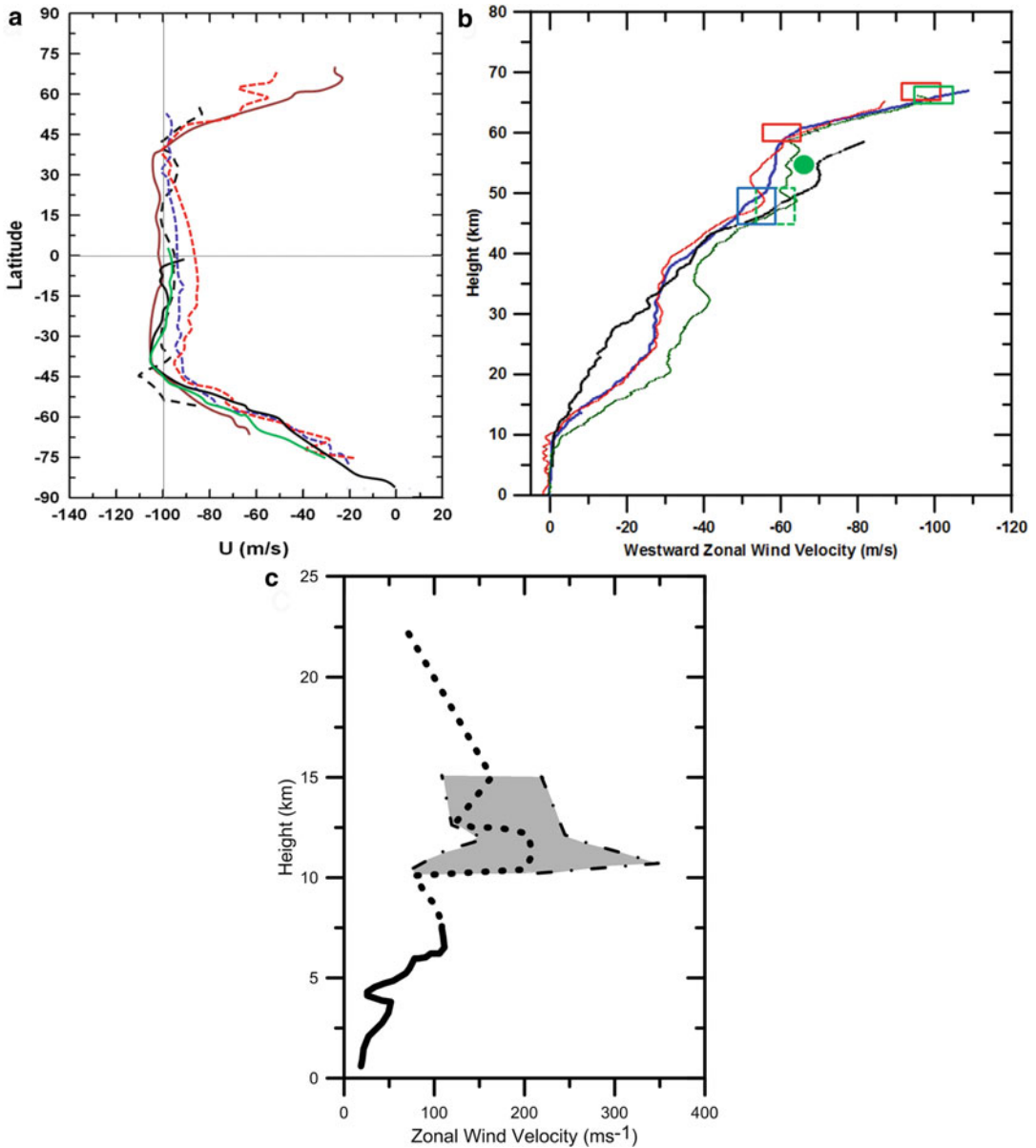
Venus and Titan

Venus is the planet with the longest rotation period in the solar system (Table 1). However, its atmosphere is in a state of superrotation at cloud level (at an altitude from the surface between 40 and 65 km) and exhibits a period in the range 4–6 days. The atmospheric circulation is dominated by prograde zonal motions (i.e., in the direction of rotation of the planet) which given the high inclination of the rotation axis of the planet are from East to West. The zonal wind velocity (u) has practically a constant value in the range -100 to -110 ms^{-1} at cloud tops at 65 km of altitude and in a wide range of latitudes from 50°N to 50°S (Fig. 1a). This zonal velocity decreases towards the poles where forms two large polar cyclones that have rotation periods of 2–3 days. This zonal wind system has a large vertical shear with velocity decreasing with altitude at a rate of $\partial u/\partial z = 1.5\text{ ms}^{-1}/\text{km}$ from cloud tops to the surface (Fig. 1b). At the surface, the speed is practically zero in the 10 km above the surface. Meridional winds (across latitudes) have been measured at an altitude of 65 km with peak velocities of 15 ms^{-1} probably related to a Hadley circulation. Vertical motions with speeds fluctuating between 1 and 3 ms^{-1} were measured at 50–55 km altitude by the Vega balloons. Superimposed to the prevailing zonal flow coexist a variety of waves with

Atmospheric Circulation, Table 1 Planetary and orbital parameters

Body	Mean radius (km)	Rotation period	Orbital period	Obliquity
Venus	6051.8	−243.018 d	0.615 y	177.4°
Earth	6371.0	23.93 h	1.00 y	23.45°
Mars	3389.5	24.62 h	1.88 y	25.2°
Titan	2575.5	15.95 d	15.95 d	26.73°
Jupiter	69,911	9.925 h	11.86 y	3.13°
Saturn	58,232	10.656 h ^a	29.45 y	26.73°
Uranus	25,362	−17.24 h	84.02 y	97.77°
Neptune	24,622	16.11 h	164.79 y	28.32°

^aNot precisely constrained
Ref.: NASA JPL Horizons (https://ssd.jpl.nasa.gov/?planet_phys_par)



Atmospheric Circulation, Fig. 1 Wind profiles in Venus and Titan: (a) Venus zonal wind as a function of latitude as measured at the upper cloud level at an altitude of 65–70 km above the surface. Averaged wind values from the following missions: Mariner 10, 1974 (black dashed); Pioneer-Venus, 1980 (blue dotted); Pioneer-Venus, 1982 (red dotted); Galileo, 1990 (brown line); Venus Express VIRTIS, 2006–2012 (black line); Venus Express VMC, 2006–2012 (green line). (b) Venus vertical zonal wind profile measured at different latitudes and local times. Continuous lines as measured by four Pioneer-

Venus probes (1978): Sounder (green), North (black), Night (red), and Day (blue). The green dot is the velocity measured by the Vega 1 and 2 balloons (1985) at latitudes (+7.3°, −6.6°) and sounded day and night time. The rectangles are mean values from long-term measurements of cloud tracers using the VIRTIS instrument on Venus Express (2006–2012) at different altitudes: daytime (red) and nighttime (blue). (c) Titan vertical profile of the zonal wind as measured from different techniques. (a) and (b) from Sánchez-Lavega et al. (2017), (c) adapted from Hörst (2017)

different wavelengths. Notoriously are the Y- and Psi-shaped features prominent at ultraviolet wavelengths where an unknown chromophore absorbs solar radiation. Another is the large arc-shaped feature extending from north to south observed at infrared wavelengths.

The superrotation of Venus atmosphere is due to the angular momentum stored in the atmosphere and its meridional and vertical transport. Atmospheric waves, the solar (thermal) tide and eddies generated by different types of dynamical instabilities are the essential ingredients that drive its general circulation. The heating and cooling rates, including the effects of the clouds, are also essential in modeling Venus global motions. Models show that the superrotation is generated by the transport of angular momentum upwards from the surface and poleward (between latitude circles) by a thermally direct Hadley cell and, equatorward by eddy momentum fluxes. Other important mechanisms intervening in the superrotation are viscous phenomena at the planetary surface due to a combination of torques produced by frictional and turbulent exchanges in the boundary layer and with topography.

Titan is Saturn's major satellite and the second largest in the solar system (Table 1). It has a dense nitrogen atmosphere. There are few measurements of atmospheric motions, most of them in the deep and middle atmosphere from the surface to about 140 km in height. The descent of the Huygens probe in 1995 allowed obtaining the vertical zonal wind velocity profile at the entry site (Fig. 1c). Like Venus, the zonal winds increase from zero to about 40 ms^{-1} at 60 km (resulting in a vertical shear $\partial u / \partial z = 0.7 \text{ ms}^{-1}/\text{km}$) and after a velocity minimum at 80 km, they increase again to reach 100 ms^{-1} at $z = 120\text{--}140 \text{ km}$ ($\partial u / \partial z = 1.7 \text{ ms}^{-1}/\text{km}$). This means that Titan's atmosphere is in a superrotating state. Above this altitude, the superrotation reinforces again with zonal winds reaching velocities of $\sim 150\text{--}300 \text{ ms}^{-1}$ from 200–300 km and up to 340 ms^{-1} at the thermosphere at $z = 1000 \text{ km}$. These winds have been retrieved using indirect methods as the thermal winds resulting from a cyclostrophic balance between the pressure gradient force and centrifugal force, and from direct

measurements of Doppler shifts in spectral lines. Like Venus, polar vortices form in both hemispheres of Titan although their aspect looks different. The Huygens probe allowed also to measure meridional winds with velocities $< 1 \text{ ms}^{-1}$ from the surface up to 20 km altitude.

Because Titan is like Venus a slowly rotating body, the fundamental mechanisms involved in its general circulation are similar to those of Venus. The low value of the Coriolis force allows the formation of a global tropospheric Hadley cell consisting of ascending motions in the summer hemisphere (up to 500 km altitude) and descending motions in the winter pole (down to 50 km altitude). These are the approximate altitudes where this circulating cell transports heat and momentum across latitudes. Titan has a significant obliquity (Table 1), hence seasonal changes affect its upper atmospheric circulation. Therefore, this single cell pattern can break into two cells near equinoxes.

Earth and Mars

The general circulation of the atmospheres of these two planets is driven by the sunlight energy deposited on them and in the surface and is controlled by their rapid rotation periods and inclinations of their axis of rotation (and consequently of their seasonal insolation cycle) (Table 1). Both planets have variable hemispheric surface properties that influence the motions, in the case of Mars due to different albedo markings and in the case of the Earth to the continents and oceans dichotomy, including topography. A major difference between both planets is in their mass per unit area that is 53 times higher on Earth than on Mars. The atmospheric composition and the presence of clouds and aerosols (with abundant dust on Mars close to the surface) control the heating and cooling rates. On Earth, the atmosphere is composed by two diatomic molecules (nitrogen and oxygen) lacking of a significant infrared absorption spectrum. On the contrary, in Mars, carbon dioxide is the main atmospheric compound, which possesses a rich infrared absorption spectrum, heating and cooling the

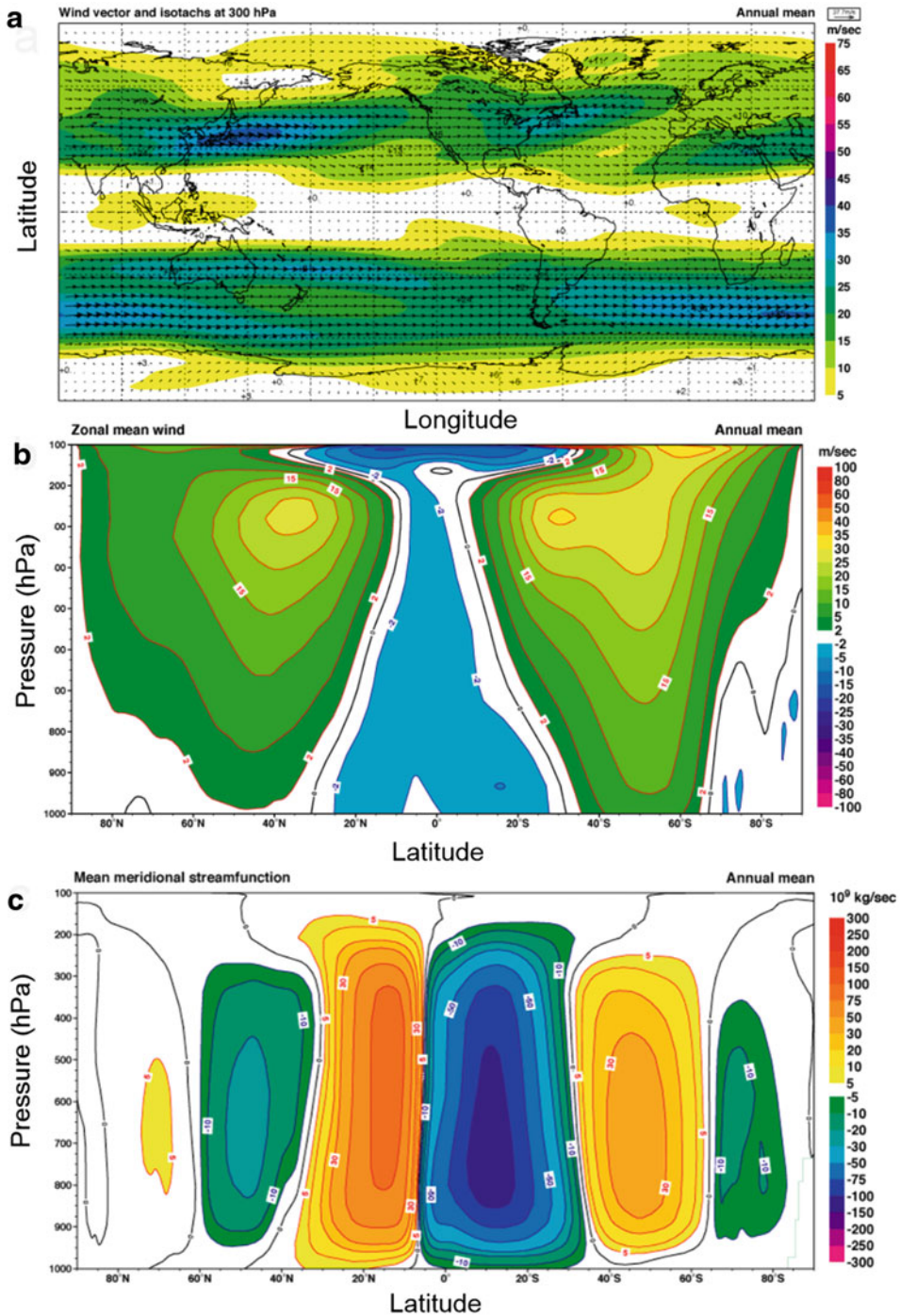
atmosphere. In addition, this carbon dioxide can condense under the low temperatures of Mars winter polar regions, generating a “condensation flow” towards and from the poles, unique to this planet. Water vapor is another key element on Earth and Mars since, besides its radiative properties, it can condense in both planets forming clouds that are much more massive on Earth than on Mars. Water vapor and its condensation are key ingredients in Earth’s tropical dynamics. The seasonal cycles of carbon dioxide, water, and dust on Mars control the variability of the atmospheric circulation.

Both planets are rapidly rotating bodies and hence the Coriolis and pressure gradient forces dominate to first order the momentum equation. When these two forces balance, the atmosphere is under a geostrophic regime. Close to the surface, the friction force must be taken into account in the momentum equation. When considering the continuity equation, the equation of state and the thermodynamic equation, the circulation outside the equatorial-tropical latitudes obeys the thermal wind equation that relates the horizontal temperature gradient with the vertical shear of the horizontal wind velocity. On Earth and Mars outside the equator, the global motions are essentially zonal, dominated by eastward jets in each hemisphere (Figs. 2 and 3). On Earth, a weak subtropical jet stream is centered at latitude $\sim 30^\circ$ and altitude ~ 12 km, and a polar jet stream is present at an altitude $z \sim 8\text{--}10$ km between latitudes $\sim 40^\circ\text{--}60^\circ$ with peak velocities of $\sim 25\text{ ms}^{-1}$ (but peak speeds reach in occasions $\sim 100\text{ ms}^{-1}$) (Fig. 2a, b). The two jets merge at some locations and times producing a single jet while at other times both jets are intense and well separated. These jets show undulations in latitude due to Rossby waves generated by the meridional gradient of the Coriolis force. The jets follow the thermal wind equation under geostrophic balance with intense vertical shear in the zonal velocity. These jets weaken above the tropopause ($z \sim 10$ km) but then increase their strength with altitude from ~ 25 km to 70 km, reaching speeds up to $\sim 60\text{ ms}^{-1}$ in the stratosphere-mesosphere. On Mars, due to the low atmospheric mass and

radiative time constant, the jet streams are strongly seasonal dependent (Fig. 3). They reach peak velocities of $\sim 100\text{--}180\text{ ms}^{-1}$ at altitudes $z \sim 35\text{--}45$ km.

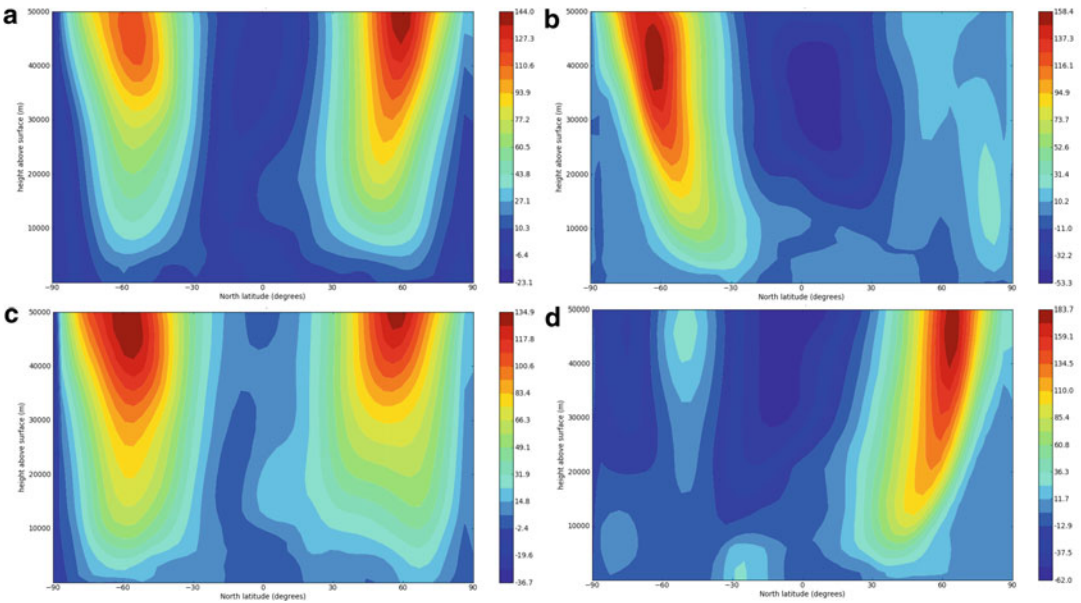
In between these zonal jets, meridional circulations of a Hadley-cell type are present. On Earth, it consists of a main Hadley cell between equator and tropics ($\sim 30^\circ$ latitude) and two additional cells, the Ferrel cell (circulating in a thermodynamically indirect sense from $\sim 30^\circ$ to 60° latitude) and a polar cell (from $\sim 60^\circ$ to 90° latitude) (Fig. 2c). At the equatorial surface, the Hadley cell is in the origin of the “trade winds” (westward tilted) when converging air in the equator forms the Intertropical Convergence Zone (ITCZ). In the ITCZ, strong ascending moist and warm air forms massive cumulus cloud along a planetary-scale narrow cloudy belt. The ITCZ shows seasonal and geographical variability and is related to a number of instabilities and waves that develop in the equatorial region. On Mars, the meridional circulation consists of a Hadley circulation that varies seasonally in its meridional extent and strength. At solstices, there is a single (global) Hadley cell that moves air from one hemisphere to the other. It drives the air in opposite directions in summer and winter solstice: warm air rises in the summer hemisphere of Mars (the hottest subsolar latitudes are $\sim 25^\circ\text{--}30^\circ$) and sinks in the winter hemisphere. At equinoxes, a dual Hadley cell forms with air rising near the equator fed by a surface flow from both hemispheres.

Two additional mechanisms contribute to the global atmospheric motions on Mars. On the one hand, there is a seasonal flow due to the pressure gradient generated by the condensation of CO_2 in winter in the polar caps. This condensation flow transports heat, momentum, and mass between low and high latitudes with a velocity of $\sim 0.5\text{ ms}^{-1}$. On the other hand, the low mass of the Martian atmosphere and its low radiative time constant favors large temperature differences (tens of degrees Kelvin) between the illuminated and shadowed hemispheres, driving thermal tides that propagate in the direction of motion of the Sun in the Martian skies.



Atmospheric Circulation, Fig. 2 Winds in Earth's troposphere. (a) Earth map with wind vector and isotachs at 300 hPa altitude level (~10 km). An isotach is a line connecting points of equal wind speed. (b) Mean zonal wind as a function of altitude and latitude. (c) Mean

meridional stream-function in altitude and latitude showing. From ERA-40 Atlas, European Centre for Medium-Range Weather Forecasts (2021) (<https://sites.ecmwf.int/era/40-atlas/docs/>)



Atmospheric Circulation, Fig. 3 Mean zonal wind velocity on Mars for longitude 0° and as a function of altitude (0–50 km) and latitude. Four different seasons are shown: (a) northern hemisphere spring equinox; (b)

northern summer solstice; (c) northern autumn equinox; and (d) northern winter solstice. From Mars Climate Data-base (<http://www-mars.lmd.jussieu.fr/mars/access.html>)

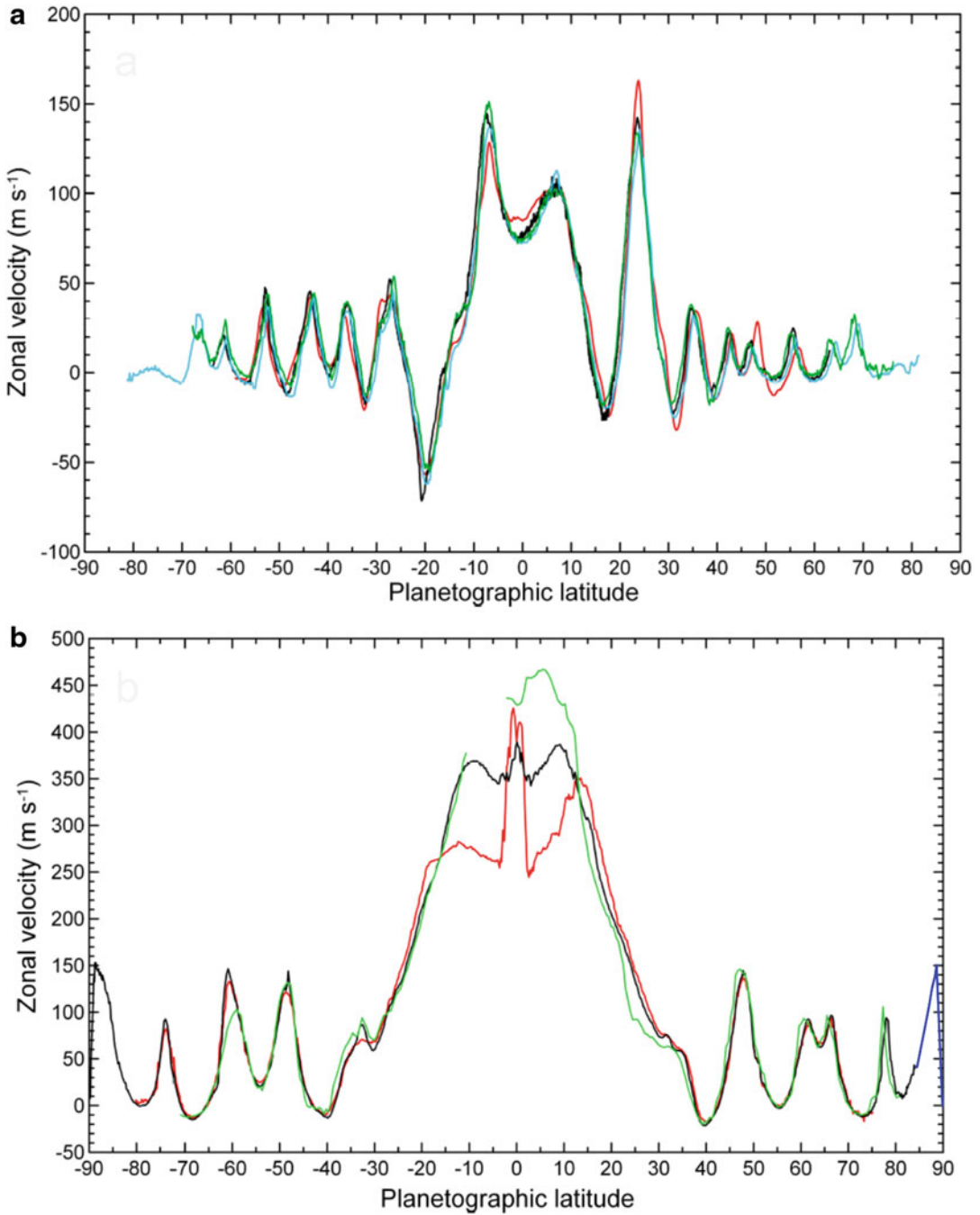
Jupiter and Saturn

The gaseous giants (Jupiter and Saturn) and the icy planets (Uranus and Neptune) are rapidly rotating fluid bodies that lack of a solid surface. The wind speeds at the upper visible cloud level are measured with respect to the bulk rotation of the planet determined from the modulated radio emissions by the rotation of the magnetic field. This magnetic field is generated in the deep massive electrically conducting interior and its axis tilts relative to the planet rotation axis except in the case of Saturn for which both axes are parallel. This is why the bulk rotation of Saturn is not yet fixed within an interval of a few minutes. The wind speed and its direction are measured by tracking the motion of cloud features. In the upper ammonia cloud (altitude range between pressure levels $P \sim 0.5\text{--}1.5$ bar), all four planets show a dominant zonal circulation consisting of a system of jet streams showing different intensities and alternating in their East-West direction with latitude (Fig. 4).

Jupiter has about eight jets per hemisphere exhibiting maximum speeds at the equator,

where a broad eastward jet reaches velocities $\sim 100\text{--}125\text{ ms}^{-1}$, and at latitude 23° N , where a narrow strong eastward jet reach velocities up to 180 ms^{-1} (Fig. 4a). This jet breaks the symmetry between north and south hemispheres. Saturn has six jets per hemisphere with a very strong and broad eastward equatorial jet with peak speed of $\sim 450\text{ ms}^{-1}$ relative to the radio-rotation period determined by the Voyager 1 and 2 spacecraft (known as System III and used as standard) (Fig. 4b). Jupiter and Saturn westward jets are less intense than those eastward. At the poles, Jupiter shows a system of 5–6 circumpolar cyclones, while in Saturn, a single, intense cyclone with winds at periphery of $\sim 150\text{ ms}^{-1}$ is centered at each pole.

Because of the rapid rotation of these planets, the atmospheric motions are under geostrophic balance in all latitudes except in the equatorial region (typically considered between the latitudes that contain the equatorial jet, case of Jupiter and Saturn). From the measurements of the temperature field above clouds, the use of the thermal wind equation allows to infer the vertical wind



Atmospheric Circulation, Fig. 4 Mean zonal winds in Jupiter (a) and Saturn (b) measured from cloud tracking. The Jupiter profiles were obtained at different years (red in 1979; black and blue in 2000; green in 1995–2000). The Saturn profiles correspond to different years (green in

1981; black and red in 2004–2009) and pressure level altitudes in the equatorial region: ~100 mbar (red), ~500 mbar (black), and ~1 bar (green). From Sánchez-Lavega and Heimpel (2018)

shears and obtain the zonal wind speeds above the clouds. Outside the equator in both planets, the winds decrease with altitude at a rate of about $\sim 5 \text{ ms}^{-1}/10 \text{ km}$. At stratospheric altitudes above clouds (between pressure levels ~ 0.1 and $\sim 50 \text{ mbar}$) in the equatorial region, the zonal winds exhibit a vertical, cyclic pattern of alternating velocities that propagate slowly downwards with a period of 4–5 years in Jupiter and ~ 15 years in Saturn. These are known as the Jupiter quasi-quadrennial oscillation (QJO) and as Saturn Equatorial Oscillation (SEO).

Deeper the upper cloud, in the weather layer where most clouds form (~ 1 – 5 bar in Jupiter, ~ 1 – 10 bar in Saturn), winds have velocities similar to those found in the upper cloud according to dynamical studies of convective storms. In December 1995, the Galileo probe penetrated the Jovian atmosphere at latitude 7°N in a peculiar dynamical region known as a “hot spot.” The direct measurement of the winds showed to increase from 100 ms^{-1} in the upper cloud to 160 ms^{-1} down to a depth of 24 bar . Beneath the weather layer, Jupiter and Saturn wind system extends deep in the atmosphere as determined by recent precise measurements of the gravity and magnetic fields by Juno spacecraft in Jupiter and Cassini spacecraft in Saturn. Accordingly, the cloud-level winds on Jupiter (Saturn) extend with very little decay down to a depth of around 2000 km (7000 km) and then decay rapidly in the electrically semiconducting region within the next 600 km (1000 km) where their value reduces to about 1% of that at the cloud-level.

Basically two theories have been proposed to explain the atmospheric motions on both planets. The zonal winds could be driven by convection in a deep spherical shell due to the release of stored internal energy in both planets coupled to their rapid rotation. This rotation organizes convection in axially oriented geostrophic columns that through dynamical stresses feeds the energy into zonal flows. The other hypothesis is that the zonal winds are driven by the solar energy deposited in the shallow upper weather layer, in a manner

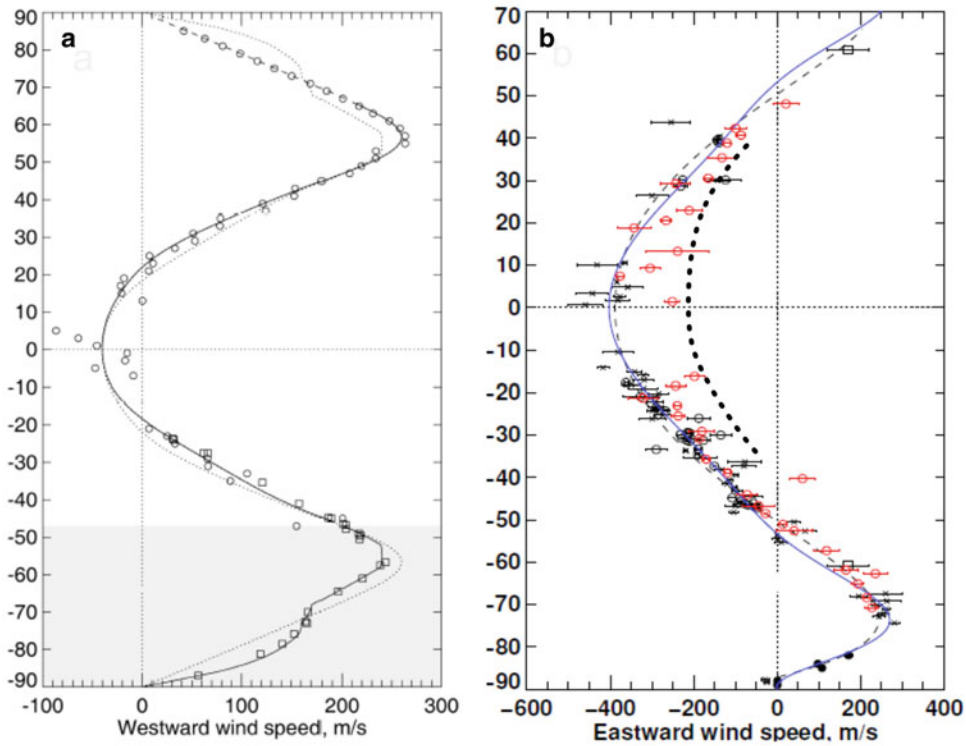
similar to what occurs on Earth. The zonal winds form from the turbulent motions due to a variety of dynamical phenomena in the stably stratified weather layer.

Uranus and Neptune

As Jupiter and Saturn, the zonal wind profile of both planets has been measured from the tracking of cloud features. In contrast to the two giants, Uranus and Neptune, have comparatively simple circulations, both highly zonal and characterized by a broad retrograde equatorial jet with direction opposed to the planetary rotation (retrograde) and with high-latitude prograde jets (in the direction of rotation of the planet) (Fig. 5). In Uranus the equatorial velocity reaches $\sim -50 \text{ ms}^{-1}$ and in Neptune -400 ms^{-1} . The two mid-latitude symmetric eastward jets in Uranus (latitude 55°) reach velocities of $\sim 230 \text{ ms}^{-1}$. In Neptune, it is not evident that this symmetry exists and there is only a confirmed jet close to the pole at 75°N with peak velocity of 275 ms^{-1} . The atmospheric circulation in both planets is surprisingly similar considering their very different inclinations of the rotation axis and their internal heat sources. Also surprising is the high speeds of their jets which, considering the differences in the strengths of their energy sources, suggests that it is the rapid rotation that essentially drives the atmospheric circulation. The available data on their structure of the gravity field and state-of-the-art interior models suggests the winds to be confined to a thin weather layer of no more than 1600 km on Uranus and 1000 km on Neptune, shallower than the deep winds of Jupiter and Saturn.

Basic Methodology

The study of the atmospheric circulation is based on the determination of the intensity of the winds in the three directions: zonal (along latitude circles, East-West), meridional (along meridian circles, i.e., across latitude circles, North-South), and vertical (radial or perpendicular to the plane tangent to the spheroid surface under consideration).



Atmospheric Circulation, Fig. 5 Mean zonal winds measured from cloud tracking since 1986 in Uranus (a) and 1989 in Neptune (b). The solid curves are fits to the individual data points measurements compiled by L. A. Sromovsky as shown in Sánchez-Lavega and Heimpel

(2018). The dashed curve in the Neptune profile is a fit to additional data points measured in the equatorial region where wind data have a large uncertainty due to temporal changes or altitude differences in the cloud tracers as shown in Hueso and Sánchez-Lavega et al. (2019)

The techniques and methods used in the study of atmospheric motions are based, on the one hand, on the direct observation and measurements in situ of the wind (platforms, rovers, soundings by probes), and on the other hand, on remote sensing methods using telescopes on Earth and in space (orbiting the Earth) and with spacecrafts visiting the planets (flybys, orbiters). The velocity and direction of the wind is measured directly using tracers of the fluid motion, such as clouds and aerosols, or of the gas itself through its spectral lines by means of the Doppler effect. Indirectly it can be determined from measurements of the temperature or pressure field and simple mathematical approximations to the fluid motion, such as the thermal wind equation or the meridian cell circulation. Numerical simulations of the atmospheric circulation under a variety of mathematical approaches and methods, known as general circulation models (GCM), are used for the

interpretation of the observable magnitudes and for short-term weather forecast and long-term climate predictions.

Key Research Findings

Venus: Three-dimensional structure of the winds, existence of traveling and stationary planetary waves, and presence of polar vortices in both hemispheres.

Venus and Titan: State of superrotation of their atmospheres.

Earth: Mid-latitude jet streams, planetary-scale Rossby waves, and system of three meridional cells per hemisphere. Existence of a single polar vortex in each hemisphere.

Mars: System of mid-latitude jet streams and interhemispheric Hadley cell, and their seasonal variability.

Jupiter and Saturn: System of stable alternating jets with latitude and presence of strong and wide in latitude prograde equatorial jets. The vertical structure of the winds in both planets and their deep extent, decaying to zero velocity at the electrically conductive deep layer.

Jupiter poles: Existence of a system of five to six cyclones surrounding both poles.

Saturn: Existence of a single polar vortex (an intense cyclone) in each hemisphere.

Uranus and Neptune: The atmospheric circulations dominated by the rotation of the planet with intense retrograde equatorial jets and prograde jets (one per hemisphere in the case of Uranus) at high latitudes.

Future Directions

Venus: Improve the GCM models of the superrotation and explain the nature of the planetary-scale waves and the polar vortices.

Mars: Measurement of the three-dimensional structure of the winds and their seasonal variability. Improve the three-dimensional structure of the heating and cooling rates due to aerosols (suspended dust and clouds) and their effects on the GCM models.

Jupiter and Saturn: Development of GCM models to explain the nature of their circulations at cloud level and the deep vertical structure of the wind system.

Uranus and Neptune: Development of GCM models to explain the nature of the observed circulations at cloud level and infer the vertical structure of the wind system from remote sensing measurements.

Titan: Characterization of the circulation as a function of altitude and latitude and development of GCM models.

General observations: New measurements of the relevant parameters to determine the planetary atmospheres circulations from space missions (flybys, orbiters, probes and platforms, and rovers) and from remote sensing using large optical and infrared ground-based and space telescopes, and radio-telescopes arrays.

Cross-References

- ▶ [Climates, Diversity in the Solar System](#)
- ▶ [Climates, Terrestrial Planets](#)
- ▶ [Climates, Exoplanets](#)
- ▶ [GCM](#)
- ▶ [Hadley Cells](#)
- ▶ [Superrotation](#)

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Atmospheric Dinitrogen Fixation

- ▶ [Nitrogen Fixation](#)

Atmospheric Dusts

- ▶ [Aerosols](#)

Atmospheric Modeling, Gray Gas Model

Raymond Pierrehumbert
Department of Physics, Clarendon Laboratory,
University of Oxford, Oxford, UK

Definition

For most atmospheric gases the optical thickness has an intricate dependence on wavelength. This complicates the solution of the radiative transfer equations, since the fluxes must be sought individually on a very dense grid of wavelength, and then the results integrated to yield the net atmospheric heating. The radiative transfer equations become much simpler if the optical thickness is independent of wavelength, which is known as the gray gas approximation. For gray gases, the relevant equations can be integrated over wavelength, yielding a

single differential equation for the net upward and downward flux. With the exception of clouds of strongly absorbing condensed substances like water, the gray gas model yields a poor representation to radiative transfer in real atmospheres, but the gray gas model is nonetheless a powerful theoretical tool for exploratory work in planetary atmospheres. It is also valuable as a radiation scheme in idealized general circulation modeling studies.

Cross-References

- ▶ [Atmosphere, Structure](#)
- ▶ [Atmospheric Modeling, Non-gray Gas Model](#)
- ▶ [Atmospheric Modeling, Radiative-Convective Equilibrium](#)
- ▶ [GCM](#)
- ▶ [Habitable Planet, Characterization](#)
- ▶ [Optical Depth](#)

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Atmospheric Modeling, Non-gray Gas Model

Raymond Pierrehumbert
Department of Physics Clarendon Laboratory,
University of Oxford, Oxford, OXON, UK

Definition

For real gases, as well as for gray gases (the gray gas approximation assumes that the atmosphere is transparent to solar radiation and possesses an absorption coefficient that is constant throughout the emitting infrared wavelength region – hence “gray” – and is independent of pressure and temperature), heated by infrared emission from the lower boundary, the temperature decreases with distance from the boundary (normally, the planetary surface). Real gases behave as if they are

optically thick near the ground, exhibiting strong convectively unstable temperature gradients there and only a small temperature jump between the ground and the immediately overlying air. For most atmospheric gases the optical thickness has an intricate dependence on wavelength; therefore the radiative transfer equations must be solved individually on a very dense grid of wavelength and then the results integrated to yield the net atmospheric heating. The upper atmosphere is considerably colder than the gray gas skin temperature, since (by Kirchoff's law) the atmosphere radiates efficiently in the strongly absorbing parts of the spectrum, but the radiation illuminating the upper atmosphere is depleted in this portion of the spectrum.

Cross-References

- [Albedo](#)
- [Atmosphere, Structure](#)
- [Atmospheric Modeling, Gray Gas Model](#)
- [Atmospheric Modeling, Radiative-Convective Equilibrium](#)
- [GCM](#)

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Atmospheric Modeling, Radiative-Convective Equilibrium

Daniel D. B. Koll
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

Definition

Radiative-convective equilibrium describes the hypothetical mean state of an atmospheric

column that is subject to heat transfer by radiation as well as convection. Radiative-convective equilibrium provides a useful approximation for the average vertical temperature structure of planetary atmospheres, which in turn determines a planet's surface climate as well as its observable state.

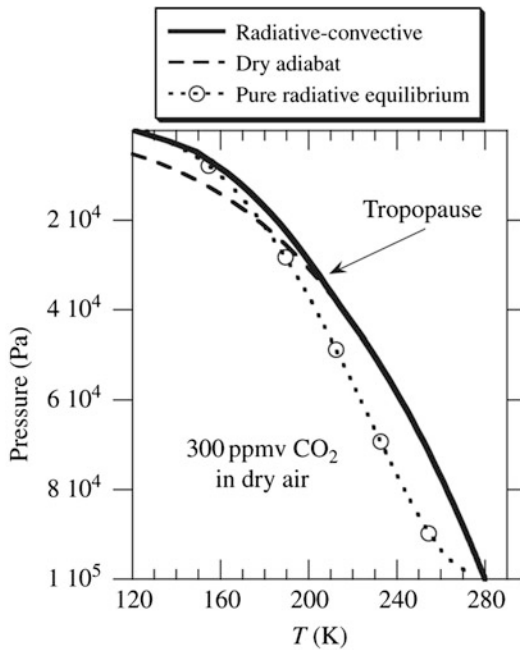
Overview

Radiative-convective equilibrium is a generalization of the concept of radiative equilibrium. An atmosphere is in pure radiative equilibrium when each part of the atmosphere radiatively emits as much energy as it absorbs. The theory of radiative equilibrium found early applications in explaining the thermal structure of the Sun's atmosphere and Earth's stratosphere.

Radiative equilibrium is a poor approximation for many planetary atmospheres, however, because physical processes other than radiation can also redistribute energy. Prime among them is convection, which arises from an atmosphere's turbulent motions. Convection redistributes energy by transporting heat as well as causing atmospheric gases to condense, which releases latent heat. In atmospheres without strong absorbers of stellar irradiation, pure radiative equilibrium tends to be unstable to turbulence. Turbulence can be triggered by strong vertical gradients in temperature, gradients in atmospheric composition, or temperature jumps near a planet's surface and cloud decks. These instabilities will cause a state of radiative equilibrium to evolve into a state of radiative-convective equilibrium (Fig. 1).

In radiative-convective equilibrium, each part of the atmosphere emits as much heat as it absorbs from radiation and convection combined. The assumption of radiative-convective equilibrium is commonly used in 1D climate models and retrieval models for planetary observations.

While the assumption of radiative-convective equilibrium is often a good approximation to the mean vertical structure of planetary atmospheres, its application becomes more questionable on



Atmospheric Modeling, Radiative-Convective Equilibrium, Fig. 1 The interplay of radiation and convection sets the mean vertical structure of planetary atmospheres. In this example, the atmosphere is largely adiabatic due to convection near the ground and evolves into a radiatively dominated profile near the top of atmosphere. (Figure from Pierrehumbert (2010))

planets with large horizontal temperature gradients. Examples include Earth's atmosphere at high latitudes, in which Earth's rotation prevents atmospheric motion from evenly redistributing heat, and tidally locked exoplanets, many of whom exhibit strong thermal contrasts between day- and nightside.

Cross-References

- [Adiabatic Processes](#)
- [Atmosphere, Structure](#)

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Atmospheric Modeling: 1D Model

Daniel D. B. Koll

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

Synonyms

[Single-column model](#)

Definition

One-dimensional (1D) models represent a planet's atmosphere as a vertical atmospheric column. 1D models are particularly useful for studying the flow of energy through an atmosphere and typically represent a planet's mean vertical structure while neglecting any horizontal inhomogeneity. Important applications of these models have included pioneering global warming predictions on Earth, defining the limits of the habitable zone and interpreting planetary remote observations.

Overview

The physics of heat transfer via radiation was developed in the nineteenth and early twentieth centuries. Radiative transfer theory found early applications in observations of stars and understanding the structure of stellar atmospheres. At the same time, observational capabilities expanded that prompted the application of these theories to planets, from early meteorological balloon measurements that discovered the stratosphere on Earth to remote spectroscopic measurements of solar system bodies.

By virtue of capturing the flow of energy through an atmosphere, 1D models can be used to understand an atmosphere's vertical thermal structure and the mean energy balance that determines its surface climate. For the same reason, 1D models are also widely used to model atmospheric

photochemistry and atmospheric escape processes. In addition, 1D models can be used as forward or inverse models to interpret measurements that probe different atmospheric altitudes, such as remote spectra of planets.

In the context of Earth's climate, 1D models produced some of the first quantitative estimates for how changes in CO₂ levels impact Earth's surface temperature. In the context of planetary habitability, 1D models have been used to identify the physical mechanisms that define the edges of the habitable zone, including the runaway greenhouse and the moist greenhouse. Finally, 1D models are widely used to interpret spectra taken of other planets; this has included remote sensing data of Mars, Venus, and Titan in the solar system and, more recently, spectra of exoplanets.

The physics that is best resolved by 1D models is the vertical flow of energy through a planet's atmosphere, in particular the redistribution of heat by radiative transfer. Other physics that can be captured well in 1D models are gravity and some atmospheric escape processes; conduction, which becomes important at low pressures, such as in Earth's thermosphere or in Pluto's atmosphere; and an atmosphere's gas-phase chemistry.

1D models often include physical processes that cannot be explicitly resolved within the model assumptions but can be mimicked through parameterizations. A prime example is convection and its effect on cloud cover. Convection arises from the turbulent motions of differentially heated gas parcels and is of first-order importance for the vertical redistribution of energy and chemical species. 1D models cannot resolve these motions but often parameterize their effect as vertical diffusion or use alternative convection schemes. Other processes which are parameterized in 1D models include precipitation and the formation of rain; ice-albedo feedbacks; and heterogeneous chemistry, which involves chemical reactions mediated by spatially inhomogeneous aerosol and cloud particles.

Physical processes that are not represented in 1D models tend to be associated with strong horizontal inhomogeneity. Inhomogeneity can arise from various sources, including the fact that planets are not uniformly irradiated by their star and variations in surface topography. Other

typical shortcomings of 1D models include their inability to resolve large-scale atmospheric fluid motions and the neglect of effects that arise from a planet's curvature. Despite these limitations 1D models remain some of the most flexible theoretical tools available, with widespread use in exploratory work and inverse modeling.

Cross-References

- [Atmosphere, Structure](#)
- [Atmospheric Retrieval for Exoplanets](#)
- [Habitable Zone](#)
- [Radiative Transfer \(Atmospheres\)](#)

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Atmospheric Particles

- [Aerosols](#)

Atmospheric Processes, Escape

Raymond Pierrehumbert
 Department of Physics, Clarendon Laboratory,
 University of Oxford, Oxford, UK

Definition

Atmospheric escape refers to the loss of a planet's atmosphere to space. Broadly speaking, escape may be energy-limited or diffusion-limited. For the energy-limited case, permanently removing a molecule from a planet's atmosphere can be compared to sending a rocket from Earth to space: One must impart enough velocity to the object, and in

the right direction, to allow the object to overcome the potential energy at the bottom of the gravitational well and still have enough kinetic energy left over to allow the object to continue moving away. The study of atmospheric escape in this case thus amounts to the study of the various ways in which the necessary energy can be imparted to molecules to reach the escape velocity, which is the minimum velocity an object needs in order to escape to infinity, provided no drag forces intervene.

Overview

The thermal escape velocity is obtained by equating initial kinetic energy to the gravitational potential energy:

$$\begin{aligned} \frac{1}{2} mv^2 &= GM_P m/r, \\ v &= \sqrt{2GM_P/r} = \sqrt{2gr} \end{aligned}$$

where m is the mass of the object (molecule in the present case), v its speed, r its initial distance from the center of the planet, M_P the mass of the planet, G the universal gravitational constant, and g the acceleration of gravity at distance r from the planet's center. In order to allow a molecule to escape, enough energy must be delivered to the molecule to accelerate it to the escape velocity. Since the kinetic energy of a molecule with mass m is $\frac{1}{2} mv^2$, light molecules such as H_2 will move faster and hence escape more easily than heavier molecules such as N_2 , given an equal delivery of energy. Dissociation of a molecule such as CO_2 or H_2 into lighter individual components also aids escape. Using the formula for escape velocity, we can define the escape energy of a molecule with mass m as mgr . For escape of N_2 from altitudes not too far from the Earth's surface, this energy is 2.9×10^{-18} J; for H_2 , the escape energy is only 0.2×10^{-18} J.

Atmospheric escape may be categorized as follows:

- Thermal (Jeans) escape – molecular speeds generally obey the Maxwell-Boltzmann distribution. Fast-moving species in the high-energy tail of the distribution may attain enough energy to escape the atmosphere. The general thermal energy of the atmospheric gas ultimately comes from, e.g., absorbed stellar radiation or from heat leaking out of the interior of the planet.
- Nonthermal escape mechanisms. Here, a “collisional process” energizes gas species above the escape barrier. For example, “ion exchange” involves charged species, e.g., hydrogen cations (H^+), which are accelerated in the planet's magnetic field to high energies. If the H^+ acquires an electron from a neighboring neutral species, it is converted into a neutral, high-energy atom (H^*) which can escape the atmosphere. Nonthermal escape can also involve interaction of, e.g., atmospheric species with the stellar wind (e.g., “sputtering” refers to the collisional ejection of a neutral species from the atmosphere by incoming high-energy species). “Impact erosion” refers to atmospheric escape driven by high-energy impacting material.

Cross-References

- [Absorption Cross Section](#)
- [Atmosphere, Structure](#)
- [Scale Height](#)

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Atmospheric Redox Change

- [Oxygenation of the Earth's Atmosphere](#)

Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey

► [Ariel Space Mission](#)

Atmospheric Retrieval for Exoplanets

Benjamin Charnay
LESIA, Observatoire de Paris, Université PSL,
CNRS, Sorbonne Université, Université de Paris,
Meudon, France

Keywords

Radiative transfer · Spectroscopy · Transit ·
Eclipse · Atmospheric models · Exoplanets

Definition

Atmospheric retrieval for exoplanets refers to the inference of atmospheric properties (atmospheric composition, thermal structure, clouds and hazes) of an exoplanet given an observed spectrum.

Overview

Objectives for Exoplanets

A spectrum of an exoplanet contains a lot of information about the atmosphere (atmospheric composition, thermal temperature, climate, clouds and hazes), coded into the molecular emission/absorption lines and bands. The goal of atmospheric retrieval is to retrieve these atmospheric properties from an observed spectrum. Measuring the molecular abundances in exoplanetary atmospheres is fundamental to understand the diversity, formation, and evolution of exoplanets. For the astrobiological context, the search for life on exoplanets is mostly focused on the detection of

potentially biogenic gases like O_2 , CH_4 , and N_2O . Accurate characterization of the whole atmosphere (composition and climate) and surface (temperate conditions, presence of liquid water, . . .) is required to give credit to a potential biological activity.

Principle

The principle of atmospheric retrieval is to compare the observed spectrum and data to several simulated spectra computed with an atmospheric model. A statistical method is applied to estimate the most likely atmospheric parameters allowing “to fit the data.”

Atmospheric Models

There are two main kinds of atmospheric models applied for retrieval:

1. **Self-consistent models** which simulate realistic temperature and composition profiles as well as spectra. These physical models include radiative transfer, chemistry (equilibrium or nonequilibrium chemistry), and potentially cloud formation. Since these atmospheric models can be computationally expensive, a grid of simulations for different parameters is usually computed before applying statistical methods to derive the parameters for the observed data. Self-consistent models cannot explore a too large parameter space and the retrieval can be biased by the physics included in the model. They are particularly useful for limited dataset (low signal-to-noise ratio or few points) compared to parametric models.
2. **Parametric models** simulate atmospheres using a limited number of atmospheric parameters and with limited assumptions on the physics and chemistry. A widely used thermal structure model is the model from Guillot (2010), using only five parameters (irradiation, internal heat, heat redistribution, visible and infrared extinction coefficients). These fast models allow to explore a large parameter space. They are not biased by the physics/

chemistry used and are really data-driven. However, they can allow degenerated solutions or physically impossible solution when only limited data is available (not high enough signal-to-noise ratio, spectral resolution, and spectral range).

Parametric models are ideal for exoplanets for which there still so many unknowns. However, the quality of spectra obtained by current telescopes is generally not high enough to make retrieval based on parametric models more accurate than with self-consistent models. The situation will likely change with future telescopes as JWST, ELTs, and ARIEL.

Statistical Methods

A modest atmospheric retrieval with the Guillot temperature profile (Guillot 2010) +3 molecule abundances (e.g., H₂O, CH₄, CO) and clouds (assuming gray cloud and with the cloud top as free parameter) corresponds to 10 free parameters. The full exploration of this parameter space for the atmospheric retrieval of an exoplanet would require a huge number of models, not achievable in a reasonable amount of time. This is why statistical methods are used to quickly explore the parameter space, focusing on the regions where are the best fits. Three methods are mostly used (see Table 1 in Madhusudhan 2018).

Optimal Estimation Method

The Optimal Estimation (OE) method is widely used for atmospheric retrieval of the Earth and Solar System planets. This method determines the best fit after a few iterations by optimizing the likelihood function using a nonlinear least squares minimization scheme. A priori probability distributions (called priors) can be specified for parameters which are already quite well constrained. The OE method is favored for high quality dataset and is limited for cases with strong degeneracies.

Markov Chain Monte Carlo (MCMC)

The MCMC method aims at exploring the parameter space a by random walk starting from an

initial guess. The parameters used for a next step are determined from the current step with a pre-defined distribution as a Gaussian distribution. MCMC determines well the posterior distribution but is not very efficient for cases with multiple plausible solutions

Nested Sampling

The Nested Sampling is quite similar to the MCMC but differs concerning the sampling of the parameter space. Instead of doing a chain starting from an initial guess, the Nested Sampling starts from several initial points, fixed by the prior distribution. At each iteration, the point with the lowest likelihood is discarded and replaced by a new point with a higher likelihood. The contour formed by these points shrinks after each iteration toward a solution. This method is computationally efficient and well suited for large parameter spaces, as it is generally the case for exoplanets.

Difficulties for Exoplanets and Future Missions

Stratospheric Thermal Inversion

Initial Spitzer eclipse observations suggested the presence of stratospheric thermal inversions on very hot exoplanets. These conclusions relied on the differences of thermal emission in the 3.6, 4.5, 5.8, and 8.0 μ m Spitzer bandpasses. Corrections of some systematics ruled out the stratospheric thermal inversion in some hot exoplanets (Diamond-Lowe et al. 2014). That issue illustrates how atmospheric retrieval can be misleading by low quality data.

Clouds/Hazes

The transit observations of exoplanets revealed that most of them are cloudy or hazy. These condensate clouds or photochemical hazes mask atmospheric molecular absorption, producing flat transit spectra. They represent a major issue for atmospheric retrieval.

Water Abundance

A major question for exoplanets is to determine the water abundance of exoplanetary

atmosphere and how is it related to the planetary mass. Following the Solar System giant planets, we can expect that the metallicity (i.e., the water abundance) decreases with the planetary mass. Several measurements of water abundance have been performed with HST data of hot giant planets. However, the conclusions differ depending on the retrieval model and how clouds are treated (see Sing 2018; Pinhas et al. 2019).

The 3D Nature of Exoplanets

Most of atmospheric retrieval codes assume that limbs or observed side are homogeneous. However, strong contrasts in temperature and cloud cover can exist between the west and east terminators, and partial cloud cover can be present on the dayside. In addition, 1D atmospheric models used phase-curve retrieval miss the heat redistribution by the atmosphere. New methods combining two terminator profiles (Line and Parmentier 2016) or doing 2D/3D retrieval for phase curves (Irwin et al. 2020) have been developed to take in account these 3D effects.

Future Telescopes

Atmospheric retrieval is very promising for JWST and ARIEL. These space telescopes will obtain transit and emission spectra of hundreds of exoplanets from 0.6 to 28 microns (for JWST) and from 0.5 to 8 microns (for ARIEL). These large spectral ranges allow to cover absorption bands of several molecules (H_2O , CH_4 , CO , NH_3 , CO_2 , PH_3 , HCN , C_2H_6 , FeH , TiO , VO , ...). They probe in the mid-infrared, where the effects of clouds are reduced. In parallel, cross-correlation technics applied to high resolution spectra from ELTs will also allow to retrieved temperature structure and molecular abundances of exoplanets (Brogi and Line 2019).

Cross-References

- [Atmospheric Modeling, Non-gray Gas Model](#)
- [Biomarkers, Spectral](#)
- [Radiative Transfer](#)

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Atomic Fine Structure Cooling

Steven B. Charnley
Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

Atomic fine structure cooling is one of the processes by which ► [interstellar medium](#) material can lose thermal energy. Atomic and molecular hydrogen collisions excite the fine structure components of ground state terms in atoms and atomic ions – e.g., in neutral carbon and oxygen atoms and in C^+ – and these subsequently decay radiatively with the escaping photon leading to a net cooling of the gas.

Cross-References

- ▶ [Interstellar Medium](#)
- ▶ [Molecular Line Cooling](#)
- ▶ [Photodissociation Region](#)

Atomic Nitrogen

- ▶ [Nitrogen](#)

Atomistic Computer Simulation

A. Marco Saitta
IMPMC, UMR 7590, Sorbonne Université,
CNRS, Muséum National d'Histoire Naturelle,
Paris, France

Keywords

Molecular dynamics · Ab initio methods · Chemical networks · Free-energy landscapes · Kinetic rates · Chemical pathways · Enhanced sampling · Gas-phase chemistry · Condensed-phase chemistry

Acronyms

QC	Quantum Chemistry
HF	Hartree-Fock
DFT	Density Functional Theory
MD	Molecular Dynamics
AIMD	Ab Initio Molecular Dynamics

Synonyms

[Ab initio = First-principles](#)

Definition

By **Atomistic Computer Simulation** methods, one generally refers to computational approaches

explicitly treating each atom of a given chemical system of interest, ranging from gas-phase quantum chemistry to condensed-phase molecular dynamics. These methods have long demonstrated their capability to explain and predict the chemical behavior of a variety of systems at different scales (of length and time), and different conditions, but only recently begin to be adopted within the prebiotic chemistry and astrobiology/origins of life research field (Perez-Villa et al. 2020). A crucial requirement for those methods to be useful, in the context of prebiotic chemical reactions, is to accurately model the electronic structure of the systems to describe the breaking and formation of chemical bonds. To this aim, different available computational chemistry methods, such as those based on molecular orbital theory (Szabo and Ostlund 1989), density functional theory (Parr and Yang 1995), or empirical valence bond theory (Warshel 1980), are able to accurately describe and predict the reorganization of electronic structure connected to changes in chemical bonding. Modern theoretical and computational challenges, particularly needed for astrobiology and prebiotic chemistry, are focused on the efficient exploration of complex, multi-dimensional chemical networks to determine, under a variety of possible geochemical environments, the most relevant chemical pathways. Thanks to the emergence of novel, innovative theoretical approaches, and to the increase of available computer power, such methods can now be applied to challenging prebiotic problems, bringing valuable insights that are complementary to experiments.

Overview

Atomistic computer simulations in chemistry comprise different types of approaches, such as classical molecular dynamics, semiempirical simulations, and ab initio quantum chemistry methods, all characterized by the explicit and generally individual treatment of each atom in the chemical system of interest. Among those approaches, ab initio methods are particularly relevant in prebiotic chemistry, as they are very

accurate in computing minima (corresponding to reactants, intermediates, and products) and barriers in the energy landscape of a quantum system containing many atoms and electrons. One generally refers to “*ab initio* quantum chemistry,” or simply “quantum chemistry (QC),” to identify approaches in which the atomic interactions are described “*ab initio*,” a Latin term that means “from the beginning” or “from first principles.” *Ab initio* quantum chemistry is indeed based on quantum mechanics, not relying on experimental information or empirical models.

QC calculations aim for the “exact” solution of the Schrödinger equation corresponding to the molecular Hamiltonian. Those methods have in general an elevated computational cost, and typically one is able to model relatively small systems (up to few tens of atoms); however, this is the most established tool to study at the atomic scale the properties and reactivity of molecular systems. Among the many methods developed in the last decades with the aim of obtaining an accurate, albeit approximate, numerical solution of the Schrödinger equation, the Hartree-Fock (HF) one was the first to provide useful and quantitative insight. In the HF equations, the electronic wave-function is approximated in an effective way, and the molecular orbitals are optimized by a numerical iterative self-consistent procedure. However, its formulation inaccurately describes states in which electron correlation plays an important role. In this regard, one of the main challenges has been to develop new approaches that include the electron correlation at a reasonable computational cost, typically known as post-Hartree-Fock methods.

Over the decades, a less accurate than QC but more effective class of computational methods for physics and chemistry, based on Density Functional Theory (DFT) (Becke 2014; Hohenberg and Kohn 1964; Kohn and Sham 1965), has emerged and become popular. DFT-methods are centered on the Hohenberg-Kohn theorem, which proves that the ground state energy of a multi-electron system is univocally determined by a functional of the ground state electronic density. The electronic density is a function of three spatial coordinates only, and not of the coordinates of all

N electrons like in the case of the QC wave function, which makes its treatment more efficiently manageable. As a consequence, and thanks to the availability of efficient approximations and algorithms, DFT-techniques provide, with respect to higher-level QC methods, a more powerful and faster way to obtain information about the structure and energy of a chemical system, at least in its electronic ground state. Conversely, low-temperature/gas-phase excited-state chemistry (for example, photochemistry in the interstellar medium) is better and more accurately described by QC approaches.

In many chemical problems, especially in prebiotic chemistry, it is paramount to assess the effects of the environment. This might comprise the presence of solvent molecules, the effect of ions and/or pH, the interaction with mineral surfaces, and so forth. In addition, for several applications it is essential to take into direct account the effect of temperature, beyond normal-mode extrapolations like the quasi-harmonic approximation, and sometimes pressure. Hence, in several cases performing QC simulations at absolute zero temperature and gas-phase might not be a very suitable choice (Voth and Hochstrasser 1996). Among the most powerful strategies to simulate complex chemical systems, a central place is held by *ab initio* molecular dynamics (AIMD) (Car and Parrinello 1985; Marx and Hutter 2009; Tuckerman 2002). AIMD combines the quantum treatment of the electronic degrees of freedom, with the numerical integration of Newton’s equation of motion, where quantum-calculated forces act on the atoms. In general, the typical timescale for individual AIMD trajectories ranges between tens and hundreds of picoseconds, with typical time steps in the range 0.1–0.5 fs. In principle, AIMD simulations are ideally suited to study the mechanisms, thermodynamics, and kinetics of chemical reactions at a given pressure and temperature. An extremely long trajectory of the system, generated from accurate forces, would ergodically sample fluctuations within metastable states as well as all possible transitions among them.

However, DFT-based AIMD simulations are presently typically limited to the subnanosecond

timescale. Of course, because of free-energy barriers, the experimental timescale of most chemical reactions is immensely slower, ruling out straightforward computer simulations. To cope with timescale limitations, but also to get fundamental insight that is not automatically provided by a bare long MD trajectory, a number of different so-called enhanced sampling approaches were introduced in the last few decades, such as umbrella-sampling (Torrie and Valleau 1977), or metadynamics (Laio and Parrinello 2002). However, even with the help of enhanced-sampling, the widespread exploitation of MD simulations in the study of chemical reactions has been slowed by the lack of general-purpose formulations of reaction coordinates. In particular, it is challenging to design coordinates that fully include the important role of solvent degrees of freedom (Ensing et al. 2006; Prasad et al. 2013) and that are general enough to be applied to a range of diverse reaction mechanisms. Ref. (Pietrucci and Saitta 2015) proposed a new way to tackle this problem. The method deals in the same formal way (namely, in the same space of coordinates) with gas phase and solutions, allowing a direct comparison of the two environments and an easier assessment of the effects of a given solvent on reaction pathways. Several impactful applications of this novel approach have been successful in describing the prebiotic synthesis, in aqueous solution, of RNA nucleotides (Pérez-Villa et al. 2018), and of amino acids (Saitta and Saija 2014; Pietrucci et al. 2018; Magrino et al. 2021).

The most advanced methods in computational physics and chemistry can play a particularly useful role in the modeling and simulation of prebiotic chemical reactions. The level of accuracy has increased significantly, and the implementation of highly demanding algorithms is becoming more feasible, allowing the investigation of very specific and complex problems in physics and chemistry. Simulations are notably very effective in the determination of free-energy landscapes based on reaction coordinates built from the structural topological properties of the reactants and the products. However, the need to describe, at the quantum level, the forces acting between atoms

and the complexity of the calculations therein have until now only permitted the processing of reactions of very small systems in solutions. Consequently, the work undertaken until now in the field of prebiotic chemistry and the molecular origins of life is still in its preliminary stages.

Cross-References

- [Activation Energy](#)
- [Artificial Chemistries](#)
- [Chemical Reaction Network](#)
- [D-Amino Acids](#)
- [L-Amino Acids](#)
- [Nucleotide](#)
- [Prebiotic Chemistry](#)
- [Primordial Soup](#)
- [Thermodynamical Chemical Equilibrium](#)

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ATP

Shin Miyakawa¹ and Kensei Kobayashi²

¹Tokyo Institute of Technology, Tokyo, Japan

²Department of Chemistry, Yokohama National University, Yokohama, Japan

Synonyms

[Adenosine triphosphate](#); [pppA](#)

Definition

ATP is one of the four activated nucleotides incorporated into [RNA](#) by RNA polymerases. It is also extremely important in biochemistry as a high-energy molecule that releases the energy needed for many metabolic reactions by coupling hydrolysis into ADP and inorganic phosphate, or

AMP and pyrophosphate, with various synthetic and mechanical processes. The formation of ATP in living organisms takes place through two main biochemical pathways: substrate-level phosphorylation (in which phosphate is transferred to ADP from activated phosphorylated intermediates) and membrane-associated processes (found in respiration and photosynthesis).

Although prebiotic phosphorylation may have led to ATP from adenosine, ATP is usually not considered to have been abundant in prebiotic environments, and polyphosphates have been proposed as alternative primordial energy carriers. In prebiotic oligonucleotide synthesis, adenosine 5'-phosphoimidazolide was often used in place of ATP.

Cross-References

- [Adenine](#)
- [Nucleotide](#)
- [Oligonucleotide](#).
- [RNA](#)

ATP Phosphohydrolase

- [ATPase](#)

ATP Synthase

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

ATP synthase is an enzymatic complex responsible for converting the energy of a transmembrane [electrochemical potential](#) of an ion (H^+ or Na^+) into chemical energy of the system ATP-ADP. ATP synthases have a universal phylogenetic distribution, and hence, it is supposed that they were present in the universal common ancestor.

Cross-References

- ▶ [ATP](#)
- ▶ [Bioenergetics](#)
- ▶ [Electrochemical Potential](#)
- ▶ [Last Universal Common Ancestor](#)
- ▶ [Transduction](#)

ATPase

José Pascual Abad

Facultad de Ciencias, Departamento de Biología Molecular, Universidad Autónoma de Madrid, Cantoblanco, Madrid, Spain

Keywords

A-ATPase · ABC-transporter · ATP synthase · F-ATPase · P-ATPase · Proton gradient · Proton motive force · Rotary ATPase · Transmembrane ATPase · V-ATPase

Synonyms

[Adenosine 5'-triphosphatase](#); [Adenosine triphosphatase](#); [ATP phosphohydrolase](#).

Definition

Enzymatic activity that catalyzes the decomposition of adenosine triphosphate (ATP) into adenosine diphosphate (ADP) and phosphate (Pi). A protein with ATPase activity.

Overview

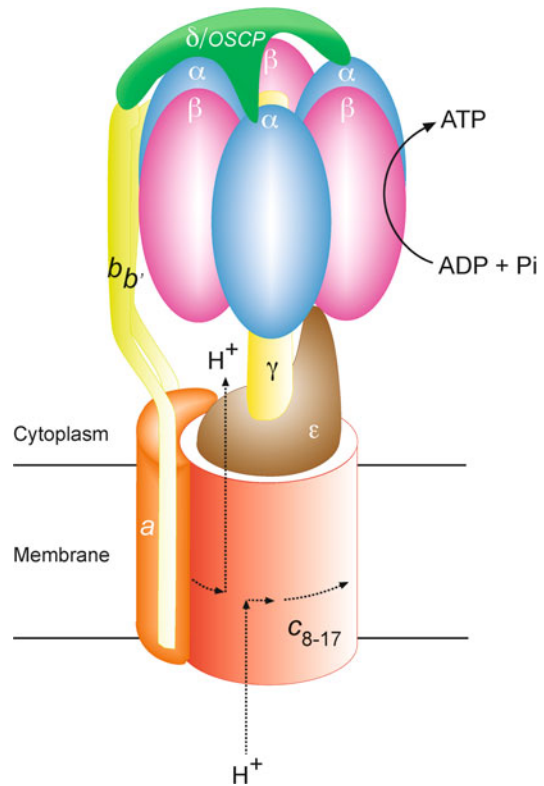
The term ATPase applies to the activity of any *enzyme's* ability to decompose *ATP*, including metabolic enzymes involved in anabolic processes that need energy, as well as enzymes promoting *transport* across *membrane*. In the former case, the enzyme decomposes ATP using the energy liberated to do work; for instance, enzymes such as DNA helicases, RecA protein, AAA proteins, or the muscle contraction protein myosin

hydrolyze ATP, applying the liberated *free energy* directly to their functions. In other cases, i.e. glutamine synthetase, decomposition of ATP is performed in two steps, helping to perform chemical work, phosphorylating a substrate or enzyme in a first step, and releasing the *phosphate* (Pi) in a second step. Sometimes this type of reaction involves the transfer of pyrophosphoryl or adenylyl groups instead. There are many known ATPases, which promote ATP *hydrolysis* coupled to transport solutes across membranes into another compartment. These are integral membrane proteins called transmembrane ATPases, and there are many different types found in all kind of organisms, performing functions in which energetic exchanges are quantitatively quite relevant. These include at least five general types of this kind of ATPases: F (F comes from original name of the enzyme: Coupling Factor (CF)), V (vacuolar), A (archaeal), P (phosphate), and ABC (ATP-binding cassette)-multidrug transporters. Because of their mechanism of functioning, the three-first ones indicated are rotary ATPases. An additional rotary ATPase, specifically fueled by Na⁺ and named N-ATPase, will not be addressed here.

F-ATPases are present in the plasma membrane of *bacteria*, *mitochondrion* inner membrane, and thylakoid membranes of chloroplasts of photosynthetic *eukaryotes*, A-ATPases are found in *Archaea* and some *extremophilic* bacteria, and V-ATPase are located in the endomembrane of intracellular compartments of eukaryotic cells and the plasma membrane of several specialized cells. In vitro, all are reversible enzymes able to promote the generation of a *proton motive force* (PMF) at the expense of ATP hydrolysis or to synthesize ATP from ADP and Pi using a pre-existing proton gradient. In this second type of function, the enzyme is more appropriately named *ATP synthase*. However, in vivo, mitochondrial and chloroplast enzymes only function as ATP synthases, V-ATPases only perform the hydrolytic reaction, and bacterial enzymes can work in both ways depending on growth conditions. The process of ATP synthesis is often called oxidative phosphorylation. In the case of fermenting bacteria, which lack an electron transport chain (to produce a proton motive force) and cannot

perform oxidative phosphorylation, the enzyme acts as a real ATPase producing a proton gradient, which is used to energize other *transport* processes.

Structurally, F-ATPases are related to V-ATPases and A-ATPases, but each of these groups presents differential characteristics, as well as differences among those of the same type but in different organisms have been observed. For instance, the plant's F-ATPases have structural characteristics that allows their redox control (Hahn et al. 2018; Yang et al. 2020), or adaptations to an environment with high pH of a thermo-alkaliphilic bacterium has been described implying changes in the α subunit (McMillan et al. 2007). In F-ATPases, also called F_1F_0 -ATPases, a F_0 complex of proteins integral to the membrane is a transmembrane proton translocase, and the F_1 protein complex, at the surface of the membrane, is a molecular machine that can either decompose ATP, promoting the passage of protons through F_0 uphill the protons gradient, or transform the energy liberated by the passage of protons, downhill the gradient, through F_0 , into chemical energy, thus synthesizing ATP from ADP and P_i . The insertion of the enzyme in the membranes is quite relevant for ATP synthase function (Liu et al. 2021). Both complexes consist of assemblies of several subunits that together form a rotary motor. Binding of protons to F_0 causes the rotation of some of the subunits, which together with the subunits of F_1 conform three binding sites for ADP and P_i . The complex undergoes rotationally conformation changes through different affinity states, in one of which ADP and P_i can react before the synthesized ATP is released (rotational catalysis). The equivalent protein complexes in A-ATPases or V-ATPases are named A_1/A_0 or V_1/V_0 , respectively. Sometimes the expressions R_1 and R_0 are used referring to the two components in a general form. R_0 and R_1 complexes are bound through two kinds of stalks, a central one involved in the rotational coupling between both complexes, and one (F-ATPases) (Fig. 1), two (A-ATPases), or three (V-ATPases) (Fig. 2) peripheral stalks that connect the two complexes (Colina-Tenorio et al. 2018). Moreover, the F-ATPases found in mitochondria form dimeric structures by interactions

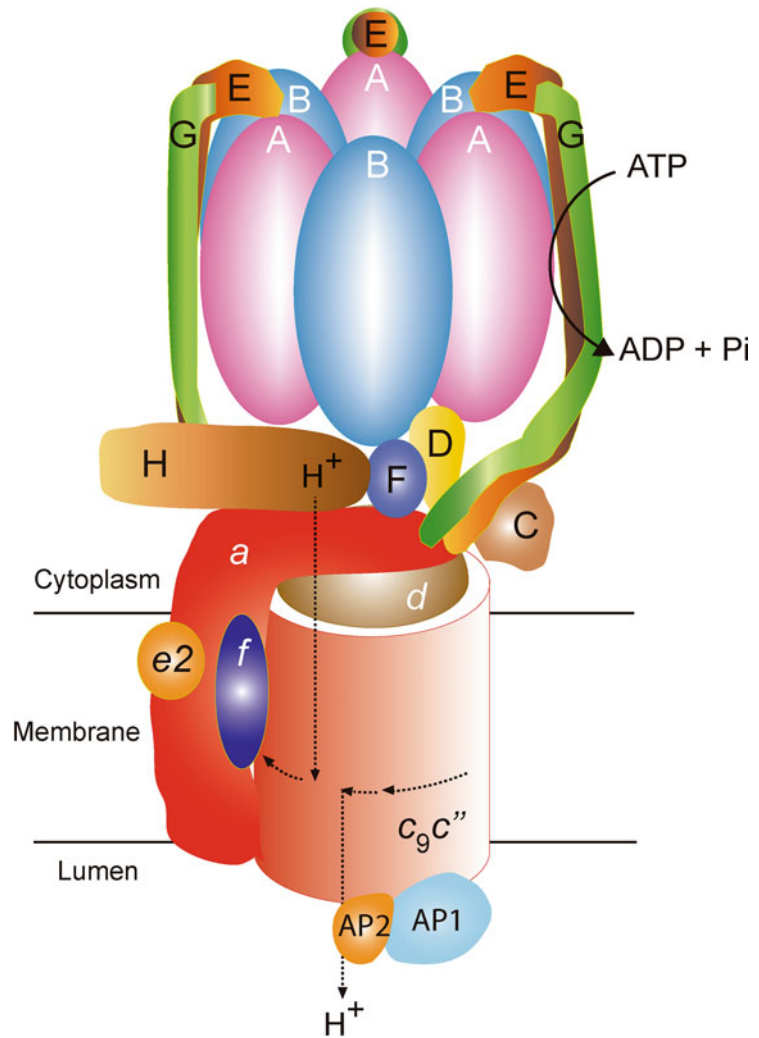


ATPase, Fig. 1 Model of the structure and function of F-ATPases. OSCP (oligomycin sensitivity conferral protein) is the mitochondrial-F-ATPase subunit corresponding to δ subunit in other F-ATPases. Subunit b' is a variant of b subunit found in some F-ATPases; in other cases, there are two identical b subunits

established by specific additional proteins (Spikes et al. 2020).

V-ATPases are proton-transporting proteins that generate a lower pH inside the compartments, thus activating the hydrolytic enzymes present in them. V-ATPases are also found in the plasma membranes of a wide variety of animal cells, including certain tumor cells, where they are involved in processes such as pH *homeostasis* or metastasis. V-ATPases have also been found in plants and *fungi*. The structures of these enzymes are more complex than those of F-ATPases and even than A-ATPases, to which they are more related both structurally and phylogenetically (Grüber and Marshansky 2008; Kühlbrandt 2019). Among the functional differences of V-ATPases and other rotary ATPases, they can be regulated by reversible disassembly in V_0

ATPase, Fig. 2 Model of the structure and function of mammalian brain V-ATPase

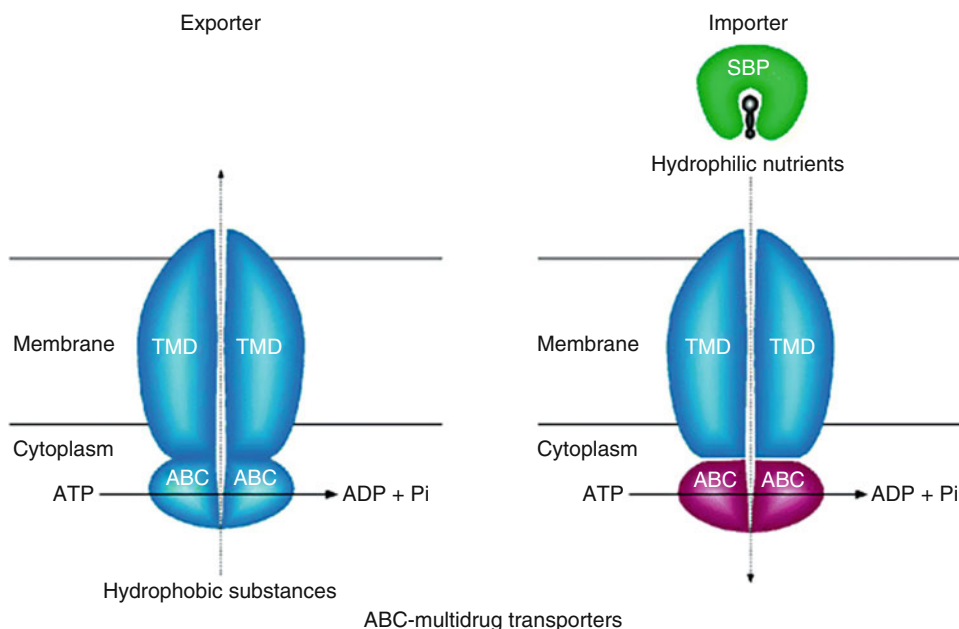


and V₁ complexes, and by the use of isoforms of *a* subunit (Sharma et al. 2018; Wang et al. 2020).

In some anaerobic bacteria, *extremophiles* (particularly, thermophilic and *alkaliphilic*), and Archaea, the coupling ion used by F and V-types ATPases is Na⁺ instead or in addition to H⁺, and a sodium motive force (SMF) substitutes the PMF (Schlegel et al. 2012). Certain studies suggest that the Na⁺-dependent ATPases came first in terms of evolutionary history; however, some others consider them as a secondary adaptation to survival in extreme environments (Dibrova et al. 2015; Lane et al. 2010; Mulikdjanian et al. 2008).

The ABC family of proteins constitutes a large and ubiquitous superfamily that includes both

soluble and integral membrane proteins (Furuta 2021; Locher 2009; Wilkens 2015). These last ones are responsible for the ATP-powered translocation of many substrates across membranes, existing importers, and exporters. ABC transporters found in *prokaryotes* can be importers or exporters; however, eukaryotic ones are mainly dedicated exporters. Their hydrophilic nucleotide-binding domains (NBD) are highly conserved and provide the nucleotide-dependent engine that drives transport. By contrast, the transmembrane domains (TMD) that generate the translocation pathway are more variable. In importers, both domains are in separate subunits while in exporters are in a unique protein (Fig. 3). In prokaryotes, the

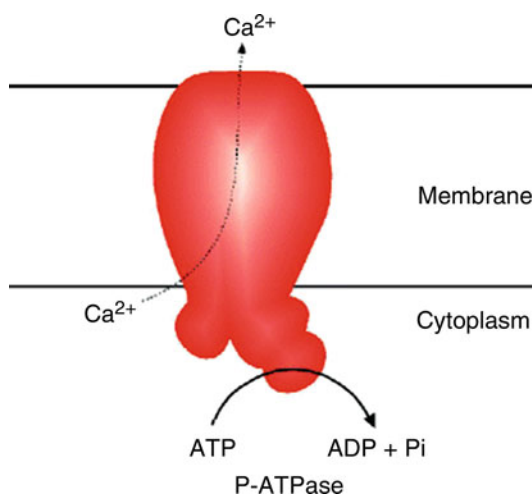


A

ATPase, Fig. 3 Model of the structure and function of ABC-multidrug exporters and importers *TMD* transmembrane domain, *ABC* ATP-binding cassette, *SBP* substrate-binding protein

importers provide the cell with hydrophilic nutrients, while exporters remove different xenobiotics and hydrophobic substances from the cell. The prokaryotic exporters are responsible for the efflux of drugs that cause certain *antibiotic* resistances, and the eukaryotic ones can prevent the inhibitory effect of anticancer drugs by preventing their accumulation within the tumor cells. For functioning, the importers require a substrate-binding protein (SBP).

P-ATPases are enzymes present in some biological membranes of prokaryotes and eukaryotes, which promote cations or lipid transport using the energy from ATP hydrolysis (Kühlbrandt 2004). All members of this family have certain amino acid sequence conservation, particularly the Asp residue that suffers the phosphorylation/dephosphorylation involved in the process, and is inhibited by vanadate. Some are unique polypeptides with multiple membrane-spanning regions, while others have a second subunit. Based on phylogenetic analysis, P-ATPases have been classified into five main classes named P1-P5 (Pedersen et al. 2012). This type of enzyme is widely distributed and includes representatives in animals (Na^+K^+ -ATPase, Ca^{2+} -



ATPase, Fig. 4 Model of the structure and function of the Ca^{2+} -ATPase, a P-ATPase

ATPase, H^+K^+ -ATPase), plants and fungi (plasma membrane H^+ -ATPase), and bacteria (Ag^+ , Cd^{2+} , Cu^{2+} , Hg^{2+} , or Zn^{2+} ATPases). P4-ATPases transport or flip phospholipids. Albeit their diversity in ion specificity, all P-ATPases are homologues (Fig. 4).

Basic Methodology

The main methodologies used for the studies on ATPases include crystallization and structure determination by X-ray diffraction; nuclear magnetic resonance (NMR) of particular subunits or complexes; electron and fluorescence microscopy including visualization of the rotational movement of F₁-ATPase, after attaching the rotating subunit to a *fluorescent* structure (Noji et al. 1997) and kinetic and binding studies of the enzyme activities, as well as genetic studies based on the effect of protein sequence modifications. Since the implementation of single-particle analysis of protein complexes by high-resolution cryogenic electron microscopy (cryo-EM) techniques, a revolution in the knowledge of the structure and function of rotary ATPases has taken place (Kühlbrandt 2019).

Key Research Findings

Boyer's group proposed in 1973 (Boyer et al. 1973) that the step requiring energy in the synthesis of ATP by ATP synthase was the release of the ATP molecule from the enzyme. Three years later, the binding change mechanism was proposed by this group. The first X-ray structure of an incomplete F₁ complex was published by Walker's group in 1994 (Abrahams et al. 1994). In 1997, Yoshida's group was able to record the movement of the F₁ complex during ATP hydrolysis, now including the gamma subunit (the rotating shaft of the enzyme), after attaching individual complexes to a surface and looking to a fluorescent actin filament attached to the γ subunit (Noji et al. 1997). In 2004, the mechanically-driven synthesis of ATP by the F₁ complex was also demonstrated in experiments, in which the γ subunit inserted in the F₁ complex was induced mechanically to rotate in the presence of ADP and phosphate, and ATP was afterward released to the medium, with a more complete view of the process in more recent studies (Kühlbrandt 2019). Many more research findings have been reported since the use of cryo-EM, and high-resolution structural models of different rotary ATPases from different organisms are available (Colina-Tenorio et al.

2018; Hahn et al. 2018; Nakanishi et al. 2018; Guo et al. 2019; Abbas et al. 2020; Pinke et al. 2020; Sobti et al. 2020; Sobti et al. 2021; Spikes et al. 2020; Srivastava et al. 2018; Wang et al. 2020), since the first report using these techniques on ATPases proteins by Allegretti et al. 2015.

Future Directions

Although we begin to have a good view of how ATPases work, deeper structural analyses are needed to determine the mechanisms of ions that pass through the ATPases domains and of torque generation. Comparison of the structures of ATPases of different origins should also help in determining the most relevant aspects of this issue, including the function of dimerization in mitochondrial F-ATPases. The biogenesis, assembly, and regulation of the rotary ATPases are also issues to be clarified in the next future, as some researchers are beginning to do (Miranda-Astudillo et al. 2021). Acquiring a more dynamic view of the functioning of these enzymes will have to be addressed by molecular dynamics studies based on more developed informatic systems when available. In the astrobiological field, the rising of this enzymatic activity, and the ions that could have been used by the first ATPases, in the *origin of life*, are still controversial, and thus research in this field would be of great interest.

Cross-References

- ATP Synthase
- Bioenergetics
- Electrochemical Potential
- Membrane
- Proton Motive Force

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AU

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Astronomical unit](#)

Definition

AU stands for astronomical unit. It is the average Earth-Sun distance, corresponding to 149.6×10^6 km (or approximately 8 light-min or 100 Sun diameters). This is one of the basic units of astronomy. Other distance units (pc, kpc, etc.) are derived from it.

Cross-References

► [Parsec](#)

Australian Centre for Astrobiology

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Definition

Founded in 2001 at Macquarie University, the Australian Centre for Astrobiology (ACA) has been located at the University of New South Wales since 2008. It interacts closely with NASA, ESA, and other international space agencies and institutions. Research carried out through ACA is centered on planetary science, the origin and early evolution of life, and modern analogs of ancient life.

Cross-References

► [ESA](#)
► [NASA](#)

Austrian Space Agency, Austria

► [ASA, Austria](#)

Autocatalysis

Olga Taran¹ and Günter von Kiedrowski²
¹Chemistry and Chemical Biology, Harvard
University, Cambridge, MA, USA
²Lehrstuhl für Organische Chemie I, Ruhr-
Universität Bochum, Bochum, Germany

Keywords

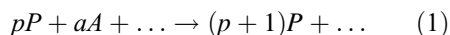
Catalysis · Origin of life theories · Self-replication

Definition

Autocatalysis is catalysis by one or more of the products of a reaction. Autocatalysis is often seen as the minimal requirement for the emergence of ► [life](#), as it is at the core of modern biogenetic theories based on genetic replicators, metabolic networks, and containment reproducers. Autocatalysis is one of the pathways for chiral symmetry breaking and is also responsible for the formation of patterns and ordered periodic behavior in chemical reactions. While autocatalytic phenomena have been observed in fields as diverse as cell biology and nonlinear physics, their general study is the subject of the emergent field of “Systems Chemistry.”

Overview

Autocatalytic reactions are described by the equation:

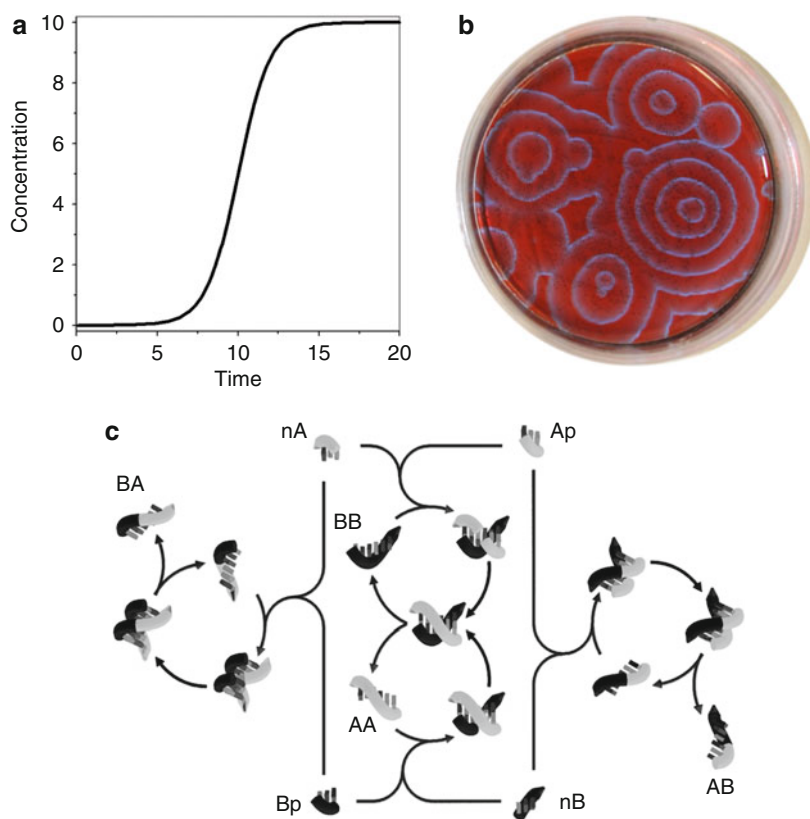


where a and p are reaction orders, P is the autocatalyst, and A is a precursor molecule. The autocatalytic reaction order p determines the “explosivity” of the product growth, which increases from parabolic ($p = \frac{1}{2}$) to exponential ($p = 1$) and hyperbolic ($p = 2$). Each type of growth has distinct evolutionary consequences. Competition between two or more autocatalysts – for a common resource constituent A – leads to coexistence (“survival of everybody”) for

parabolic, selection (“survival of the fittest”) for exponential, and fixation (“survival of the least common”) for hyperbolic growth.

Typically, the concentration-time curve of formation of an autocatalyst has a sigmoidal form (see Fig. 1), which is the result of a self-accelerating growth phase followed by deceleration due to the consumption of precursors.

Coupling of autocatalytic cycles with other reactions including autocatalytic ones can lead to oscillating behavior and spatiotemporal pattern



Autocatalysis, Fig. 1 (a) Typical sigmoidal concentration-time curve observed in many autocatalytic reactions. Initially, the reaction rate is slow, while the catalyst concentration is low. The reaction rate increases as more products are formed and then slows down when the reagents are consumed or inhibition by template takes place. The character of the growth phase can be parabolic, exponential, or hyperbolic, according to the reaction mechanism involved in the process. (b) Periodic concentration

oscillations of ferroin (Fe (II)) and ferritin (Fe (III)) complexes in Belousov-Zhabotinsky reaction. Reaction with limited diffusion creates spatial patterns as observed in this photo. (c) Scheme of a simple four-component cross-catalytic network. Precursors A and B can form two autocatalysts AB and BA or a group of cross-catalysts AA and BB . The scheme represents the reaction mechanism reported by Sievers and von Kiedrowski (1994)

formation. One example is the well-known Belousov-Zhabotinsky reaction.

Autocatalysis can be found in both catabolic reactions (e.g., hydrolysis of simple esters) and anabolic reactions (e.g., template replicators). Feedback may result from simple autocatalysis by one product, cross-catalysis between two products, or an “autocatalytic set” of molecules forming a network of mutually catalytic interactions.

Many genetic theories of the origin of life (e.g., the ► “RNA world” model) demand self-replication of nucleic acids in the absence of enzymes. Self-replication means autocatalysis plus information transfer. The latter is usually based on a templating principle according to which the product transfers its blueprint as constitutional information. It has been demonstrated using nucleic acids, peptides, and small organic molecules as templates.

Metabolic theories call for cycles that generate larger molecules from small building blocks in an anabolic direction, whereas the autocatalysis itself results from a catabolic split to yield medium-sized intermediates (as in the ► “Formose reaction”).

Autopoietic theories require self-reproduction of a container as well as the included components. Experimental examples have been found in reactions where lipid molecules forming micelles or vesicles are generated from non-lipid precursors via phase-transfer autocatalysis.

Several modern theories for the origin of (bio) molecular homochirality are supported by examples of enantioselective autocatalysis and chiral symmetry breaking.

Current research challenges in the field of Systems Chemistry are programmed design of autocatalytic systems and their integration into dynamic supersystems.

Cross-References

- Evolution, Molecular
- Formose Reaction
- Hypercycle
- Life
- RNA World

- Self-Replication
- Template-Directed Polymerization

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Automaton, Chemical

André Brack
Centre de Biophysique Moléculaire CNRS,
Orléans Cedex 2, France

Keywords

Algorithmic chemistry · Autopoiesis ·
Chemical reaction network · Chemoton ·
Minimal metabolism

Synonyms

Self-replication

Definition

There is a remarkable gap between complex chemical systems that generate self-organizing

patterns (e.g., oscillations in Belousov-Zhabotinsky types of reactions) and the chemical self-construction that any living being achieves through its metabolism. Chemical self-organization mechanisms operate at many different levels in biological systems, but the network of continuous transformation processes underlying the constitution of an organism is something clearly distinct. The idea of a **chemical automaton** addresses precisely this issue, trying to determine what an autocatalytic reaction network requires to become an autonomous, self-producing system. So far we lack experimental evidence of chemical automata that are not living metabolic systems, but synthetic biology and current projects to fabricate artificial cells may soon provide interesting insights to this problem, which has been extensively explored theoretically in the past.

Cross-References

- [Autocatalysis](#)
- [Chemical Reaction Network](#)
- [Self-Assembly](#)
- [Self-Replication](#)

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Autopoiesis

Alvaro Moreno¹ and Kepa Ruiz-Mirazo²

¹Departamento de Lógica y Filosofía de la Ciencia, Universidad del País Vasco, San Sebastián, Spain

²Department of Logic and Philosophy of Science, FICE, UPV-EHU, Biophysics Research Unit (CSIC – UPV/EHU), San Sebastián, Spain

Synonyms

[Metabolic organization](#); [Minimal autonomy](#); [Self-producing network](#)

Definition

Autopoiesis is a recurrent set of component production processes that creates a physical/topological boundary, within which that set of processes is continuously realized.

History

The term was originally proposed by H. Maturana and F. Varela in the early 1970s (from Greek: *auto*, “self,” and *poiesis*, “production”) and proposed as an abstract definition of ► [life](#). According to these authors, an autopoietic system is “organized as a network of processes of production (transformation and destruction) of components which: (1) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produce them; and (2) constitute it (the machine) as a concrete unity in the space in which they (the components) exist, by specifying the topological domain of its realization as such a network.”

Cross-References

- ▶ [Automaton, Chemical](#)
- ▶ [Cell, Minimal](#)
- ▶ [Life](#)
- ▶ [Metabolism](#)

Autotroph

Elena González-Toril
Laboratorio de Extremófilos, Centro de
Astrobiología (INTA-CSIC), Madrid, Spain

Synonyms

[Primary producer](#)

Definition

Autotroph is an organism capable of biosynthesizing all cell material from carbon dioxide as the only carbon source. With respect to energy, autotrophs can obtain it from two sources: (1) photoautotrophs from radiation (sunlight) and (2) chemolithoautotrophs from the oxidation of reduced inorganic substrates. Autotrophs are capable of growth exclusively at the expense of inorganic nutrients, and they are of vital importance in the cycling of inorganic compounds on Earth including methanogens, which produce methane from H_2 and CO_2 , and nitrifiers, which convert ammonia to nitrate. Autotrophs are the source of reduced carbon substrates for the heterotrophs. Autotrophs are key elements of the ▶ [carbon cycle](#). For this reason, autotrophic organisms are also called primary producers.

Cross-References

- ▶ [Autotrophy](#)
- ▶ [Calvin-Benson Cycle](#)

- ▶ [Carbon Cycle, Biological](#)
- ▶ [Carbon Dioxide](#)
- ▶ [Carbon Source](#)
- ▶ [Chemolithoautotroph](#)
- ▶ [Photoautotroph](#)

Autotrophic Denitrification

- ▶ [Nitrate Reduction](#)

Autotrophy

Elena González-Toril¹ and Juli Peretó²
¹Centro de Astrobiología (INTA-CSIC),
Madrid, Spain
²Institute for Integrative Systems Biology
I²SysBio, Universitat de València-CSIC,
València, Spain

Keywords

Calvin-Benson cycle · Carboxysomes ·
Chemolithoautotrophy · CO_2 fixation ·
Photoautotrophy · Rubisco

Synonyms

[Primary production](#)

Definition

Autotrophy is a lifestyle in which inorganic compounds provide for all nutritional needs of an organism. Implicit in this definition is the capacity of an organism to derive all cell carbon from carbon dioxide. Energy can be derived from two sources: (1) Photoautotrophs are photosynthetic and obtain energy from sunlight. (2) Chemolithoautotrophs obtain energy by the oxidation of inorganic substances. Table 1 shows a general classification of organisms on the basis of carbon and energy sources.

Autotrophy, Table 1 Classification of metabolisms according to energy, reducing power, and carbon sources

Metabolism	Energy source	Reducing power	Carbon source
Chemo-litho-autotrophic	Oxidation of inorganic compounds	Inorganic compounds	CO ₂
Photo-litho-autotrophic	Visible light	Inorganic compounds	CO ₂
Photo-organo-heterotrophic	Visible light	Organic compounds	Organic compounds
Chemo-organo-heterotrophic	Oxidation of organic compounds	Organic compounds	Organic compounds

Overview

Autotrophs are capable of growth exclusively at the expense of inorganic nutrients, and they are vital in the cycling of inorganic compounds (Alberts et al. 1994; Campbell and Reece 2002). Such autotrophs not only completely satisfy their own needs for reduced carbon monomers from inorganic matter but could also feed the already existing heterotrophs. Thus, autotrophic organisms are also called primary producers. Carbon dioxide that is fixed into organic compounds as a result of autotrophic activity is available for consumption or respiration by animals or heterotrophic microorganism. The end products of respiration in heterotrophic organisms are water and carbon dioxide, and this way the carbon cycle is completed (Alberts et al. 1994; Campbell and Reece 2002). Now it is accepted that autotrophy is an extremely important process on Earth and autotrophic microorganisms, as primary producers, support the growth of non-autotrophic organisms (Maier et al. 2000).

Photoautotrophs

A large number of microorganisms, as well as the green plants, algae, and protists, are phototrophic. They use light as an energy source in the process called photosynthesis. The result of this mechanism is the generation of a proton motive force that can be used in the synthesis of ATP and the synthesis of reducing power (e.g., NADPH). Most phototrophs use energy conserved in ATP and electrons in NADPH for the assimilation of carbon dioxide as the carbon source for biosynthesis. These phototrophs are called photoautotrophs. There are also phototrophs able to use organic compounds as carbon sources with light as energy source; they are

called photoheterotrophs (Table 1) (Campbell and Reece 2002; Maier et al. 2000; Madigan et al. 2003).

Chemolithoautotrophs

In the 1880s, Sergei Winogradsky (1856–1953) proposed the concept of chemolithotrophy, the oxidation of inorganic compounds as a source of energy and electrons for autotrophic growth. Studying sulfur bacteria (*Beggiatoa* and *Thiothrix*), he concluded that these organisms obtained their carbon from CO₂ in air, and they were called autotrophs. The discovery of autotrophy in chemolithotrophic bacteria was of major significance in the advance of our understanding of cells physiology because it showed that CO₂ could be converted to organic carbon without photosynthesis. Chemolithotrophy is shown by members of both the Bacteria and Archaea domains. Chemolithoautotrophs are important in the cycling of inorganic compounds in Earth, including methanogens, which produce methane, and nitrifiers, which convert ammonia to nitrate (Madigan et al. 2003; Ehrlich 2002).

Key Research Findings

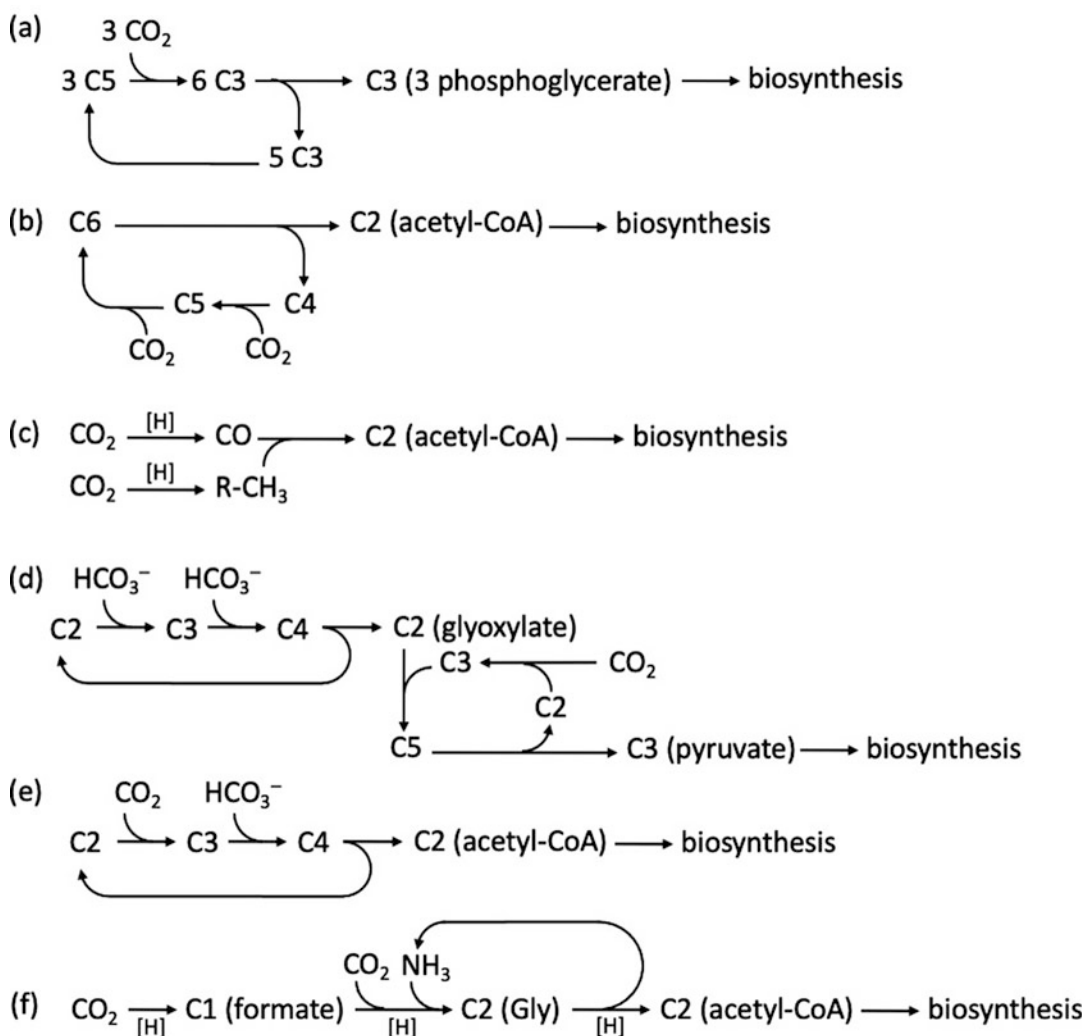
Autotrophic Pathways

Eight biochemical mechanisms are known for the autotrophic fixation of CO₂ into cell material. The pathways differ in the participating enzymes, ATP, and reducing power requirements and carbon isotope fractionation (Maier et al. 2000; Madigan et al. 2003; Berg et al. 2010).

1. The Calvin-Benson cycle, discovered in the 1950s in Melvin Calvin's lab, starts with the

condensation of a 5-C sugar (ribulose 1,5-bisphosphate) with CO_2 to yield two molecules of 3-C (3-phosphoglycerate) (Fig. 1a). From these molecules, both the initial 5-C sugar is regenerated and organic materials are biosynthesized. The cycle is operative in plastids of plants, algae, and protists, as well as in cyanobacteria, some aerobic or facultative anaerobic proteobacteria, CO-oxidizing mycobacteria, some iron- and sulfur-oxidizing

firmicutes, and green sulfur bacteria. The ability to fix carbon by this pathway is conferred by the activity of two enzymes (together with fragments of central metabolism like gluconeogenesis and the pentose phosphate pathway): ribulose 1,5-bisphosphate carboxylase-oxygenase (► [Rubisco](#)) and phosphoribulokinase (Campbell and Reece 2002; Maier et al. 2000; Madigan et al. 2003). Although Rubisco activity has been

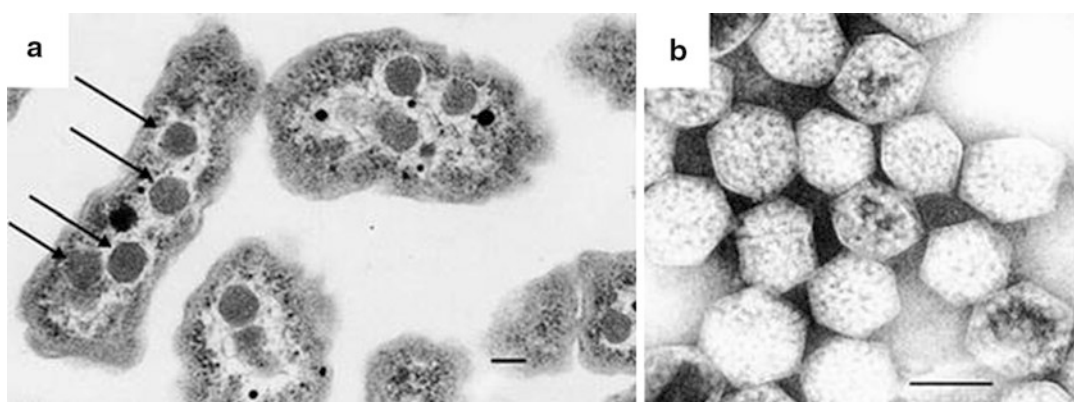


Autotrophy, Fig. 1 The diversity of autotrophic pathways. A scheme of stoichiometric relationships in (a) the Calvin-Benson cycle, (b) the Arnon cycle, (c) the Wood-Ljungdahl pathway, (d) the hydroxypropionate bicycle, (e)

the hydroxypropionate/dicarboxylate-hydroxybutyrate cycles, and (f) the reductive glycine pathway. In each case, the identity of the net product of C fixation, the starting point of biosynthesis, is indicated

detected in some Archaea, it has not been possible to demonstrate Calvin-Benson-dependent autotrophic growth (Berg et al. 2010).

2. Several autotrophic prokaryotes that use the Calvin-Benson cycle for CO₂ fixation produce polyhedral cell inclusions called carboxysomes. Carboxysomes are made of polyhedral protein shells about 80–120 nm in diameter (Fig. 2). These compartments are surrounded by a thin membrane and consist of a tightly packed crystalline array of molecules of Rubisco (Tsai et al. 2007). Thus, the carboxysomes would be a mechanism to increase the amount of Rubisco in the cell to allow for higher rates of CO₂ fixation. Carboxysomes have been found in obligately chemolithotrophic sulfur-oxidizing bacteria, nitrifying bacteria, cyanobacteria, and prochlorophytes. They are not present in facultative autotrophs like purple anoxygenic phototrophs, despite the fact that when these organisms grow as photoautotrophs, they use the Calvin-Benson cycle to fix CO₂. Thus, the carboxysome may be an evolutionary adaptation to life under strictly autotrophic conditions (Madigan et al. 2003).
3. In the green sulfur bacterium *Chlorobium*, CO₂ fixation occurs by a reversal (or reductive) citric acid cycle, also known as the Arnon cycle (Madigan et al. 2003; Evans et al. 1966). This is the analogue of a Krebs cycle operating in reverse mode (Fig. 1b). Since the Arnon cycle involves some enzymes (e.g., the carboxylating and reducing steps) that are inhibited by oxygen, this pathway is only found in microorganisms growing under anaerobic conditions. These include some proteobacteria, green sulfur bacteria, and microaerophilic bacteria like *Aquifex* (Maier et al. 2000; Madigan et al. 2003).
4. In some Gram-positive bacteria and methanogenic archaea, the ability to synthesize acetyl-CoA from CO and/or CO₂, the Wood-Ljungdahl pathway, was identified (Madigan et al. 2003; Ljungdahl et al. 1965). One CO₂ molecule is reduced to CO and another one to a methyl group (attached to a cofactor). Then, acetyl-CoA is synthesized from CO and the methyl group (Fig. 1c). The key enzymes of this pathway are inhibited by oxygen; thus it is restricted to obligate anaerobic microorganisms. These include some proteobacteria, planctomycetes, spirochaetes, and archaea (Maier et al. 2000; Madigan et al. 2003; Berg et al. 2010).
5. The 3-hydroxypropionate bicycle is present in some green non-sulfur phototrophic bacteria like *Chloroflexus* (Herter et al. 2002). A succinyl-CoA molecule is synthesized from acetyl-CoA and two bicarbonate molecules (Fig. 1d). Although the same intermediates as



Autotrophy, Fig. 2 (a) A thin-section electron micrograph of *Halothiobacillus neapolitanus* cells with carboxysomes inside. In one of the cells shown, arrows highlight the visible carboxysomes. (b) A negatively stained image of intact carboxysomes isolated from

H. neapolitanus. The features visualized arise from the distribution of stain around proteins forming the shell as well as around the Rubisco molecules that fill the carboxysome interior. Scale bars indicate 100 nm (Figure from Tsai et al. (2007))

the hydroxypropionate-hydroxybutyrate cycle (see below) are used, most of the participating enzymes are different. The final product of the cycle is glyoxylate. Its assimilation requires a second metabolic cycle. This pathway is restricted to the family *Chloroflexaceae* and might represent an early attempt of autotrophy in anoxygenic phototrophs (Maier et al. 2000; Madigan et al. 2003).

6. The hydroxypropionate-hydroxybutyrate cycle occurs in some aerobic archaea, like *Sulfolobus*. Albeit this pathway is formally the same as the 3-hydroxypropionate bicycle, the non-homologous participating enzymes indicate that both pathways evolved independently in a remarkable case of evolutionary convergence in metabolism (Berg et al. 2010) (Fig. 1e).
7. The dicarboxylate-hydroxybutyrate cycle occurs in some anaerobic archaea like the Thermoproteales and Desulfurococcales. The pathway can be divided into two parts (Fig. 1e): (1) one acetyl-CoA, one CO₂, and one bicarbonate are converted into succinyl-CoA; (2) this C4 molecule is transformed into two molecules of acetyl-CoA (one serves as biosynthetic precursor, the other as acceptor of the cycle) (Berg et al. 2010).
8. The reductive glycine pathway (rGly) was predicted by the late Arren Bar-Even and collaborators, and demonstrated in the autotrophically grown sulfate-reducing bacterium *Desulfovibrio desulfuricans* (Sánchez-Andrea et al. 2020). As shown in Fig. 1f, in the first step, CO₂ is reduced to formate, which is reduced and condensed with a second CO₂ and ammonia to generate the amino acid glycine. Finally, glycine is further reduced to produce acetyl-CoA. Since the immediate precursor of acetyl-CoA is acetyl phosphate, ATP may be produced. The rGly is considered one of the most energy-efficient autotrophic pathways. Although its real impact on the global carbon cycle is as yet unknown, preliminary phylogenomic analyses indicate that it may have a wide distribution in bacteria.
9. In 2018, the reverse operation of a conventional oxidative TCA cycle was independently described in two strictly anaerobic

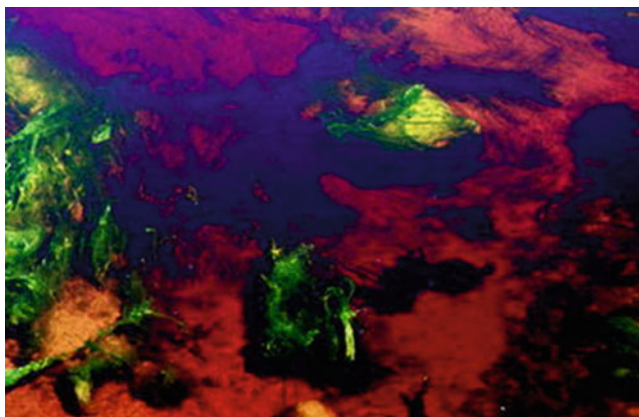
chemolithotrophs: the *Thermosulfidibacter takaii* (Nunoura et al. 2018) and *Desulfurella acetivorans* (Mall et al. 2018). Although the stoichiometric balance is represented by Fig. 1b, this is not an analogous reverse TCA cycle, as the Arnon cycle, but the thermodynamic reversion of a TCA cycle using the same enzyme repertoire as in the oxidative mode. Although the ancestral character of this metabolic mode, as suggested by Nunoura et al. (2018), is doubtful, it really represents a challenge for metabolic prediction solely based on bioinformatic analyses of environmental metagenomes, as pointed out by Mall et al. (2018). This is because the same genotype (the Krebs cycle enzyme repertoire) gives support to both phenotypes, heterotrophic (oxidative mode) and autotrophic (reductive mode), depending on the environmental conditions (for instance, CO₂ concentration, as shown by Steffens et al. 2021).

Applications

Ecology

Autotrophs are present in all ecosystems. They take energy from the environment in the form of sunlight or inorganic chemicals and use it to create energy-rich molecules such as carbohydrates. Thus, they meet their requirements easily and can be constitutive around the world. Moreover, autotrophic organisms are primary producers and, as a consequence, they are at the pyramidal base of the ecosystems. Thus, heterotrophs depend on autotrophs for the energy and raw materials they need (Maier et al. 2000). On the other hand, autotrophs, as a consequence of their poor requirements, have greater adaptability; thus, they are especially important in oligotrophic environments, like oligotrophic lakes, glaciers and ice, acid waters, geothermal systems, etc.

Rio Tinto (Huelva, Southwestern Spain) is an example of an environment dominated by autotrophic bacteria. This ecosystem is of great interest to astrobiology (Fig. 3). It is an extreme environment with a rather constant acidic pH along the entire river and a high concentration of heavy metals. The extreme conditions of the Tinto



A

Autotrophy, Fig. 3 Rio Tinto is an example of an ecosystem dominated by autotrophic microorganisms. The Iberian Pyritic Belt (IPB) is a 250-km long geological entity located in the southern Portuguese geotectonic zone of the Iberian Peninsula. Massive bodies of iron and copper sulfides constitute the main mineral ores. When part of the IPB was exposed to the atmosphere, autotrophic iron-oxidizing bacteria, giving rise to a river of extremely acidic water with an intense red color due to the resulting

ferric. This extreme site presents a high microbial diversity, especially of photosynthetic eukaryotes (mainly algae). The central role of chemolithoautotrophic organisms and the high photosynthetic biomass make Rio Tinto an excellent model for the study of autotrophy. The spectacular contrast between the green of the algae and the intense red of the water can be observed at numerous places of the river

ecosystem are generated by the metabolic activity of chemolithotrophic microorganisms thriving in the rich complex sulfides of the Iberian Pyrite Belt. In this system, more than 70% of the cells are affiliated to autotrophic bacteria (iron-oxidizing bacteria), with only a minor fraction corresponding to heterotrophic. The special interest shows also autotrophic microalgae, present in the river, primary producer, together with iron-oxidizing bacteria, of the system (González-Toril et al. 2003).

Autotrophy and Early Evolution of Life

The autotrophic metabolism has emerged independently several times during evolution, that is, it is a polyphyletic trait (Berg et al. 2010; Pereto et al. 1999). The Calvin-Benson cycle seems idiosyncratic to bacteria, whereas the Arnon cycle and the Wood-Ljungdahl pathway show a wider phylogenetic distribution. The different versions of the hydroxypropionate pathway likely emerged independently (Berg et al. 2010). At this moment, phylogenetic analysis of the participating enzymes does not allow us to infer which one is the older pathway.

Mainstream hypothesis on the [origin of life](#) postulates that the first prokaryotes were anaerobic heterotrophs, for example, fermenters. In the beginning, they may have fed on externally available abiotic organic molecules, either synthesized on Earth or delivered by extraterrestrial bodies. It is generally supposed that autotrophic metabolism emerged later.

Whether the first autotrophs were chemosynthetic or photosynthetic is a matter of debate. One school of thought favors chemosynthetic autotrophs in the form of methanogens, which formed methane. Microorganisms (methanogenic archaea) with such metabolism exist today, and they are strict anaerobes. The other school of thought favors photosynthetic prokaryotes in the bacterial domain as the first autotrophs. This notion is supported by the existence of the Warrawoona stromatolites, which are around 3.5 billion years old. Those microfossils have been interpreted, on the basis of comparison with modern counterparts, to have been formed by cyanobacteria. However, modern cyanobacteria are aerobes. Because the primordial atmosphere at this

time is thought to have been almost free of oxygen, the emergence of anaerobic photosynthetic bacteria, of which modern purple and green bacteria must be a counterpart, must have preceded that of cyanobacteria (Campbell and Reece 2002).

On the other hand, in 1988, Wächtershäuser proposed the surface metabolism theory for the origin of life (Wächtershäuser 1988). According to it, life arose as a form of autocatalytic two-dimensional chemolithotrophic metabolism on a pyrite surface, using the energy and electrons of the anaerobic synthesis of FeS₂ (pyrite) from FeS and H₂S. According to this proposal, the ancestral carbon fixation pathway would be a primitive version of the Arnon cycle (Wächtershäuser 1990). The Wood-Ljungdahl pathway has also been proposed as a candidate of the older autotrophic mechanism (Pereto et al. 1999; Russell and Martin 2004). The lack of experimental evidences is the weaker aspect of the autotrophic hypothesis on the origin of life.

Future Directions

Engineering Autotrophy

With the aim to moderate carbon emissions and the building of a more sustainable circular economy, research on the enzyme mechanisms of CO₂ fixation and the development of new-to-nature carboxylases and synthetic autotrophic pathways has been stimulated. For instance, a fully artificial carbon fixation cycle was obtained by combining enzymes from nine different organisms of all three domains of life using enzyme and metabolic engineering tools (Schwander et al. 2016). On the other hand, by metabolic engineering and directed evolution, it was possible to convert a heterotrophic organism like *Escherichia coli* in a full-fledged autotrophic system able to build all the biomass with CO₂ as a sole carbon source (Gleizer et al. 2019). Finally, the endogenous, hidden capacity of heterotrophic metabolic networks to operate in autotrophic mode has also been discovered (Satanowski et al. 2020). All these pioneering works explore a diversity of natural and artificial

carbon fixation pathways with potential applications in biocatalysis, biotechnology, and artificial photosynthesis (Bernhardsgrütter et al. 2021).

Cross-References

- [Calvin-Benson Cycle](#)
- [Chemolithoautotroph](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Origin of Life](#)
- [Photoautotroph](#)
- [Rubisco](#)

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Autumnal Point

- [Equinox](#)

Available Water

- [Water Activity](#)

Axial Tilt

- [Obliquity and Obliquity Variations](#)

Azane

- [Ammonia](#)

Azulmin

- [HCN Polymer](#)

B

Background

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A background is a diffuse radiation field originating from no specific location in the sky. When observing a given field, it is that part of the signal which is not due to the objects of interest and comes from extended or unresolved sources behind them. At millimeter wavelengths, the microwave background, the fossil emission from the Big Bang, is present in any direction of the sky. By extension, the molecular glow or the thermal infrared emission from the atmosphere as well as from the telescope that is superimposed on the astronomical signal is also called background.

Bacteria

Francisco Rodriguez-Valera
Microbiologia, Universidad Miguel Hernandez,
San Juan, Alicante, Spain

Keywords

Cell · Domain · Phylogeny · Prokaryote · Tree of life

Definition

Bacteria are a large group of single-celled phylogenetically related prokaryotes distinct from ► [Archaea](#). Bacteria have a wide range of shapes, ranging from spheres to rods and spirals. They are ubiquitous, growing in soil, water, extreme environments, and deep in the Earth's crust (Vreeland et al. [2000](#); Wanger et al. [2008](#)). There are typically 40 million bacterial cells in a gram of soil and a million bacterial cells in a milliliter of fresh water. There are approximately 5×10^{30} bacteria on Earth, forming much of the world's biomass (Whitman et al. [1998](#)). Bacteria are vital in recycling nutrients and important elements of the geobiological cycles. Most have not been characterized, and only about half of the phyla of bacteria have species that can be grown in the laboratory.

Once regarded as plants constituting the class Schizomycetes, bacteria are now classified as prokaryotes. Unlike the cells of animals and other eukaryotes, bacterial cells do not contain a nucleus and rarely harbor membrane-bound organelles. Although the term bacteria traditionally included all prokaryotes, the scientific classification changed after the discovery in the 1970s that prokaryotes consist of two very different groups of organisms (domains) that evolved independently from an ancient ► [common ancestor](#). These evolutionary domains are called bacteria and ► [Archaea](#).

History

Bacteria were first observed by Antonie van Leeuwenhoek in the seventeenth century, using a single-lens microscope of his own design (Porter 1976). He called them “animalcules” and published his observations in a series of letters to the Royal Society (van Leeuwenhoek 1684). The name bacterium was introduced much later, by Christian Gottfried Ehrenberg in 1838.

Louis Pasteur demonstrated in the mid-eighteenth century that ► [fermentation](#) is caused by the growth of microorganisms and that this growth is not due to spontaneous generation. Along with his contemporary, Robert Koch, Pasteur was an early advocate of the germ theory of disease. In his research into tuberculosis, Koch finally proved the germ theory, for which he was awarded a Nobel Prize in 1905. In Koch’s postulates, he set out criteria to test if an organism is the cause of a disease, and these postulates are still used today. A major step in the study of bacteria was the development, in the middle of the last century, of molecular biology techniques with which much was learned about their biochemistry and genetics. In 1977, Carl Woese (Woese and Fox 1977) made an important breakthrough in our knowledge of evolution, when, in comparing the sequences of 16 S ribosomal RNA genes, he observed that a group of prokaryotic organisms, Archaea, have a separate line of evolutionary descent from that of bacteria (Woese et al. 1990).

Overview

Bacteria is one of the two types of prokaryotic organisms, the other is Archaea. Eukaryotic cells actually represent a consortium of cells including a host or nucleus cytoplasm and the endosymbiotic organules: mitochondria and chloroplast, both of bacterial origin (Dyall et al. 2004). The separation between bacteria and Archaea is largely derived from molecular biology studies, mostly on ► [ribosome](#) structure and components (proteins and ribosomal RNA) and ► [transcription](#) machinery (RNA polymerase). Bacteria indeed have representatives carrying out most

known metabolic pathways and driving the functioning of most ecosystems. The only known metabolic strategy that is not found in bacteria is the archaeal methanogenesis (DeLong and Pace 2001). Bacteria can actually close all biogeochemical cycles on their own, so that a uniquely bacterial biosphere can be envisioned. This is not true of either eukaryotes or Archaea (at least with the admittedly limited knowledge that we have about this group).

The classification of bacteria has undergone frequent changes in the last few years and is subject to continuous controversy as is their relationship with the other major cellular types. The widely accepted classification scheme is based on the 16S rRNA sequence comparisons. The most recent classification schemes describe the following groups of Bacteria: ► [Proteobacteria](#) (*Alpha*-, *Beta*-, *Gamma*-, *Delta*-, *Epsilonproteobacteria*), *Acidobacteria*, *Aquificae*, *Chlorobi*, *Bacteroidetes*, *Chlamydiae/Verrucomicrobia*, *Planctomycetes*, *Spirochaetes*, *Actinobacteria*, *Chloroflexi*, *Cyanobacteria*, *Firmicutes*, *Tenericutes*, *Fusobacteria*, *Synergistetes*, *Thermotogae*, and *Deinococcus/Thermus*.

Some of these groups are extremely diverse in metabolism, while others are very restricted. However, the availability of cultivated species, properly studied for their physiology, is very uneven (Rappé and Giovannoni 2003). At least in some cases, this might influence our perception of their true diversity. Cellular organization and structure is also highly variable although most bacteria have a rigid cell wall consisting of one single group of tridimensional polymers, mureins, or peptidoglycans. Some bacteria, gram-negative bacteria, also have an extra membrane outside the rigid polymer that provides a second permeability barrier. The outer membranes of the gram-negative bacteria have a very characteristic structure with a long chain polysaccharide facing the extracellular environment and providing a hydrophilic envelope. Some groups of gram-positive bacteria also have an outer membrane, very different chemically and more interlinked to the underlying polymer. Sometimes these gram-positive bacteria outer membranes are also quite hydrophobic. Finally some bacteria have

glycoprotein S layers as rigid envelopes and some have no rigid envelope at all.

► **Motility** is common in bacteria and is achieved by a characteristic structure, the bacterial flagellum (Kojima and Blair 2004). This nanorotor is unique and different structurally and phylogenetically from its archaeal and eukaryotic counterparts. The archaeal flagellum is more similar to a different bacterial structure that is actually involved in some types of bacterial motility by gliding. In spirochetes, the flexing spiral body rotation is achieved by inward directed flagella that are coiled over the cell. Some bacteria have other types of motility such as gliding over surfaces. This capacity is particularly efficient in social bacteria that move in multicellular consortia. This is the case for myxobacteria (a group within the deltaproteobacteria).

Although no organelles have been described in bacteria, there are examples of fairly complex cellular structures, including the presence of nuclear membranes, previously considered unique to eukaryotes (Fuerst 2005). Other cellular organelle-like structures (Yeates et al. 2008) are magnetosomes, peroxisomes, gas vesicles, and storage granules. Cell division in bacteria is achieved by a cross-divisional cell wall septum, a constriction encompassing all the cell envelope layers. Although there is no mechanical cell machinery such as the mitotic apparatus of eukaryotes, bacteria have proteins homologous to actin that can produce mechanical modification of cell morphology (Shih and Rothfield 2006).

Cell shape and size varies widely in bacteria. However, most bacterial cells conform to relatively simple geometric shapes based in the cylinder (rod), sphere (coccus), or the spiral coil (spirillum) (Young 2006). Cells can vary in size from fractions of a micron to many hundreds of microns in giant bacteria such as *Thiomargarita* or *Epulopiscium* (Schulz and Jorgensen 2001). Bacterial size is limited by their osmotrophic feeding, that is, their need to transport all nutrients across the membrane. This is only efficient as long as a high surface/volume ratio is maintained.

Bacterial reproduction is asexual, by clonal duplication of the cell, and originates large populations of clonal descent. This has been used

for pure culture isolation and study since the origins of microbiology. However, bacteria have sex, often referred to as horizontal gene transfer or lateral gene transfer. The impact of this genetic exchange that has no part in reproduction is considered fundamental in the evolution of bacteria. The absence of meiotic processes and zygote formation leads to the possibility of genetic exchange among very different partners. In this way, the barriers to genetic recombination in bacteria are very leaky, if present at all. The impact of horizontal gene transfer in the evolution of the prokaryotic (bacterial and archaeal) world is still a matter of controversy, but some authors consider that a biologically consistent tree of life based on evolutionary relationships could simply be a human fabrication.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Anoxygenic Photosynthesis](#)
- [Bioenergetics](#)
- [Biofilm](#)
- [Carbon Cycle, Biological](#)
- [Chemolithotroph](#)
- [Chemoorganotroph](#)
- [Common Ancestor](#)
- [Fermentation](#)
- [Genotype](#)
- [Gram-Negative Bacteria](#)
- [Gram-Positive Bacteria](#)
- [Lateral Gene Transfer](#)
- [Metabolic Diversity](#)
- [Metabolism, Secondary](#)
- [Microorganism](#)
- [Motility](#)
- [Organelle](#)
- [Peroxisome](#)
- [Phenotype](#)
- [Photosynthesis](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Phylum](#)
- [Prokaryote](#)
- [Proteobacteria](#)
- [Quorum Sensing](#)

- [Respiration](#)
- [Ribosome](#)
- [Sequence Analysis](#)
- [Transcription](#)
- [Translation](#)

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Bacterial Microcompartments

- [Carboxysomes, Structure and Function](#)

Bacterial Spore

- [Endospore](#)

Bacteriochlorophyll

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

[Chlorophylls](#)

Definition

Bacteriochlorophylls are a family of magnesium-porphyrin pigments present in

anoxygenic photosynthetic bacteria and function both as light receptors and photochemical reaction centers.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [Photosynthesis](#)

Bacteriorhodopsin

Ricardo Amils
Departamento de Biología Molecular, Madrid,
Spain

Definition

Bacteriorhodopsin is a membrane protein that captures radiation energy which is used to create a proton gradient. It can be found mainly in Haloarchaea. Bacteriorhodopsin is a membrane protein usually found in two-dimensional crystalline patches known as purple membrane. The repeating element of the hexagonal lattice is composed of three identical protein chains, each rotated by 120° relative to the others. Each chain has seven transmembrane alpha helices and contains one molecule of retinal buried deep within. It is the retinal molecule that changes its conformation when absorbing a photon, resulting in a conformational change of the bacteriorhodopsin promoting the proton pumping action. It can be considered the simplest photosynthetic system known. All other phototrophic systems (bacteria, algae, chloroplasts) use chlorophylls instead of bacteriorhodopsin to generate proton gradients.

Baltic Shield

- [Fennoscandia](#)

Baly's Experiment

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

Definition

Regarding origin of life, Baly's experiment (1922) is one of the most emblematic organic chemistry experiments of the beginning of the twentieth century (Baly 1871–1948). It has demonstrated that ultraviolet light could act on a solution of water, carbon dioxide, and ammonia and produce a lot of organic compounds, such as sugars and amino acids.

J.B.S. Haldane quoted these experiments in his famous text in 1929; for him, this was a chemical proof of the possibility of a link between mineral and organic chemistry in the prebiotic soup.

Cross-References

- [Haldane's Conception of Origins of Life](#)

Band Scan

- [Molecular Line Survey](#)

Banded Iron Formation

A. M. Mloszewski, Rasmus Haugaard,
Ernesto Pecoits and Kurt O. Konhauser
Department of Earth and Atmospheric Sciences,
University of Alberta, Edmonton, AB, Canada

Keywords

Geobiology · Precambrian · Iron oxides · Chert

Synonyms

BIF; Itabirite; Taconite

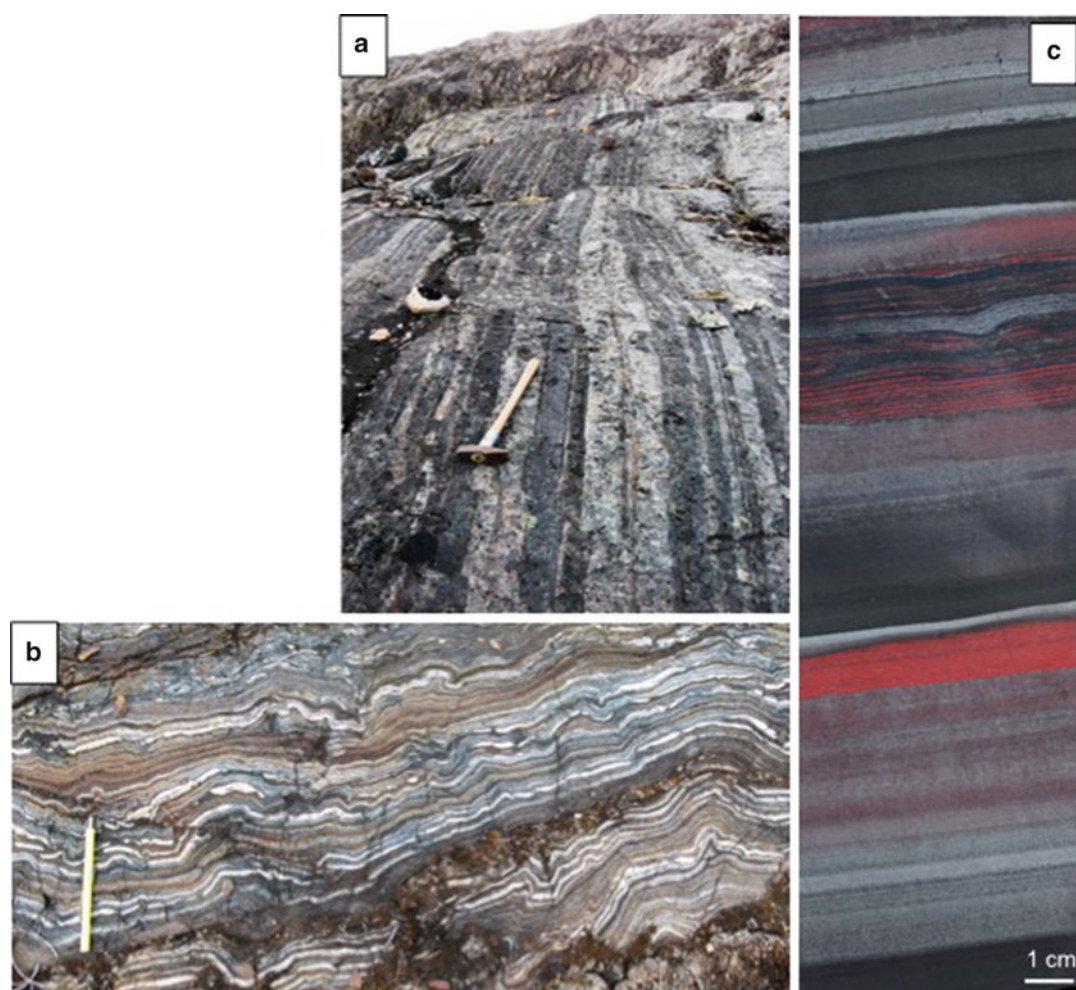
oxides, carbonates, and/or silicates, typically containing 20–40% iron and 40–50% silica (James 1954; Trendall 2002; Klein 2005) (Fig. 1).

Definition

A lithological term applied to a thinly bedded or laminated chemical sedimentary rock consisting of successive layers of fine-grained quartz, iron

Overview

Banded iron formations (BIFs) comprise the largest iron resource on Earth. They formed throughout much of the Precambrian (~3800–543 Ma),



Banded Iron Formation, Fig. 1 (a) Outcrop photograph of Algoma-type BIF with layers of magnetite BIF interbedded with felsic volcanoclastic rocks from the 2.9 Ga Itilliarsuk BIF, West Greenland (Haugaard et al. 2013); (b) outcrop photograph of weakly folded magnetite-quartz BIF from the ca. 2.85 Ga Central Slave Cover Group, Slave Craton, Northwest Territories, Canada (Haugaard et al. 2016a). *Brownish* bands are secondary

iron oxides and iron oxyhydroxides; and (c) a pristine BIF core sample from the Joffre Member, Brockman Iron Formation, Hamersley Province, West Australia. Black mesobands are composed mostly of dense magnetite, red micro- and mesobands are composed of chert + hematite, and gray micro- and mesobands are composed of chert + magnetite + Fe-rich carbonate (Haugaard et al. 2016b) (All photos courtesy of Rasmus Haugaard)

reaching their maximum abundance between 2700 and 2400 Ma ago. Numerous examples can be found on almost every continent. Their deposition has been linked to significant compositional changes in the Earth's atmosphere and hydrosphere and possibly even to the diversification of the biosphere.

BIF has been classified on the basis of mineralogy, tectonic setting, and depositional environment (Trendall 2002). The main iron mineral phases were used to define four "iron formation facies": oxide, silicate, carbonate, and sulfide. The dominant minerals, in their least metamorphosed state, are hematite [$\text{Fe}_2^{3+}\text{O}_3$] and magnetite [$\text{Fe}^{2+}\text{Fe}^{3+}\text{O}_4$] in the oxide facies, greenalite [$(\text{Fe}^{2+}\text{Mg})_6\text{Si}_4\text{O}_{10}(\text{OH})_8$] and minnesotaite [$(\text{Fe}^{2+}\text{Mg})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$] in the silicate facies, siderite [$\text{Fe}^{2+}(\text{CO}_3)_2$] and ankerite [$\text{CaFe}^{2+}(\text{CO}_3)_2$] in the carbonate facies, and pyrite [Fe^{2+}S_2] in the sulfide facies (Klein 2005). Today, sulfide-facies iron formations (i.e., pyritic carbonaceous shale or slate) are no longer classified as BIF as they represent rock types that were deposited in different environments and developed in sedimentary successions of different ages without systematic association with BIF.

In terms of their size and lithological associations, BIF are subdivided into Algoma and Superior types. Algoma-type BIFs are comparatively small, with lateral extents rarely exceeding 10 km, thicknesses ranging from 10 to 100 m, and primary iron contents typically less than 10^{10} t (e.g., Condie 1981). They are associated with volcanogenic complexes and are inferred to have formed close to volcanic centers such as hydrothermal vents, back-arc basins, and intracontinental rift zones. By comparison, Superior-type BIFs are hundreds of meters thick, have areal extents to the order of 10^5 km², and have total primary iron contents that exceed 10^{13} t. They are typically associated with sedimentary lithologies (dolomite, quartzites, and shales) and are inferred to have been deposited on the continental shelves and slopes of passive margins (Simonson 1985). Though the water depth of deposition is still poorly constrained, the absence of wave- and current-generated features suggests a minimum water depth of ~200 m (Trendall 2002).

Banding in BIF is observed on a wide range of scales, from coarse meter-thick macrobands and centimeter-thick mesobands to millimeter- and submillimeter-scale bands. Among the latter is a wide variety of varve-like repetitive laminae, known as microbands, which may represent annual deposits (Trendall and Blockley 1970). Some Proterozoic iron formations are also found to contain iron granules, oolites, and other fragments embedded in a silica matrix (e.g., in the Lake Superior Region and the Labrador Trough, Canada; Nabberu Basin, Australia; Klein 2005). This granular variety, called granular iron formation, possesses clear detrital textures and is thought to represent eroded and redeposited fragments of preexisting BIF (Trendall 2002).

A third type of BIF, the younger (750–560 Ma) Rapitan type, is a special case in that it is linked to global glaciations ("▶ snowball Earth" events). The isolation of the oceans from the atmosphere by worldwide glacial ice cover led to ocean stagnation and buildup of dissolved, hydrothermally sourced Fe^{2+} . As the ice melted and ocean circulation reestablished itself, the iron became oxidized and formed a suite of iron formations in the oxic zone of upwelling areas (Klein 2005).

Most Eo- and Mesoarchean BIFs belong to the Algoma-type and are associated with granite-greenstone belts (volcano-sedimentary sequences). They are found in the North Atlantic Craton (Northern Labrador, southwestern Greenland), Guiana Shield (Venezuela, Guyana), Kaapvaal Craton (South Africa and Swaziland), Liberian Shield (Sierra Leone, Guinea, Liberia, and Ivory Coast), and Yilgarn Craton (Western Australia). Neoarchean to Proterozoic BIFs are mostly of the Superior type and are found in the Pilbara Craton (Hamersley Group, Western Australia), Kalahari Craton (Transvaal Supergroup, South Africa), São Francisco Craton (Quadrilátero Ferrífero), and the Superior Province (Labrador Trough and Lake Superior Regions, Canada/USA) (Trendall 2002; Klein 2005). Major deposits of the Rapitan type include the Rapitan Group in northern Canada and those in the Urucum district of Brazil (Klein 2005).

Key Research Findings

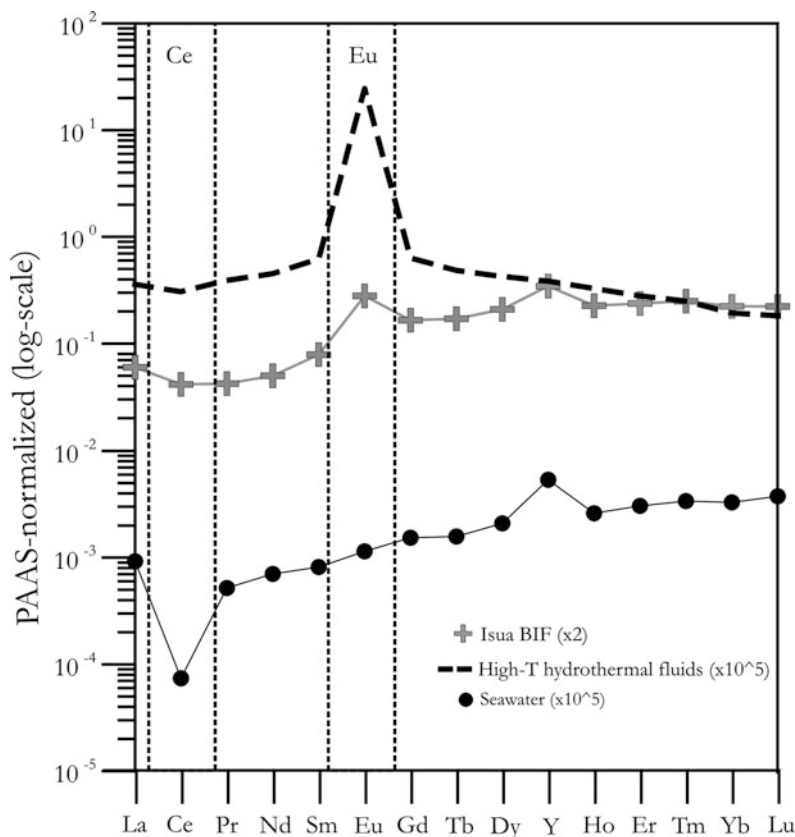
BIF Composition

Iron formations can retain the chemical signatures of the seawater from which they precipitated provided that postdepositional element mobility was minimal and may therefore be used as potential proxies for ancient seawater composition through time. Rare-earth element and yttrium (REE + Y) profiles are extensively used to determine the origin of iron formations. Two aspects of the deviation of BIF REE + Y profiles from that of modern seawater, the Eu and Ce anomalies of shale-normalized profiles, provide key information about their depositional environments (Fig. 2).

BIFs typically display positive Eu enrichments which are thought to reflect the relative influence of hydrothermal fluids on the seawater REE load at the time of deposition (Derry and Jacobsen 1990). The more pronounced Eu anomalies of

Algoma-type BIFs compared to their Superior-type counterparts suggest a higher hydrothermal component in the former due to a higher input of high-temperature hydrothermal fluids ($>250^{\circ}\text{C}$) to Archean seawater caused by a hotter mantle (Arndt 1991). The redox-sensitive element Ce is used as a proxy for the redox state of ancient seawater. Modern oxygenated seawater has a negative Ce anomaly due to oxidation of soluble Ce^{+3} to insoluble Ce^{+4} while the lack of Ce anomalies in Archean and early Paleoproterozoic BIF REE + Y profiles suggests that they were instead precipitated from anoxic seawater (e.g., Alexander et al. 2008 and references therein). Negligible fractionation of REE + Y during the initial precipitation of the precursor BIF iron oxyhydroxide minerals and their ability to withstand metamorphic conditions of up to amphibolite facies (Bau 1993) make these elements an invaluable tool for deciphering the evolution of ancient seawater conditions.

Banded Iron Formation, Fig. 2 Typical REE + Y distribution in BIF showing Eu and Ce anomalies as depicted by average values of BIF from the ca. 3700 Ga-old Isua Supracrustal Belt (southern West Greenland), compared to the average REE + Y signature of high-temperature hydrothermal fluids and average Pacific seawater (Graph modified after Alexander et al. (2008); see references therein)



To better understand the change in seawater chemistry through time and the effects of nutrient limitations on early life, recent studies derived ancient seawater composition by applying laboratory-derived partitioning coefficients between trace elements in seawater and iron oxyhydroxide particles to the absolute concentrations of these elements in BIF (P, Bjerrum and Canfield 2002; Ni, Konhauser et al. 2009; Zn, Robbins et al. 2013). Because the partitioning of P onto iron oxyhydroxides occurs in a predictable way, Bjerrum and Canfield (2002) used BIF to infer P concentrations in ancient seawater and its availability to ancient organisms. Konhauser et al. (2009) showed that Ni concentrations through time have changed drastically, with concentrations reaching up to 400 nM in the Archean (compared to an average 9 nM in modern seawater) due to an abundance of Ni-rich ultramafic rocks produced by a hotter mantle. Based on the Zn concentrations in BIF of various ages (an essential metal in the metabolism of eukaryotes), Robbins et al. (2013) suggested that Zn concentrations in seawater have remained constant through time, contrary to previously accepted ideas (e.g., Saito et al. 2003), forcing a reassessment of the influence of this metal on the timing of eukaryote evolution. Future studies of this kind on other bioessential trace metals will advance our understanding of the timing and evolution of ancient microbial metabolisms.

Yet another tool used to understand BIF genesis and the environmental conditions under which they precipitated is stable isotopes. The main traditional stable isotopes used in BIF studies are carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) while non-traditional isotopes include iron ($\delta^{56}\text{Fe}$), silicon ($\delta^{30}\text{Si}$), and most recently, chromium ($\delta^{53}\text{Cr}$), uranium ($\delta^{238}\text{U}$), and germanium ($\delta^{74}\text{Ge}$). Carbon isotopes are primarily used as a means of understanding the genesis of iron formations. Because the organic carbon fraction in BIF is so small (typically <0.5 wt.%; Gole and Klein 1981), carbon-isotope studies tend to focus instead on the carbonate mineral fraction. The $\delta^{13}\text{C}$ signature in BIF is typically light, ranging from +2.4‰ to −20.0‰ (Johnson et al. 2008). While one school of thought interprets this light signature as evidence

of the direct carbonate precipitation from an iron-rich, carbon-isotope-stratified water column with respect to dissolved inorganic carbon (e.g., Beukes and Klein 1990), petrographic evidence suggests that much of the carbonate mineral fraction in BIF is secondary, having grown during diagenesis (e.g., Ayres 1972). More widely accepted opinions involve microbially mediated precipitation of carbonate during burial diagenesis, including carbonate precipitation through microbially mediated remineralization of (naturally isotopically light) organic matter or due to the reduction of ferric iron and precipitation of carbonate minerals by means of the bacterial oxidation of methane (see Bekker et al. 2010; Konhauser et al. 2017 and references therein).

The oxygen isotope ($\delta^{18}\text{O}$) composition of cherts in BIF is often used as a paleotemperature proxy of the seawater from which they precipitated because the oxygen isotope fractionation between silica and seawater is thought to be temperature dependent. Knauth and Lowe (2003) interpreted the depleted $\delta^{18}\text{O}$ composition of synsedimentary to very early diagenetic cherts in >3.2 Ga-old BIF (Barberton greenstone belt, South Africa) as indicative of high ocean temperature values (55–85 °C). This evidence was later corroborated by $\delta^{18}\text{O}$ data from an extensive dataset of Archean to Phanerozoic cherts, proposing that sea surface temperatures decreased drastically from about 70 °C 3500 Ma ago to about 20 °C 800 Ma ago (Robert and Chaussidon 2006). However, caution must be exercised when deriving paleo-seawater temperatures in BIF whose origin is associated with syn-depositional hydrothermal alteration (e.g., BIF older than 3500 Ma), since the derived temperatures will instead reflect local mixing conditions of hydrothermal fluids with overlying seawater.

The study of iron isotopes ($\delta^{56}\text{Fe}$) in BIF has gained momentum in recent years (e.g., Dauphas et al. 2004; Johnson et al. 2008; Haugaard et al. 2016b). While the trace element distribution in BIF will be influenced by postdepositional processes such as recrystallization and metasomatism, the iron isotope system has been known to retain its premetamorphic signature despite such conditions (e.g., Dauphas et al. 2004). Iron isotope values in BIF span the entire natural range

(−2.5‰ to +1.0‰), in contrast to the near-constant $\delta^{56}\text{Fe}$ of igneous rocks (~0‰) and other sedimentary rock types. They reflect a combination of three main processes: (a) mineral-specific equilibrium fractionation, (b) variation in the composition of fluids from which they precipitated, and (c) the effects of bacterial Fe metabolic processing (Johnson et al. 2003). Therefore, there are two important applications of $\delta^{56}\text{Fe}$ in BIF: to provide information on the abiotic and biogenic controls on ancient redox processes in the early oceans and to determine the origins for heavily metamorphosed rocks.

The $\delta^{30}\text{Si}$ compositions of early diagenetic cherts in BIF are often used to decipher the genetic processes involved in their deposition and infer the ambient surface conditions on early Earth (e.g., Andre et al. 2006). Typical compositions which range from −2.5‰ to −0.5‰ reflect relative inputs by hydrothermal (negative $\delta^{30}\text{Si}$, e.g., Andre et al. 2006) and continental (positive $\delta^{30}\text{Si}$, e.g. van den Boorn et al. 2010) sources into the depositional basin. A predominantly hydrothermal silica source can manifest itself as correlations in band-scale variations of Fe and Si isotopes, reflecting the dynamics of the hydrothermal discharge (e.g., ca. 2700 Ma-old Wanderer BIF, Zimbabwe; Steinhöfel et al. 2009). However, some of the well-studied Superior-type BIFs whose silica precipitated from a well-mixed water column far away from hydrothermal vents and continental drainage (e.g., on an isolated continental shelf platform) show a uniform $\delta^{30}\text{Si}$ composition within a single locality (e.g., the ca. 2500 Ma-old Transvaal BIF, South Africa, and Hamersley, Western Australia).

Analytical advances in stable isotope geochemistry have only recently allowed for high-precision measurements of trace element isotopes such as Cr, U, and Ge in BIF. Chromium isotope ($\delta^{53}\text{Cr}$) compositions in BIF can be used to investigate the oxygenation of the ancient atmosphere, where oxidative weathering will oxidize Cr(III) on land to the more mobile Cr(VI) which becomes enriched in surface seawater (e.g., Frei et al. 2009). It has been recently found that $\delta^{238}\text{U}$ in BIF and other marine sediments fractionate differently under oxic and suboxic to euxinic

conditions, making it another novel geochemical tracer of the Earth's redox evolution (Weyer et al. 2008). Germanium in the oceans has a short residence time (about 10,000 years). As Ge/Si ratios in seawater appear to vary in response to climate, the $\delta^{74}\text{Ge}$ composition of BIF and other marine sediments may offer new insight into the Earth's climate history (Rouxel et al. 2006).

Controls on BIF Deposition

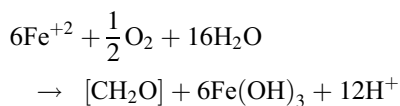
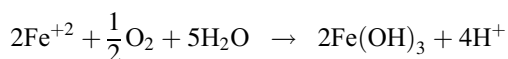
Because the Fe contents of larger BIF are upward of 10^{13} ton, the potential Fe source must be capable of supplying these vast quantities. A widely accepted idea stems from classical BIF studies by Cloud (1973) and Holland (1973) which established that the major components (Fe and Si) in these rocks were derived from seawater. Additionally, certain aspects of the typical REE content in BIF led to the conclusion that these components were initially hydrothermally sourced and later mixed with overlying seawater (e.g., Graf 1978). The characteristic positive Eu anomalies found in BIF, a trait shared by modern hydrothermal vent fluids, are thought to indicate a strong influence of hydrothermal fluids on the BIF REE load and, by extension, Fe (Derry and Jacobsen 1990). This contrasting behavior of Eu to neighboring REE is thought to be related to the reduction of Eu^{3+} in hydrothermal solutions characterized by high temperatures (>250 °C) and low oxidation-reduction potentials. The generally positive, mantle-like ϵNd values in BIF (where the ϵNd notation defines the departure of $^{143}\text{Nd}/^{144}\text{Nd}$ from the Chondritic Uniform Reservoir evolution line), which contrast with the negative ϵNd values of seawater, support the idea that a large part of the Fe in BIF had been sourced from ancient submarine hydrothermal systems (Jacobsen and Pimentel-Klose 1988).

Our knowledge of the other major component in BIF, silica, begins with the understanding that Precambrian seawater was likely close to supersaturation with respect to amorphous silica until the evolution of organisms which incorporate silica in their skeletons, such as diatoms and radiolarians. The main sources of Si to the oceans are hydrothermal fluids and continental runoff, which have compositionally distinct Ge/Si ratios that can

be used to identify the origin of the silica in BIF. Hamade et al. (2003) established, using the Ge/Si ratios of chert bands in ca. 2500 Ma BIF of the Dales Gorge Member (Hamersley Basin, Western Australia), that most of the silica in BIF was continentally derived. Frei and Polat (2007) and Haugaard et al. 2017 later confirmed that this was also true for Algoma-type BIFs, proposing that the spread in Ge/Si ratios observed in both the ca. 3800 Ma-old Isua Supracrustal Belt and the ca. 2600 Ma-old BIF of the Slave craton (northwestern Canada) was due to the interaction of hydrothermally iron-fertilized bottom waters with silica-rich surface seawaters derived from pre-4000 Ma-old mafic land masses. Silicon isotopes have added some complexity to the issue of source since they show a perceptible hydrothermal signature in some BIFs (e.g., Steinhöfel et al. 2009), suggesting that the silica in BIF may be derived from mixed hydrothermal and continental sources.

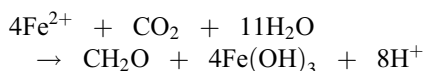
Prerequisites for BIF deposition necessitate not only a source of Si and soluble (reduced) Fe but also a way to oxidize Fe^{2+} into insoluble Fe^{3+} (Fig. 3).

Traditional models of BIF deposition propose that Fe^{2+} was oxidized in the presence of free oxygen derived from oxygenic microbial photosynthesis by cyanobacteria (Cloud 1965) and later through the direct utilization of O_2 by aerobic chemolithoautotrophic bacteria (Holm 1989):



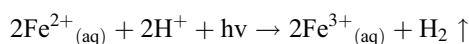
Indeed, the most voluminous BIFs (e.g., Hamersley Group, Western Australia; Transvaal Supergroup, South Africa) overlap in age with the rise of atmospheric oxygen at ~2.4 Ga. While this suggests that the Fe^{3+} component in these BIF formed via an oxic mechanism, the low atmospheric oxygen concentrations in the Archean suggest that the pre-2400 Ma BIF formed via an anoxic mechanism. Both abiotic and biogenic BIF

formation mechanisms have been suggested. In the latter case, the oxidation of Fe^{2+} into Fe^{3+} in an anoxic world can occur via anoxygenic phototrophy, whereby some photosynthetic bacteria (e.g., green and purple sulfur bacteria) can use Fe^{2+} as an electron donor for carbon assimilation instead of water, thus producing Fe^{3+} instead of O_2 (Garrels et al. 1973):



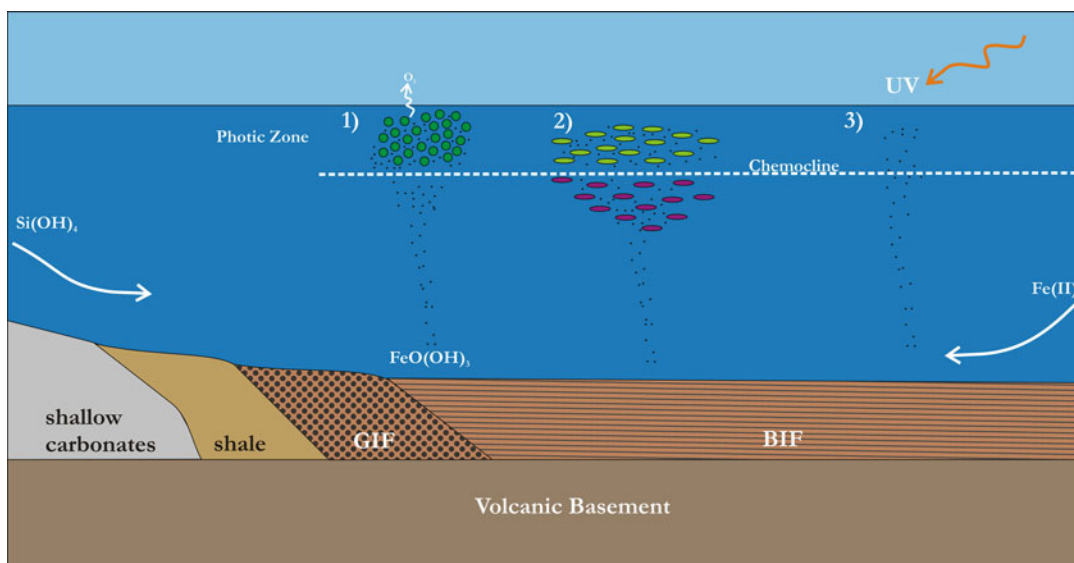
The biogenic precipitation of iron oxides by several species of modern phototrophic bacteria has been observed in both freshwater and marine environments, and laboratory experiments demonstrate that this form of metabolism could generate sufficient quantities of Fe^{3+} to account for all the oxidized iron in BIF (Kappler et al. 2005).

It has also been postulated that the absorption of ultraviolet radiation by either Fe^{2+} or $\text{Fe}(\text{OH})^+$ in the water column could have triggered the hydrolyzation of these species according to the following equation (Cairns-Smith 1978):

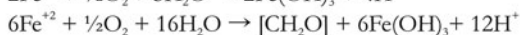


Although laboratory experiments have demonstrated that this oxidative process could have generated enough Fe^{3+} to account for all the ferric oxides in BIF, the process remains contentious as the experiments were not done in solutions that actually mimicked Precambrian seawater composition (Konhauser et al. 2007).

The signature feature of many iron formations is the distinctive banding made by alternating assemblages of silica/silicate and iron oxide minerals. Two fundamentally different models have been proposed as to their formation. The first suggests episodic pulsing of an iron-rich plume into the shallow waters of a depositional basin. During periods of upwelling, increased bacterial activity in the photic zone would induce the oxidation of Fe^{2+} to Fe^{3+} , while periods of no upwelling corresponded to low iron mineralization and high silicification from background waters (Morris 1993). Posth et al. (2008) demonstrated



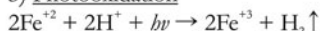
1) Oxygenic Photosynthesis



2) Photoferrotrophy



3) Photooxidation



Banded Iron Formation, Fig. 3 Three simplified models for the oxidation of Fe^{2+} and the deposition of banded iron formations: (1) oxygenic photosynthesis and oxidation of Fe^{2+} by cyanobacterially produced oxygen in

the photic zone; (2) $\text{Fe}(\text{II})$ oxidation in an anoxic water column by photoautotrophs such as green and purple sulfur bacteria; and (3) abiotic oxidation of Fe^{2+} via photooxidation

experimentally that banding could also be due to natural fluctuations in seawater temperature. In the summer, the warm waters promote increased bacterial Fe^{2+} oxidation while maintaining Si in solution, while during the winter, the decline in water temperature diminishes bacterial activity but induces silicification. The second view proposes that banding is the result of postdepositional diagenetic processes in which Si was remobilized and segregated into bands (Trendall and Blockley 1970). Significantly, coupling the reduction of Fe^{3+} minerals to the oxidation of organic matter not only explains the reduced Fe mineralogy in BIF and the low organic-matter content but also explains the abundance of light C isotope signatures associated with the interlayered carbonate minerals (Konhauser et al. 2005).

BIF and Iron Ore

Apart from being an important proxy for Precambrian seawater composition, BIFs are the main source of metallic iron for the steel industry. Almost all iron extracted from BIF-hosted iron ore deposits are used to make pig iron (a mixture of iron ore and coke produced in a blast furnace), which is the main component in the manufacture of steel.

BIF-hosted iron ore deposits can be divided into three classes on the basis of their iron content: (1) iron-rich primary BIFs containing 30–45 wt.% Fe, (2) high-grade martite-goethite ores with 56–63 wt.% Fe, and (3) high-grade hematite ores containing 60–68 wt.% Fe (Clout and Simonson 2005). The bulk of iron ore mined today corresponds to high-grade iron deposits (class 1 and 2) formed by supergene iron enrichment of precursor

BIFs. The supergene enrichment process (Fig. 4) involves deep weathering from the downward movement of oxidizing meteoric fluids that leach out the chert and carbonate components, leaving a residual accumulation of oxidized and hydrous Fe^{3+} phases such as hematite, martite, and goethite (Webb et al. 2003; Clout and Simonson 2005). Martite is often used as a textural term for hematite pseudomorphs after magnetite. The formation of these high-grade iron ores took place long after deposition, likely during the Phanerozoic, when the concentration of atmospheric oxygen, and thus meteoric waters, was sufficient to oxidize precursor mineral phases such as magnetite (Fig. 4).

In some deposits, however, hydrothermal fluids facilitated the formation of high-grade iron ore prior to supergene enrichment. Within the depositional basin, chert bands were hydrothermally replaced by carbonates, which in turn were dissolved and leached during later supergene enrichment (e.g., Taylor and Dalstra 2001).

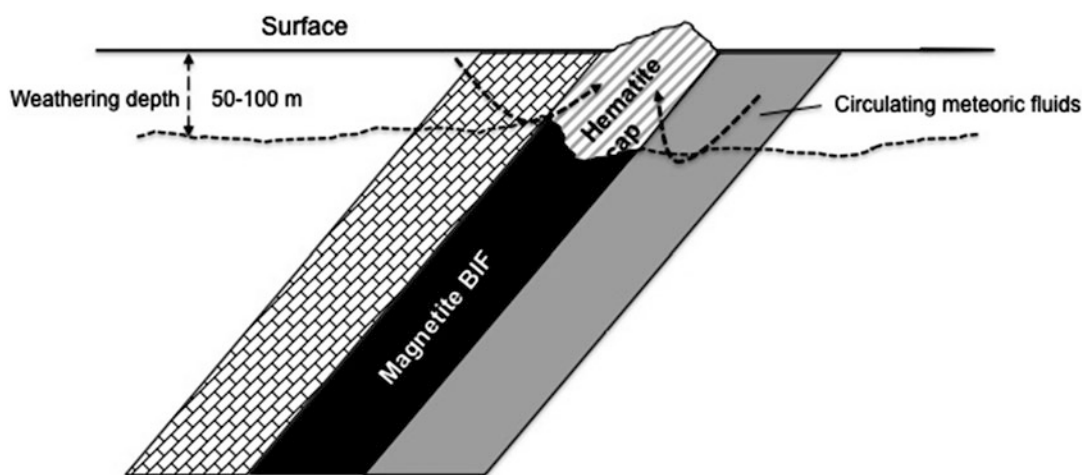
The world's leading iron ore producers and their historical and future estimated output of Fe are shown in Table 1.

The iron reserves (part of the mineralization that is economically feasible to extract at the time of determination) for each country as in 2011 are also presented. As observed in Table 1, the world output of iron is projected to increase from 2010

to 2013 by about 13%, that is, from 1.32 billion metric tons (Gt) in 2010 to 1.52 Gt in 2013 (Menzie et al. 2013). The world iron resources (parts of the mineralization that is in such form and amount that economic extraction is not feasible) reached ca. 800 Gt of crude ore (defined as it leaves the mine in an unconcentrated form) containing 230 Gt of iron (US Geological Survey, Mineral Commodity Summaries, January 2013).

Superior-type BIF are the largest source of iron used in industry, where three of the largest deposits in the world are located in the Carajás and Quadrilátero Ferrífero iron provinces in Brazil and the Hamersley iron province in Western Australia. These provinces account for close to 40% of the world's iron reserves (Table 1). An example of the magnitude of these BIF deposits is seen within the Hamersley iron province where the Paleoproterozoic Brockman Iron Formation contains some of the largest single lithostratigraphic BIF units known. These units are up to 360 m thick (e.g., the Joffre Member; Haugaard et al. 2016b), having an areal extent of 10^5 km^2 and estimated initial Fe content of $4.3 \times 10^{13} \text{ t}$ at the time of deposition (e.g., Trendall and Blockley 1970).

Table 1 shows that China is the largest producer and importer of iron in the world. The main iron ore reserves of China, however, possess relatively low-grade Fe content (~30% Fe);



Banded Iron Formation, Fig. 4 Sketch showing typical supergene enrichment of a magnetite-rich BIF leading to a high-grade hematite-goethite ore deposit within the weathering zone (Modified from Clout and Simonson (2005))

Banded Iron Formation, Table 1 The world's largest producers of iron 2000–2017 (estimated). See text for details. Values extracted from Menzie et al. (2013) and US Geological Survey Mineral Commodity Summaries, January 2013

Country	Average ore grade (% Fe)	Fe content in thousand metric tons										Reserves in billion tons (Gt)		
		2000	2005	2010	2013	2015	2017	Crude ore (2011)	Fe content			Crude ore (2011)	Fe content	
Australia	62	107,000	163,000	271,000	330,000	350,000	370,000	35,000				35,000	17,000	
Brazil	66	141,000	186,891	247,772	250,000	250,000	260,000	29,000				29,000	16,000	
Canada	64	22,700	19,333	23,300	28,000	28,000	30,000	6300				6300	2300	
China	64	73,600	134,000	350,000	410,000	420,000	430,000	23,000				23,000	7200	
India	64	48,600	97,500	166,000	170,000	172,000	174,000	7000				7000	4500	
Russia	58	50,000	56,100	58,500	59,000	59,500	60,000	25,000				25,000	14,000	
South Africa	62–65	21,570	24,900	36,900	46,700	48,900	49,500	1000				1000	650	
Ukraine	55	30,600	37,700	43,000	45,000	48,000	50,000	6000				6000	2100	
USA	–	39,703	34,202	32,000	32,000	32,000	32,000	6900				6900	2100	
World		607,000	837,00	1,320,000	1,520,000	1,660,000	1,750,000	170,000				170,000	80,000	

therefore, high export rates of high-grade iron ore are expected from China's largest suppliers in the future (e.g., Australia and Brazil).

Future Directions

As marine chemical precipitates, BIFs hold great importance as proxies for ancient seawater chemistry and, in this regard, may provide new insights into the composition of the ancient marine biosphere and, ultimately, the atmosphere, through the biogenic gases that ancient plankton emitted. Recent studies have begun to examine changing Precambrian seawater chemistry in terms of bioessential trace metals, and the results obtained from the BIF record are being corroborated by the record of these trace metals in marine black shales (e.g., Zn; Scott et al. 2012). Future work on BIF will undoubtedly investigate the temporal variations in more metals. Such geochemical studies will be enhanced by new analytical developments in trace metal stable isotopes, whereby relatively novel metal isotopes (e.g., $\delta^{53}\text{Cr}$ and $\delta^{238}\text{U}$) or multi-isotope surveys (e.g., combining $\delta^{56}\text{Fe}$ and $\delta^{30}\text{Si}$; Steinhöfel et al. 2009) will improve our understanding of the paleoredox conditions under which BIF formed. New BIF-based studies examining the paleoredox conditions a few million years prior to and after the great oxidation event (GOE, ca. 2.45 Ga) indicate that this event likely occurred more gradually than previously thought. As the products of the interplay between the mantle, the ocean, and the biosphere, BIFs are important chemical archives of ancient seawater composition. They not only grant us an understanding into ancient mantle and surface process systematics but also provide important insights into the evolutionary pathways of early life.

Cross-References

- [Archean Environmental Conditions](#)
- [Archean Traces of Life](#)
- [Bacteria](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Iron Cycle](#)

- [Iron Isotopes](#)
- [Iron Oxyhydroxides](#)
- [Jaspilite](#)
- [Magnetite](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygenation of the Earth's Atmosphere](#)

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Bandpass

Daniel Rouan
Observatoire Paris-Site de Meudon, Meudon,
France

Definition

The bandpass is a well-defined range of frequencies (or wavelengths) determined by a filter

that cuts out all other frequencies (or wavelengths) above and below this band. In visual and infrared photometry, different sets of standard filters with well-defined bandpasses have been defined and are used to perform color photometry. A given set defines a photometric system, the measured values in the different filters being generally given in ► [magnitudes](#).

Cross-References

► [Johnson UVB Bandpasses](#)

Barberton Greenstone Belt

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Keywords

Chert · Greenstone belt · Komatiite ·
Sediment · South Africa · Traces of life

Definition

The Barberton greenstone belt in South Africa is one of the best-preserved successions of mid-Archean (3.57–3.21 Ga) supracrustal rocks in the world, together with the ► [Pilbara Craton](#) in Western Australia. As such, it is a remarkable natural laboratory where conditions and processes at the surface of the Archean Earth can be studied in detail. The volcanic sequences include thick flows of ► [komatiite](#), a type of ultramafic lava named after the Komati River that flows through the belt, and records of large phreatomagmatic eruptions. Sedimentary sequences include ► [cherts](#), ► [banded-iron formations](#), and barite whose compositions constrain the composition and temperature of Archean oceans and preserve some of the earliest traces of life on Earth. The granitic rocks and metamorphic sequences provide information about Archean tectonic processes.

History

Geological mapping and research has been carried out in the Barberton belt over much of the past century, but only in the 1970s did its geological significance become apparent. Three developments were particularly important: The first was the development of increasingly accurate age dating that revealed the emplacement of volcanic and sedimentary rocks between 3.5 and 3.2 Ga ago (e.g., Lopez Martinez et al. 1984; Armstrong et al. 1990). This discovery showed that the Barberton terrain, together with those of the Pilbara Craton in Western Australia, contained the oldest known, well-preserved (i.e., metamorphosed to only a low degree) volcanic and sedimentary sequences. The second important discovery was the recognition by Richard and Morris Viljoen of the University of the Witwatersrand that many of the ultramafic rocks of the sequence were volcanic. They named this new rock type komatiite after the Komati River that flows through the belt. The geological and tectonic significance of these rocks has been developed in numerous publications (e.g., Viljoen and Viljoen 1969; Anhaeusser 1980; Jahn et al. 1982; de Wit et al. 1987; Dann 2000). The third important development stemmed from the work on clastic and chemical sedimentary rocks. Following the recognition of the ancient age of the sedimentary sequences in the 1970s, several research groups undertook a systematic search for microfossils in carbonaceous black ► [cherts](#) and shales. Detailed sedimentological and geochemical studies followed and led to major advances in the understanding of surface processes on the early Earth, including the observation of shallow-water sedimentary rocks and silicified evaporites (Lowe and Knauth 1977), sedimentary barite horizons (Heinrichs and Reimer 1977), seafloor alteration (Duchac and Hanor 1987), seafloor hot springs (de Ronde and Ebbesen 1996), semiquantitative evidence for tides (Eriksson and Simpson 2000), a record of temperature of the Archean ocean (Knauth and Lowe 2003), and photosynthetic microbial mats (Tice and Lowe 2006). In addition, it was found that at least four sedimentary beds in the

Barberton belt contained sand-sized spherical particles (spherules) interpreted to have formed by condensation of clouds of impact-generated rock vapor and thus represent the oldest terrestrial impact deposits (Lowe et al. 2003; Hofmann et al. 2006; Ozdemir et al. 2017).

Overview

The Barberton greenstone belt is a small, cusp-shaped succession of volcanic and sedimentary rocks invaded on all sides by granitoid plutons or truncated by ductile shear zones. It is located in the Mpumalanga province of South Africa, about 350 km east of Johannesburg. It is world famous for its komatiites, a type of ultramafic lava named after the Komati River that runs through the southern part of the belt, and for thick sequences of sedimentary rocks, which have yielded some of the earliest records of early life and of Earth's early surface conditions. The greenstone sequences, assigned to the ► [Barberton Supergroup](#), have been subdivided into three stratigraphic units. From base to top, these are (1) the Onverwacht Group, dominated by ultramafic and mafic volcanic rocks; (2) the Fig Tree Group, a volcano-sedimentary succession made up of graywackes (a variety of sandstone with a clay-rich matrix), shales, cherts, and felsic volcanoclastic rocks; and (3) the Moodies Group, characterized by coarse-grained clastic sedimentary rocks, mainly sandstones and conglomerates. Geological mapping has provided an increasingly clearer picture of the detailed stratigraphy despite the complex structure (Lowe et al. 2012). The protracted, 350-million-year-long evolution of the region encompassed multiple tectonic events that include three or more cycles of volcanism and sedimentation, deformation, and granite intrusion (Lowe 1999). This rich history led de Wit et al. (1992) to use the region as the basis of their model for the formation of continental crust.

Extensive field-based studies in the Barberton belt, starting from the early 1960s, provided evidence for the existence, as early as 3.5 Ga, of

a rich microbial ecosystem. Spherical, coccoidal, rod-shaped, and filamentous microscopic structures made up of carbonaceous matter and interpreted as microfossils have been recorded from Onverwacht and Fig Tree Group cherts. These rocks were deposited in shallow and deep marine environments, possibly in part on normal Archean oceanic crust and possibly associated with hydrothermal activity (Walsh 1992; Altermann 2001; Westall et al. 2001, 2015; Tice and Lowe 2006; Hickman-Lewis et al. 2018; Gourier et al. 2019; Homann 2019).

Domal stromatolites are also present in the Barberton belt (Byerly et al. 1986), but their origin, together with other early Archean occurrences, is controversial (Lowe 1994). More recently, Furnes et al. (2004) reported micrometer-scale tubular structures, interpreted to represent bioerosion features, in the rims of Onverwacht Group pillow basalts. Stable isotopic data have revealed the possible emergence of diverse groups of prokaryotes including carbon-fixing Bacteria and Archaea, methanogens, sulfate reducers, and possibly photosynthesizers. Structures reminiscent of modern microbial mats in shallow-water sandstones are widespread in parts of the Moodies Group (Heubeck 2009; Gamper et al. 2012).

The sedimentary sequences themselves can be mapped in detail and measured at high stratigraphic resolution. They thus provide abundant information about conditions at the Earth's surface: the spatial and temporal sequence of depositional systems; the interface between various regimes of erosion, transport, and deposition; the diagenetic processes near the surface; structural control on sedimentary composition, thickness, and geometry; the thermal history and evolution of sedimentary basins; and thus the overall geodynamic setting on the early Earth.

The ultramafic lavas of the Barberton belt have unusual compositions that define the Al-depleted or Barberton-type komatiite (Nesbitt and Sun 1976; Arndt et al. 2008). These rocks are formed through melting under unusual conditions in the mantle. Controversy surrounds the exact setting: most geologists support a model in which the

melts form in an unusually hot mantle plume (e.g., Arndt et al. 2008), but others advocate melting in cooler conditions in an Archean subduction zone (e.g., Grove and Parman 2004). Resolution of the issue has important implications for our understanding of Archean geodynamics. Despite more than 30 years of research, very few complete chemical analyses of Barberton komatiites are available, yet this information is crucial if the potential of these rocks as tracers of Archean geodynamic processes is to be realized. Black and white smokers on the Archean ocean floor, the exits of hydrothermal fluids that circulated through basaltic crust, could represent one possible setting for the emergence and evolution of life (Russell et al. 2005). Examples of these may well exist in the Barberton greenstone belt, but, as for most of the crucial geological and biological aspects of the Archean mentioned above, also these are the subject of considerable debate (e.g., de Ronde and Ebbesen 1996; Lowe and Byerly 2007).

Future Directions

Much of future work in the belt will focus around scientific drilling projects that are aimed at recovering continuous sections of well-preserved volcanic and sedimentary rocks. Work on the sedimentary sequences will provide information about erosion and sedimentation on the early Earth, the composition and temperature of Archean seawater, and possible sites where life may have emerged and evolved. The study of tidal sequences will provide information about the dynamics of the Earth-Moon system, and the investigation of spherule layers (including impact debris) provides information about the nature and magnitude of meteorite impacts on the early Earth. Work on the ultramafic to felsic volcanic rocks will provide new insights into volcanic processes, dynamics of the crust and mantle, and the interaction between oceanic volcanic crust and the hydrosphere and biosphere. The sources of hydrothermal fluids on the ocean floor, driven by the circulation of seawater through the volcanic pile,

constitute a second habitat of early life. Work on deeper sections through the lower parts of the succession will provide information about tectonic processes that operated during deposition of volcanic, sedimentary, and granitic rocks and during accretion of these materials to the continent.

Cross-References

- [Archaean Traces of Life](#)
- [Barberton Supergroup](#)
- [Chert](#)
- [Impact Melt Rock](#)
- [Komatiite](#)
- [Pilbara Craton](#)
- [Stromatolites](#)

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Barberton Greenstone Belt, Sedimentology

Axel Hofmann

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Keywords

Archean Eon · Chert · Sedimentary rock · Onverwacht Group · Fig Tree Group · Moodies Group

Definition

► **Sedimentary rocks** can be found throughout the ► **Barberton Supergroup**. In the volcano-sedimentary Onverwacht Group, sedimentary rocks make up less than 5% of the succession. They consist of bedded ► **cherts**, representing a variety of silicified clastic, chemical, and biogenic sediments. Deep- to shallow-marine, fine-grained siliciclastic sedimentary rocks make up the dominant part of the Fig Tree Group. The Moodies Group is characterized by relatively coarse-grained, siliciclastic, alluvial, fluvial, shoreline, and shallow-marine deposits. Detailed sedimentological and geochemical studies of the sedimentary rocks of the Barberton Supergroup have provided major advances in the understanding of surface processes in the Paleoarchean.

Overview

Bedded chert horizons of the Onverwacht Group are typically 1–20 m thick and represent interflow sedimentary units that were deposited on the seafloor between phases of extrusive submarine volcanic activity. The cherts consist of a variety of

Barberton Greenstone Belt, Sedimentology,

Fig. 1 Carbonaceous chert with discontinuous layers of silicified ultramafic ash (*gray chert*) showing ripple lamination (characteristic of subaqueous deposition). Onverwacht Group, Kromberg Formation, Farm Josefsdal



silicified sediments (Lowe 1999; Tice and Lowe 2006; Hofmann et al. 2013). Extensive early silicification took place as a result of low-temperature hydrothermal activity on the seafloor, resulting in excellent preservation of the sedimentary strata. Silicified volcanoclastic sediments are common and include silicified beds of ultramafic to mafic ash and accretionary lapilli. Laminated cherts of various shades of gray to black represent mixtures of volcanoclastic material and carbonaceous matter (Fig. 1). Deposition took place in low-energy, predominantly sub-wave base settings with episodic, high-energy current events during which coarse-grained volcanoclastic material and, in rare cases, meteorite impact ► *ejecta* were deposited. Cherts have been used extensively to study surface processes, seawater composition, and life in the Archean.

The Fig Tree Group consists of a 2–3 km thick, largely siliciclastic, and volcanoclastic sequence that is capped by felsic volcanic and volcanoclastic rocks (Heinrichs 1980; Lowe and Nocita 1999; Hofmann 2005; Drabon et al. 2019). In the southern part of the belt, a variety of siliciclastic lithofacies with abundant felsic volcanic detritus are present that formed in deep- to shallow-water, fan delta, and alluvial environments (southern facies). The local presence of beds of jaspilitic banded iron formation, chert, and barite indicates syndepositional hydrothermal activity. In the northern part of the Barberton greenstone belt, the Fig Tree Group is mainly characterized by turbiditic

sandstones and shales that formed in relatively deep-water environment (northern facies). Several spherule beds of quenched liquid silicate droplets in the Fig Tree Group represent fallout and partially tsunami-reworked meteorite impact deposits (Lowe et al. 2014).

The ► *Moodies Group* consists of up to 3.7 km thick, quartz-rich, predominantly arenaceous rocks, in contrast to the quartz-poor and matrix-rich Fig Tree graywackes. It consists of alluvial conglomerate, braided fluvial, tidal and shallow-marine sandstones, and minor siltstone and banded iron formation (Anhaeusser 1976; Heubeck and Lowe 1994; Heubeck 2019). Intertidal sedimentary rocks and microbial mat-related sedimentary structures are locally well preserved (Homann et al. 2015). Moodies strata may include some of the oldest preserved aeolian deposits (Simpson et al. 2012). Deposition of the Moodies Group was syntectonic with final greenstone belt deformation and occurred within only a few Ma under initially extensional and later compressional deformation (Heubeck 2019).

Cross-References

- [Archean Environmental Conditions](#)
- [Barberton Greenstone Belt](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Chert](#)
- [Earth, Formation, and Early Evolution](#)

- ▶ Ejecta
- ▶ Greenstone Belt
- ▶ Sedimentary Rock

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Barberton Greenstone Belt, Traces of Early Life

Frances Westall¹ and Keyron Hickman-Lewis²

¹CNRS-Centre de Biophysique Moléculaire, Orléans, France

²Natural History Museum, London, UK

Keywords

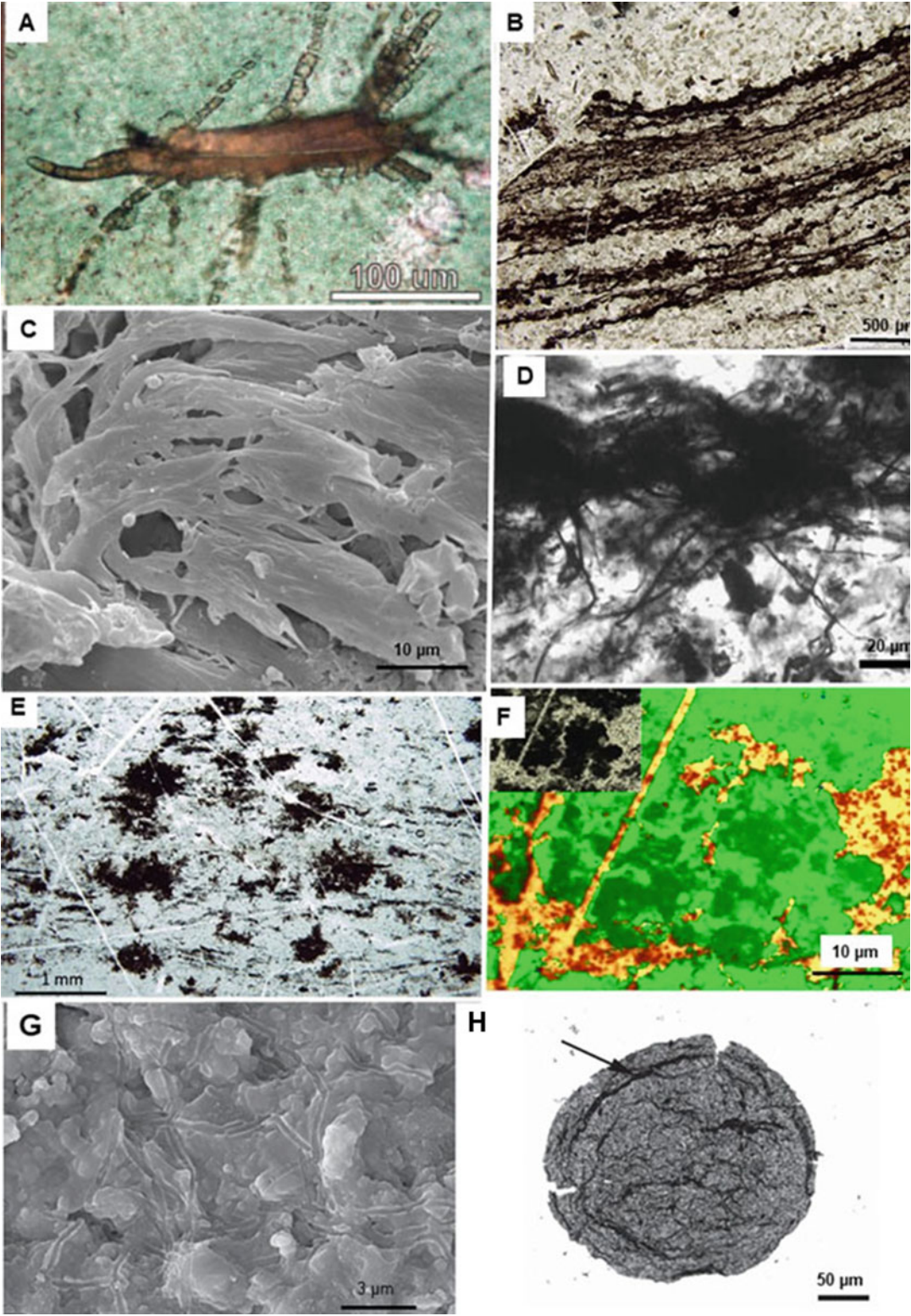
Palaeo- to Mid Archaean · Volcaniclastic sediments · Shallow basins · Hydrothermal activity · Chemotrophs · Phototrophs · Coelobionts

Definition

The Barberton Greenstone Belt is an ensemble of lightly to moderately metamorphosed igneous rocks and sediments dating between about 3.5 and 3.2 billion years old (Ga). Together with the similarly-aged Pilbara Greenstone Belt, it is one of the only two locations in the world hosting the oldest, well-preserved sediments.

Overview

The Barberton greenstone belt of South Africa and Swaziland, together with the greenstone belts of the Pilbara region in Australia, hosts the oldest (3.5–3.3 Ga) well-preserved rocks containing fossil signatures of life. These traces occur in thin layers of volcanoclastic sediments, sandwiched between thick successions of mostly mafic to ultramafic volcanic lavas. The remains of



Barberton Greenstone Belt, Traces of Early Life, Fig. 1 Barberton Greenstone Belt, traces of early life. (a) Purported microbial tunnels in the vitreous rind of an ~3.4 Ga-old pillow lava from the Barberton Greenstone

microbial mats are relatively common in shallow-water deposits dating to almost 3.5 Ga, while deeper-water deposits contain reworked, detrital remains of organic matter and microbial mats. More recently identified remains of chemotrophic colonies co-located with hydrothermal influence complement the microbial diversity. Somewhat younger clastic sediments of the 3.2 Ga Moodies Group have yielded relatively large cellular remains of possible planktonic organisms and abundant microbial mats.

The Palaeo- to Mid-Archaeon (3.5–3.2 Ga) Barberton greenstone belt consists of kilometer-thick, largely subaqueous volcanic rocks and their erosional products, together with sedimentary rocks including BIFs, cherts, shales, baryte, siltstones, sandstones, and conglomerates. Largely mafic to ultramafic lavas were extruded onto relatively shallow-water platforms. Interspersed with these volcanics are thin horizons of volcanoclastic and hydrothermal sediments deposited at water depths ranging from littoral to sub-wave base. Early diagenetic silicification of sediments and underlying volcanics was related to circulating hydrothermal fluids (Hofmann and Bohlar 2007; Westall et al. 2015; Hickman-Lewis et al. 2020a) and seawater oversaturation with respect to silica (Lowe and Byerly 1986). These sediments host a variety of traces of early life.

Early studies reported the occurrence of possible cellular microfossils (e.g. Walsh 1992). Microbial corrosion features, typical of those produced by chemolithotrophic microorganisms in the vitreous rinds of pillow lavas, were described by Furnes et al. (2004, Fig. 1a) from the Hoogenoeg Formation (ca. 3.4 Ga) but their biogenicity has been questioned (Grosch et al. 2014; Grosch and McLoughlin 2014). These once hollow structures

in the outer glassy layers of pillow basalts are lined by Ti-oxides that contain early sulphide inclusions showing $\delta^{34}\text{S}$ depletions (–45‰ to –3‰), which is consistent with a biogenic origin for the sulphides. No microfossils are associated with these tunnels.

The surfaces of volcanoclastic sediments deposited in shallow-water environments such as the Buck Ridge and Josefsdal Cherts hosted microbial mats and biofilms which were probably formed by anaerobic photosynthetic organisms. When observed in petrographic thin sections, they are characterized by packets of fine-grained, carbon-rich layers that form more or less continuous wispy, wavy horizons on sediment surfaces (Fig. 1b, c) (Walsh 1992; Tice and Lowe 2004; Tice 2009; Westall et al. 2006, 2015) and occur even in the oldest preserved sediments in Africa, the 3.472 Ga Middle Marker Formation (Hickman-Lewis et al. 2018). Biogeochemical signatures from these mats are consistent with diverse bacterial and archaeal precursors (Hickman-Lewis et al. 2020a). Tice (2009) demonstrated that environmental factors, such as current energy, controlled the style of microbial mats preserved in the 3.42 Ga-old Buck Reef Chert. Formed at water depths between storm base and fair-weather wave base, anastomosing and mesh-like mats occur in sediments consisting of coarse-grained fluffy carbonaceous grains, while finely laminated mats occur in finer-grained sediments deposited under quiet conditions. Importantly, Hickman-Lewis et al. (2020b) documented the influence also of riverine water on the development of phototrophic mats.

Rarely, carbonaceous filaments and spheroids considered potential microfossils are observed in silicified interstitial spaces between mat layers (Walsh 1992, Fig. 1d). Although the organisms

Barberton Greenstone Belt, Traces of Early Life, Fig. 1 (continued) Belt now questioned (Furnes et al. 2004; Grosch and McLoughlin 2014). (b) Tufted phototrophic biofilms from the 3.472 Ga Middle Marker Formation (Hickman-Lewis et al. 2018). (c) Well-preserved silicified filaments in a microbial biofilm from the 3.33 Ga Josefsdal Chert, Barberton (Westall et al. 2006b). (d) Thin-section photomicrograph of a potentially photosynthetic filamentous microbial mat from ~3.4 Ga-old cherts from Barberton (Walsh 2004). (e) 3-D stellate

chemotrophic colonies and (f) Raman spectral mapping of chemotrophic clots from the 3.33 Ga Josefsdal Chert, Barberton (Westall et al. 2015; Hickman-Lewis et al. 2020b). (g) Filamentous moulds from the vadose zone in the 3.2 Ga Moodies Group sandstones, Barberton (Homann et al. 2016). (h) Acritarch (organic-walled vesicle of unknown biological affinity) from 3.2 Ga siliciclastic sediments of the Moodies Group, Barberton (Javaux et al. 2010)

forming the mats are seldom preserved, a scanning electron microscope study of an extremely well-preserved silicified biofilm in the 3.33 Ga Josefsdal Chert documented the presence of filaments 0.25 μm in diameter and tens of microns in length embedded in chert interpreted as a thick polymer on the mat surface (Westall et al. 2006b, Fig. 1c). Detailed in situ morphological and geochemical analysis of this particular biofilm demonstrated that the biofilm had been undergoing incipient calcification, probably due to the action of sulphate-reducing microorganisms degrading the lower, dead layers of the biofilm prior to early silicification that preserved it in three dimensions (Westall et al. 2011b).

Silicified sediments also contain particles and clots of carbon that may be derived from microbial colonies. Carbon and sulfur isotope signatures have been interpreted to indicate the presence of a variety of microbial organisms, including anoxygenic photosynthesisers, and heterotrophs such as methanogens (see reviews in Westall 2011; Homann 2019; Hickman-Lewis et al. 2020c). Thick (>30 μm), spicular carbonaceous coatings on volcanic particles and stellate, 3D carbonaceous clots (Fig. 1e, f) formed in a mixture of silica gel and very fine volcanic ash document the presence of colonies of chemotrophic microorganisms in these cherts (Westall et al. 2015; Hickman-Lewis et al. 2020c). Carbon isotope signatures (averaging -21.0% to -11.5% , as well as the selective accumulation of transition metals (Fe, V, Ni, As, and Co) of biological (metallomic) importance within these clots, reinforce their biogenicity, possibly suggesting methane and/or nitrogen cycling chemotrophic metabolisms (Hickman-Lewis et al. 2020c).

Younger littoral sediments from the 3.2 Ga Moodies Group have revealed a wealth of fossil microbial structures. Crinkled, domed, and anastomosing photosynthetic microbial mats occur on the surfaces of coarse-grained, tidal-zone, and riverine sandstones (Noffke et al. 2006; Heubeck 2009; Homann et al. 2015). Vadose zone cracks in the sandstones reveal the moulds of microorganisms that have been compared with modern endoliths (Homann et al. 2015). Coeval siltstones have yielded

compressed remains of large (up to 300 μm diameter) organic, hollow, and spherical structures (acritarchs) interpreted as unicellular microorganisms or colonial envelopes (Javaux et al. 2010), thus documenting the existence of a diverse biota.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [Archaean Traces of Life](#)
- [Barberton Greenstone Belt](#)
- [Biomarkers](#)
- [Chemolithotroph](#)
- [Microbial Mats](#)
- [Microfossils](#)
- [Pilbara Craton](#)

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Barberton Supergroup

Axel Hofmann

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Synonyms

Swaziland Supergroup (outdated)

Definition

The volcano-sedimentary sequence that forms the Barberton greenstone belt has been grouped stratigraphically as the Barberton Supergroup, renamed from the Swaziland Supergroup of older literature. The Barberton Supergroup formed ~3.55–3.22 Ga ago and is subdivided, in ascending order, into three major stratigraphic units: (1) The Onverwacht Group (3.55–3.25 Ga) dominantly consists of submarine ultramafic-mafic volcanic rocks and minor felsic volcanic and silicified ► [sedimentary rocks](#). (2) The Fig Tree Group (3.26–3.23 Ga) is comprised of shale, greywacke, and felsic volcanoclastic rocks with minor conglomerate, chert, barite, and banded iron formation. (3) The Moodies Group (~3.22 Ga) consists of shallow marine to fluvial sandstone and conglomerate with minor mafic volcanics, shale, and banded iron formation. These groups have been subdivided into a number of formations, which differ in lithology, thickness, and facies across the major fault zones that separate the Barberton greenstone belt into discrete fault-bounded segments. The

excellent degree of preservation and exposure, continuous outcrop of mostly subvertically dipping strata, and the high lithologic variability made possible the detailed mapping of the units of the Barberton Supergroup. This in turn provided the base for targeted research that led to major contributions to the understanding of the Archean.

Cross-References

- [Archean Environmental Conditions](#)
- [Barberton Greenstone Belt](#)
- [Barberton Greenstone Belt, Sedimentology](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Earth, Formation, and Early Evolution](#)
- [Greenstone Belt](#)

Barite

Christoph Heubeck
Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

Definition

Barite (also Baryte), BaSO_4 , is a widespread, usually white or colorless mineral which can be deposited by biogenic, hydrothermal, and evaporitic processes. In sedimentary environments, the main sources of barium ions are submarine hydrothermal vents; the sulphate ion is common in Phanerozoic seawater.

The origin of primary stratiform bladed baryte crystals on Archean sea floors (“crystal lawns”) is debated because the highly oxidized sulfate ion is generally thought to have been in short supply in Archean oceans. However, some of these barite deposits may have formed from sulfate which had been generated photolytically as aerosols in the Archean atmosphere and then washed into the oceans. Others may be late-diagenetic

pseudomorphs after calcium sulphate. Studies on S isotopes indicate that some barite played a role in bacterial sulphate reduction, one of the earliest metabolic processes.

Barophile

- [Piezophile](#)

Barycenter

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Center of mass](#)

Definition

In astronomy, the barycenter is the center of mass of a system of two or more bodies. For the purposes of most calculations, the system can be considered to be concentrated at the position of the barycenter, with a total mass equal to the sum of the masses of the individual objects. The barycentric radial velocity of an object, such as a star, as measured by a terrestrial observer is calculated relative to the center of mass of the Solar System. This is slightly different from the heliocentric velocity of such a star, which is centered on the Sun and varies slightly with time according to the position of the planets (since the motion of the planets produces slight changes in the Solar System’s barycenter).

Cross-References

- [Astrometric Planets](#)

Barycenter Velocity

- [Center of Mass Velocity](#)

- [Mid-Ocean Ridge](#)
- [Moon, The](#)
- [Oceanic Crust](#)
- [Olivine](#)
- [Plate Tectonics](#)

Basalt

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Basalt is a fine-grained, dark-colored ► [mafic igneous rock](#) erupted at the surface of the Earth and other rocky planets (volcanic rock). Basalt contains 45–52% of SiO₂ and is composed of plagioclase (50%), ortho- or clinopyroxene (25–40%), and minor Fe-Ti oxides (2–3%), with or without ► [olivine](#) (10–25%). Porphyritic samples contain large crystals (phenocrysts) of olivine, pyroxene, or plagioclase dispersed in a fine-grained glassy matrix, also called ground-mass. Gas-rich samples contain abundant vesicles. Basalt erupts as ► [pillow lava](#), thick sheet flows, or fragmental scoria. It is the most common rock of the Earth's ► [oceanic crust](#) – which is produced at the ► [mid-ocean ridges](#) – and in lunar *maria* (ancient flood-basalt plains corresponding to the dark surfaces of the Moon). Basalt is also present in the crust of Mars and Venus. It forms by partial melting of the mantle and erupts in diverse tectonic settings: midocean ridges, oceanic islands, subduction zones, continental rifts, and volcanic plateaus.

Cross-References

- [Igneous Rock](#)
- [Mafic and Felsic](#)
- [Mars](#)

Basaltic Flood Plains

- [Mare, Maria](#)
- [Trapps](#)

Base Pair

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Base pair is a pair of nucleic acid bases each in a different nucleotide monomer in the same (intramolecular) or different (intermolecular) ► [nucleic acid](#) strands and linked to one another by specific hydrogen bonds. The canonical base pairs in ► [DNA](#) (Watson-Crick pairs) contain one purine and one pyrimidine in antiparallel positions: adenine binds thymine in DNA – uracil in RNA (through two hydrogen bonds) – and guanine binds cytosine (through three hydrogen bonds). There are also many examples of non-Watson-Crick pairing, especially in three-dimensional structures of RNAs.

Cross-References

- [Anticodon](#)
- [Codon](#)
- [DNA](#)
- [Genetic Code](#)

- [Nucleic Acid Base](#)
- [Nucleic Acids](#)
- [RNA](#)
- [Wobble Hypothesis \(Genetics\)](#)

Basic and Acid

- [Mafic and Felsic](#)

Bathybius Haeckelii

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Definition

In June 1857, the Britannic ship “The Cyclops” found a very special matter on the bottom of the North Atlantic Ocean. Some chemists and biologists considered that it was a very simple living matter and thought that it resolved the problem of the origin of life. Indeed, according to them, it constituted an example of spontaneous generation and a link between inert matter and living matter. Thomas Huxley (1825–1895) himself named it *Bathybius haeckelii*. However, in 1876, a chemist revealed that it was calcium sulfate and not living matter.

Discussions about *Bathybius* took place during the period of the debate about spontaneous generations. Therefore, during few years the possibility of the production of this matter, very closed to living matter, was highly considered by many chemists and biologists.

Cross-References

- [Huxley's Conception on Origins of Life](#)
- [Protoplasmic Theory of Life](#)

BBN

- [Big Bang Nucleosynthesis](#)

Beagle 2

Frances Westall

Centre de Biophysique Moléculaire, CNRS, Orléans, Cedex 2, France

Definition

The Beagle 2 lander, named after the famed ship in which Charles Darwin traveled the world, was part of the ► [European Space Agency's](#) Mars Express mission. It was launched in June 2003 and was supposed to land in December 2003. Unfortunately, all contact with the 33.2 kg lander was lost a few days before touchdown, and its fate remains a mystery. The lander was a compact assemblage of instruments designed to address science questions ranging from the search for traces of past and extant life, measurement of the composition of the atmosphere and other environmental parameters, the oxidation state at the surface, and analysis of the geomorphology of the landing site in a sedimentary Basin of Isidis Planitia.

Overview

The lander was constructed by a British consortium, coordinated by Prof. Colin Pillinger of the Open University. It was equipped with a 75 cm long robotic arm holding at its end an array of instruments called the PAW (Payload Adjustable Workbench) that included stereo cameras, a Mössbauer spectrometer to measure the oxidation states of iron-containing compounds, an X-ray spectrometer for determining mineral composition, and a (dentist's) drill for collecting samples. Also onboard the lander was a gas analysis package (GAP) that included a gas chromatograph-

mass spectrometer to analyze carbon isotopes as a signature for life. Finally, a “mole” or subsurface sampler (PLUTO – Planetary Undersurface Tool) was designed to penetrate beneath the loose regolith surface to obtain samples for analysis.

The 1 m diameter lander was equipped with a UHF radio antenna, telecommunications, a battery, electronic processors, heaters, solar panels, and other payload instruments, such as radiation and oxidation sensors to address the environmental objectives of the mission. Upon arrival, the lander was supposed to have broadcast a piece of music specially composed by the British rock band Blur.

Various hypotheses involving malfunctioning of various pieces of equipment have been put forward to explain the failure of the mission. The lander could have bounced off the atmosphere of Mars and burned up, or the parachute failed to deploy and/or the airbags did not function and the lander crashed onto the Martian surface, or perhaps the backshell became entangled with the parachute, the parachute could have covered the lander, thus preventing it from opening. At the beginning of 2015 it was announced that the orbital camera around Mars, HiRISE, had found the lander intact on the Martian surface, within the expected landing ellipse in Isidis Planitia but, unfortunately, it appeared to be only partially deployed. However, it can be demonstrated that the entry, descent and landing system did indeed work.

Belcher Group, Microfossils, Fig. 1 The mat-building colony of the cyanobacteria *Eoentophysallis belcherensis*, preserved in stromatolites of the 1.5 Ga Bil'yakh Group, Siberia. (Photograph courtesy of A. Knoll)

References and Further Reading

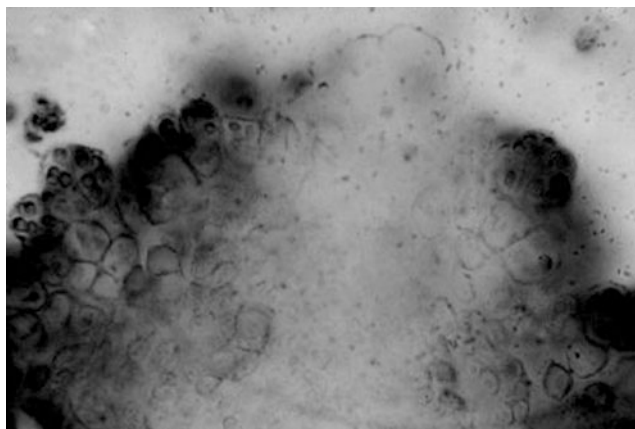
<http://www.beagle2.com/index.htm>

Belcher Group, Microfossils

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

The Belcher Group comprises ► [sedimentary rocks](#) from the Belcher Islands, Canada, dated at 1.9 Ga. These rocks include ► [chert](#) lenses and nodules in silicified ► [stromatolites](#) growing in tidal and shallow subtidal waters on a carbonate platform. The cherts contain tridimensionally preserved filamentous and coccoidal (spheroidal) ► [microfossils](#), including fossilized colonies of microscopic pigmented cells. The distribution and pattern of division of these later microfossils (called *Eoentophysallis belcherensis*) suggest a relationship to the extant genera of ► [cyanobacteria](#) *Entophysallis*. These microfossils represent some of the oldest remains of identified cyanobacteria, together with cyst-like cyanobacteria microfossils (akinetes) from Gabon dated at 2.1 Ga (Fig. 1).



Cross-References

- [Chert](#)
- [Cyanobacteria](#)
- [Fossilization, Process of](#)
- [Microbial Mats](#)
- [Microfossils](#)
- [Sedimentary Rock](#)
- [Stromatolites](#)

(101955) Benu

- [RQ36](#)

Benu Asteroid

Anny-Chantal Levasseur-Regourd
Sorbonne Univ., Campus P. & M. Curie /
LATMOS, Paris, France

Synonyms

[Asteroid 101955](#)

Definition

(101955) Benu is a near-Earth carbonaceous asteroid, suggested to belong to the taxonomic class B or more likely to the rare class F (Belskaya et al. 2005) from its spectropolarimetric properties (Cellino et al. 2018). It has been the target of the NASA OSIRIS-REx sample return mission, which rendezvoused with it in late 2018 and collected samples in 2020. The return capsule should reach Earth in September 2023 and allow detailed analyses of the samples, as well as comparisons with those returned from asteroid Ryugu.

Benu is (like asteroids Steins and Ryugu) a roundish, diamond-shaped body with an equatorial bulge, probably formed by re-accumulation of rubble ejected after catastrophic disruption of a larger parent body. Its mean size is ≈ 490 m, and

its rotation period ≈ 4.3 h. Its low density ($\approx 1190 \text{ kg m}^{-3}$) suggests a huge bulk porosity, as expected for a “rubble-pile” asteroid (Barnouin et al. 2019). Its surface gravity is thus extremely low, about only 6.27 micro-g at its equator. The surface of Benu is rough, with boulders including minerals likely to originate from its parent body, and quite dark, with a geometric albedo of $\approx 4.4\%$ (Hergenrother et al. 2020), comparable to that of cometary nuclei (Lamy et al. 2004).

Benu is a most remarkable active asteroid, which appears to eject plumes of particles, with sizes up to ≈ 10 cm (Hergenrother et al. 2020). They could possibly be released after meteoroid impacts or dehydration of abundant hydrated minerals, such as phyllosilicates (Hamilton et al. 2019). Information retrieved from remote observations of the linear polarization of solar light scattered by the surface and near-environment of Benu (Cellino et al. 2018) fairly agrees with that of comet Hale-Bopp, under similar observational conditions. Analyses of Benu samples should thus provide more insight into active asteroids and main-belt comets, together with clues on the evolution of carbonaceous matter in the Solar System.

Cross-References

- [Asteroid](#)
- [Comet](#)
- [Near-Earth Objects](#)
- [NASA](#)
- [OSIRIS-REx](#)
- [Ryugu Asteroid](#)

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Benthic Mats

► Microbial Mats

Benzene (C₆H₆)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

C₆H₆; Cyclohexa-1,3,5-triene

Definition

Benzene is an ► [aromatic hydrocarbon](#) in which the six carbon atoms are arranged in a ring, with all carbon bonds equal and intermediate in length between single and double bonds. Under standard laboratory conditions benzene is a colorless and highly flammable liquid with a sweet smell.

Benzene is a known carcinogen and has various toxic effects on humans.

History

Benzene was first isolated by the English chemist/physicist Michael Faraday in 1825, although the natural aromatic resin that contains benzene comes from Southeast Asia and was known to Arab traders during the Middle Ages. The cyclic structure of benzene was announced in 1865 by the German chemist Friedrich A. Kekulé, with the data on carbon bond lengths coming from X-ray diffraction measurements. An astronomical detection in the protoplanetary nebula CRL 618 has been reported by Cernicharo et al. (2001) from mid-infrared observations, and the measured abundance is matched by chemical models (Woods et al. 2003). In the Solar System benzene has been observed in the atmospheres of Jupiter, Saturn and Saturn's moon Titan (Fouchet et al. 2005), and in comet 67P/Churyumov-Gerasimenko (Schuhmann et al. 2019).

Cross-References

- [Aromatic Hydrocarbon](#)
- [Comet](#)
- [Molecules in Space](#)
- [Planetary Nebula](#)
- [Titan](#)

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Benzonitrile (C₆H₅CN)

Brett A. McGuire^{1,2}, Andrew M. Burkhardt³ and Ci Xue⁴

¹Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA, USA

²National Radio Astronomy Observatory, Charlottesville, VA, USA

³Center for Astrophysics, Harvard & Smithsonian, Cambridge, MA, USA

⁴University of Virginia, Charlottesville, VA, USA

Synonyms

Phenyl cyanide

Chemical Formula

C₆H₅CN

Definition

Benzonitrile (C₆H₅CN) is an aromatic hydrocarbon molecule, consisting of a benzene ring functionalized by a cyano (CN) group. It was the first benzene-ring containing a molecule to be detected by radio astronomy and was observed toward the dark cloud TMC-1.

History

The detection of benzonitrile was first reported by McGuire et al. (2018) in Green Bank Telescope observations of the TMC-1 dark cloud at cm-wavelengths. Benzonitrile is an aromatic molecule and the first such molecule to be detected by radio astronomy that contains the benzene subunit. Polycyclic aromatic hydrocarbons (PAHs), large organic molecules consisting of multiple fused aromatic rings, typically benzene, are expected to contain 10–25% of the interstellar carbon reservoir based on observations of the bright emission features known as the

Unidentified Infrared Bands. These PAHs are thought to primarily be produced in evolved stars; however, the detection of benzonitrile, a simple cousin, in a cold, starless dark cloud like TMC-1, offers an alternative formation pathway. Detailed studies of the formation of this molecule suggest that the CN-addition to benzene is barrierless and efficient in interstellar conditions, suggesting that benzonitrile is likely an excellent radio-observable proxy for benzene in the study of PAH formation and evolution (Lee et al. 2019; Cooke et al. 2020). Since the original detection, benzonitrile has been detected toward four additional prestellar sources, indicating aromatic molecules are ubiquitous in the earliest stages of star formation (Burkhardt et al. 2021). In addition, several other simple rings have been detected in TMC-1, including both isomers of cyanocyclopentadiene (c-C₅H₅CN; McCarthy et al. 2021; Lee et al. 2021) and both isomers of cyanonaphthalene (c-C₁₀H₇CN; McGuire et al. 2021). Recent chemical modeling efforts using the nautilus code (Ruaud et al. 2016) and the Kinetic Database for Astrochemistry (KIDA) network (Wakelam et al. 2015), modified to include the formation of aromatic molecules, found that the observed abundances of simple rings are greater than the model's prediction by several orders of magnitude, suggesting that the current understanding of the formation of aromaticity is incomplete.

Cross-References

- Benzene (C₆H₆)
- Interstellar Medium
- Molecules in Space
- Polycyclic Aromatic Hydrocarbon
- Unidentified Infrared Emission Bands

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Definition

BepiColombo is a joint mission between the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA) to explore Mercury, the innermost planet of our Solar System. It consists of two orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (nicknamed Mio). Both spacecraft has been launched with an ARIANE V rocket on 20 October 2018 for an arrival at Mercury in late 2025. From their dedicated orbits, the two spacecraft will be studying the planet and its environment. On its route, BepiColombo (Fig. 1) will pass by Earth, two times Venus, and six times Mercury.

History

More than 30 years ago, Mercury was seen as not very spectacular and it also gave no reasons for speculations about active surface processes, e.g., volcanism. The view of Mercury drastically changed after the very successful MESSENGER mission of NASA (McNutt et al. 2006). MESSENGER revealed some results which did not fit in our current thinking of how Mercury should have evolved or what one expected to find on a planet close to the Sun. Volcanism has played a critical role in shaping Mercury's surface, Mercury is abundant in volatile elements, Mercury showed a geologic landform called Hollows not yet been seen on other planets, and Mercury has an Earth like magnetic field albeit much weaker. In addition, Mercury is a key planet to understand

BepiColombo

Johannes Benkhoff
ESA-ESTEC, Noordwijk, Zuid Holland, The Netherlands

Keywords

Planet Mercury · Planetary evolution and formation · Planetary space missions · Magnetosphere



BepiColombo, Fig. 1 BepiColombo cruise configuration

the evolution history of our Solar System because of its position among the planets. It is the planet closest to the Sun and experiences the harsh environment of the Sun the most.

A suite of state-of-the-art scientific instruments, flying on the two BepiColombo spacecraft, allow to address these wide range of scientific questions. The science payload of MPO contains 11 instruments: **BELA** (BepiColombo Laser Altimeter) to characterize the topography and surface morphology of Mercury (Thomas et al. 2021), **ISA** (Italian Spring Accelerometer) to study Mercury's interior structure and to test Einstein's Theory of Relativity (Santoli et al. 2020), **MPO-MAG** (Magnetic Field Investigation) an instrument to describe Mercury's magnetic field and its source (Heyner et al. 2021), **MERTIS** (Mercury Radiometer and Thermal Imaging Spectrometer) to study Mercury's mineralogical composition and provide global temperature maps (Hiesinger et al. 2020), **MGNS** (Mercury Gamma-Ray and Neutron Spectrometer) to determine the elemental compositions over the entire surface of Mercury (Mitrofanov et al. 2021), **MIXS** (Mercury Imaging X-ray Spectrometer) an instrument that uses X-ray fluorescence analysis to provide a global map of the surface atomic composition (Bunce et al. 2020), **MORE** (Mercury Orbiter Radio science Experiment) two-way, multifrequency radio science measurements to describe Mercury's gravity field (Iess et al. 2021), **PHEBUS** (Probing of Hermean Exosphere by Ultraviolet Spectroscopy) an UV spectrometer to characterize the composition and dynamics of Mercury's exosphere (Quémerais et al. 2020), **SERENA** (Search for Exosphere Refilling and Emitted Neutral Abundances) a suite of four sensor units to study the interactions between the surface, exosphere, magnetosphere, and the solar wind (Orsini et al. 2021), **SIMBIO-SYS** (Spectrometers and Imagers for MPO BepiColombo Integrated Observatory) a camera and spectrometer system to provide global, high-resolution, and IR imaging of the surface (Cremonese et al. 2020), and **SIXS** (Solar Intensity X-ray and particle Spectrometer) to perform measurements of solar X-rays and particles (Huovelin et al. 2020). The science payload of

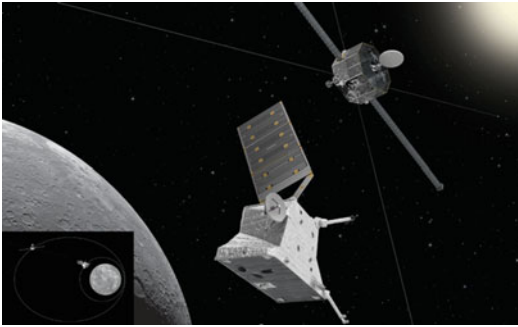
Mio contains five instruments or instrument suites: **MGF** (Magnetic Field Investigations) an instrument to provide a detailed description of Mercury's magnetosphere and of its interaction with the planetary magnetic field and the solar wind (Baumjohann et al. 2020), **MPPE** (Mercury Plasma Particle Experiment) to study low- and high-energetic particles in the magnetosphere with different sensors (Saito et al. 2021), **PWI** (Plasma Wave Investigation) to make a detailed analysis of the structure and dynamics of the magnetosphere (Kasaba et al. 2020), **MSASI** (Mercury Sodium Atmospheric Spectral Imager) to measure the abundance, distribution, and dynamics of sodium in Mercury's exosphere (Murakami et al. 2020), and **MDM** (Mercury Dust Monitor) to study the distribution of interplanetary dust in the orbit of Mercury (Kobayashi et al. 2020).

The name BepiColombo was given to the mission in honor of Professor Giuseppe (Bepi) Colombo (1920–1984) best known for his work on the planet Mercury. Colombo also explained Mercury's 3:2 spin-orbit resonance as a result of tidal forces of the Sun acting on Mercury, meaning that while Mercury orbits the Sun twice, it rotates around its own rotational axis exactly three times.

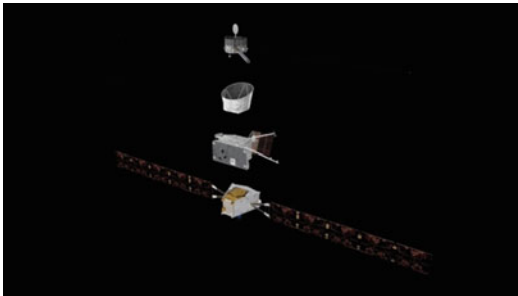
Overview

From dedicated orbits (Fig. 2), the two spacecraft will be studying Mercury, the planet and its environment. The mission will build on investigations done by the MESSENGER mission of NASA, which orbited Mercury for about 4 years from 2011 until 2015. BepiColombo will address a comprehensive set of scientific questions like:

- How has Mercury evolved and formed?
- Why is Mercury's density significantly higher than that of all other terrestrial planets?
- Is Mercury tectonically active today?
- Why does such a small planet possess a magnetic field?
- Is there any water or sulfur ice in the permanently shadowed craters at Mercury's polar regions?
- What are the production mechanisms of the exosphere?



BepiColombo, Fig. 2 Orbits of MPO and Mio. Both orbits are polar and elliptical with eccentricity and inclination optimized for the study of Mercury itself (MPO orbit: 480×1500 km) and its surrounding magnetospheric environment (Mio orbit: $590 \times 11,640$ km)



BepiColombo, Fig. 3 Exploded view of the BepiColombo spacecraft stack, which consists of four separate elements (ordered here from the bottom to the top of stack): (1) The Mercury Transfer Module, a ESA provided unit which carries an electric propulsion system to propel the stack to Mercury, (2) MPO led by ESA to study the planet surface and its interior, (3) the Sunshield and Interface Structure used to shield Mio during the cruise, and (4) Mio, the JAXA led Mercury Magnetospheric Orbiter to investigate Mercury's environment

•How does the magnetic field/magnetosphere interact with the solar wind?

•Can we take advantage of the proximity of the Sun to test general relativity with improved accuracy?and many more. In addition, it will provide information about Solar System evolution in general – not just about our own.

During its about 7-year long cruise phase to Mercury, the two science orbiter of BepiColombo, MPO and Mio, are carried by the ESA-built Mercury Transfer Module (Fig. 3). It contains the propulsion system and

will be jettisoned before the two orbiters entering their dedicated orbits at Mercury in late 2025 (Benkhoff et al. 2010, 2021).

Cross-References

- [ESA – European Space Agency](#)
- [JAXA](#)
- [Mercury](#)
- [MESSENGER](#)
- [NASA](#)
- [Planetary Evolution](#)
- [Solar System, Inner](#)
- [Space Weathering](#)
- [Terrestrial Planet](#)

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Bernal's Conception of Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Keywords

Clays · Catalysis

History

John Desmond Bernal was a pioneer of diffraction X-ray method. His interest for biology increased during the 1930s and the 1940s, probably in relation with the study of biological molecules (peptides, nucleic acids, etc.) with this new physical method.

His work on the origin of life was marked by his first publication on this topic in 1951: a little book entitled *The Physical Basis of Life*, which came from a previous lecture (1947) and from a paper published in 1949 in the *Proceedings of the Physical Society*.

In this text, Bernal gave a synthesis of previous theories, that is, Oparin's (1924, 1938), Haldane's (1929), or Dauvillier's (1947) ones. Such as he claimed that primitive atmosphere of earth contained CO₂, he described the possibility of a progressive production of organic molecules and finally of life.

His main and original assumption regarded problems of dispersion and catalysis. Indeed, Bernal claimed that fundamental reactions could exist on clay deposits, marine, and freshwater, which could insure confinement and catalysis.

During the 1950s and 1960s, he actively participated in the scientific debates on the origin of life and was very active in the diffusion of ideas on the origin of life.

Cross-References

- [Haldane's Conception of Origins of Life](#)
- [Oparin's Conception of Origins of Life](#)
- [Origin of Life](#)

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Bet Pic b

► [Beta Pictoris b](#)

Beta Electrons

► [Beta Rays](#)

Beta Pictoris b

Daniel Rouan¹ and Nader Haghighipour²

¹LESIA, Observatoire Paris-Site de Meudon, Meudon, France

²Institute for Astronomy, University of Hawaii, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[Bet Pic b](#)

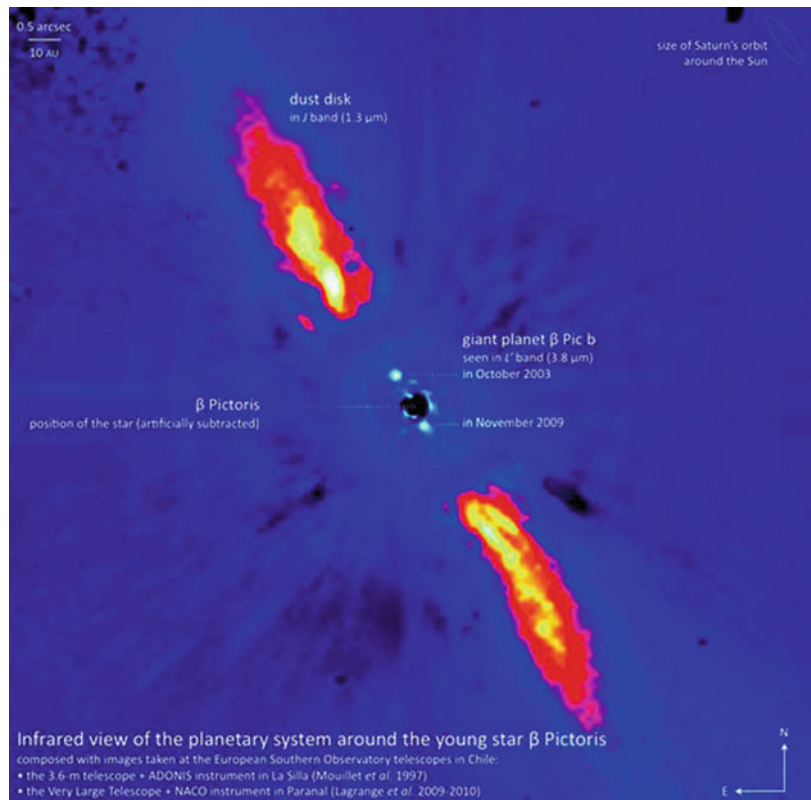
Beta Pictoris b,

Fig. 1 Beta pictoris

Definition

Beta Pictoris b is a massive exoplanet directly detected around the A-star Beta Pic, on an orbit with a semimajor axis between 8 and 11 astronomical units. This is the smallest orbital distance known so far among the small set of exoplanets observed by direct imaging. The star which is at a distance of 20 pc (60 light years) is one of the best-known examples of a star surrounded by a dusty ► [debris disk](#). The disk was the first to be imaged and is now known to extend up to about 1,000 AU. The planet has a mass of about 9 Jupiter masses. It features the right mass and location to explain the observed warp in the inner parts of the disk (Fig. 1).

A team led by A.M. Lagrange used the NAOS-CONICA instrument, an ► [adaptive optics](#) corrected near-infrared imaging system mounted on one of the 8.2 m Unit Telescopes of ESO's Very Large Telescope (► [VLT](#)), to observe Beta Pic once in 2003 and then several times after 2008. On 2003 images, a faint source inside the



disk was seen, but it was not considered as a planet as it could have been a background star. On the images taken in 2008 and spring 2009, the source had disappeared, while in the observations taken during autumn 2009, and later, the object appeared on the other side of the disk after a time fully consistent with the object being an exoplanet orbiting its host star. The size of the orbit was also consistent with this hypothesis. Since then, the spectral energy distribution in the infrared was obtained which showed the planetary parameters to be fully consistent with the first evaluation of the orbit and mass (and pointed to a dusty planetary atmosphere at 1,700 K).

Because the host star is young (12 million years old), this discovery is considered as a strong indication that ► [gas giant planets](#) can form within protoplanetary disks in only a few million years, a short time compared, for instance, to the age of the solar system (4.5 Gyr).

The monitoring of the position of the planet was continuously done until today (2021) and for instance there has been an intense campaign in 2017 since the orbital analysis by Wang et al. (2016) showed that the star could pass within 10 to 20% of the radius of the Hill sphere of β Pic b, but nothing was detected. A second planet, Beta Pictoris c, was detected through radial velocity monitoring of the star (Lagrange et al. 2019) and confirmed thanks to observations with GRAVITY (Nowak et al. 2020; Lagrange et al. 2020). It orbits the star at a distance of 2.7 UA and its mass could be of 9 M.

Cross-References

- [Adaptive Optics](#)
- [Astrometric Orbit](#)
- [Astrometric Planets](#)
- [Debris Disk](#)
- [Direct-Imaging, Planets](#)
- [Exoplanets, Discovery](#)
- [Gas Giant Planet](#)
- [VLT](#)

Beta Rays

Jun-ichi Takahashi

Faculty of Engineering, Yokohama National University, Yokohama, Japan

Keywords

Beta decay · Chirality · Radioactive particles · Weak interaction

Synonyms

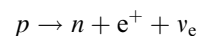
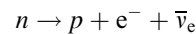
[Beta electrons](#)

Definition

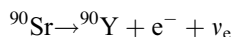
A beta ray is a stream of beta particles (electrons or positrons). In nuclear physics, beta decay is a type of radioactive decay in which a beta particle is emitted.

Overview

In the case of electron emission, the decay is referred to as beta minus (β^-), while in the case of a positron emission as beta plus (β^+). In beta minus decay, a neutron is converted to a proton, an electron, and an antineutrino; in beta plus decay, a proton is converted to a neutron, a positron, and a neutrino:



If the proton and neutron are part of an atomic nucleus, these decay processes transmute one chemical element into another. Beta decay does not change the number of nucleons in the nucleus but changes only its charge. For example:



The kinetic energy of beta particles has a continuous spectrum ranging from 0 to maximal available energy, which depends on parent and daughter nuclear states participating in the decay. A typical maximal available energy is around 1 MeV, but it can range from a few keV to a few tens of MeV. The most energetic beta particles are ultra-relativistic, with speeds very close to the speed of light.

The spin of the electrons or positrons in beta rays is longitudinally polarized due to parity non-conservation in the weak interaction mediated by charged W particles. The helicity of a beta electron, that is, the spin angular momentum component of the kinetic momentum direction, is negative (left-handed), and that of a beta positron is positive (right-handed).

In the standpoint of astrobiology, one of the hypotheses for the origin of biomolecular chirality, the so-called cosmic scenario, states that asymmetric energy sources in space-induced asymmetric chemical reactions of precursors in interstellar dust, resulting in the enantiomeric excess of terrestrial bioorganic compounds. It has been proposed that beta rays are one of the candidates for the source of such asymmetric chemical reactions, which might lead to the origin of biomolecular chirality in terrestrial organic compounds.

Cross-References

- [Alpha Rays](#)
- [Asymmetric Reaction, Absolute](#)
- [Enantiomeric Excess](#)
- [Gamma Rays](#)
- [Homochirality](#)

BIF

- [Banded Iron Formation](#)

Big Bang Nucleosynthesis

Alain Coc

IJCLab (Laboratoire Irène Joliot-Curie),
Université Paris-Saclay, Orsay, France

Keywords

Big bang · Nucleosynthesis · Helium ·
Deuterium · Lithium

Synonyms

BBN; [Primordial nucleosynthesis](#)

Definition

The nucleosynthetic process that took place within the first 20 min after the big bang is called big bang nucleosynthesis (BBN) or primordial nucleosynthesis. At this early epoch, the Universe was dense and hot enough to allow for nuclear reactions to take place, producing the “light elements,” ^4He , ^2H ($\equiv \text{D}$, i.e., deuterium), ^3He , and ^7Li , starting from neutrons and protons. The comparison between the primordial abundances of these isotopes deduced on one hand from observations and on the other hand from model calculations is one of the main support of the big bang model.

History

Prominent landmarks in the development of the big bang nucleosynthesis theory include works by Gamow in the 1940s (out of equilibrium nucleosynthesis in an expanding Universe dominated by radiation), Peebles in 1966 (big bang nucleosynthesis calculations up to ^4He), and Wagoner in 1973 (big bang nucleosynthesis calculations including ^7Li).

Overview

The big bang model is supported by three pieces of observational evidence: the expansion of the

Universe, the cosmic background radiation, and the primordial or big bang nucleosynthesis (BBN). Standard BBN is now a parameter-free model. The nuclear cross-sections and neutron lifetime, together with the number of neutrino families, have all been measured in the laboratory. The baryonic density of the Universe has been deduced from the observations of the anisotropies of the cosmic microwave background radiation (Aghanim et al. 2020). In the framework of an expanding Universe, with uniform temperature and density, decreasing with time, a temperature of 10^{11} K is reached a fraction of a second after the big bang. According to our present knowledge, the only particles present in the Universe at this time were photons, electrons, and positrons; the three families of neutrinos and antineutrinos, all in equivalent numbers; and a tiny fraction of neutrons and protons. Weak reactions (with electrons and neutrinos) maintained an equilibrium between the number of protons and neutrons until the Universe cooled down to $\approx 3 \times 10^9$ K. This occurred because the speed of weak force reactions became slower than the rate of space expansion. Consequently, the ratio of the number of neutrons to protons became frozen, except for free neutron decay. When the temperature dropped to $\approx 10^9$ K, the fusion of a proton and a neutron leading to a deuterium nucleus became favored compared to deuterium dissociation by high-energy photons. This was the starting point of primordial nucleosynthesis that stopped, after ≈ 20 min, with the formation of ${}^7\text{Li}$. This was caused by the decrease of density and temperature and lower nuclear cross-sections beyond mass seven (Coc et al. 2012). Hence, only the ${}^4\text{He}$, D, ${}^3\text{He}$, and ${}^7\text{Li}$ isotopes are significantly produced in standard BBN, involving a dozen main nuclear reactions. Despite the fact that the primordial abundances of these light isotopes span nine orders of magnitudes, the agreement between calculations (Pitrou et al. 2018; Fields et al. 2020; Mossa et al. 2020) and observations (Aver et al. 2015; Cooke et al. 2018; Bania et al. 2002; Sbordone et al. 2010) is good with the exception of ${}^7\text{Li}$ (but within a factor of ≈ 3). According to models, the big bang nucleosynthesis contributions to the solar system abundances, which

amount to $\approx 90\%$ for ${}^4\text{He}$, are uncertain for ${}^7\text{Li}$ and ${}^3\text{He}$ but are remarkably the only source of present-day deuterium.

Heavier elements, the building blocks of planets, are not significantly produced by BBN. For instance, the BBN production of carbon, nitrogen, and oxygen amounts to a total of $\approx 10^{-15}$ in the number of atoms relative to hydrogen (Coc et al. 2014).

Since all the parameters of the standard BBN model have now been measured, its abundance predictions reach the percent-level precision, at match with the precision on light element abundances deduced from observations. Hence, it can now be used as a probe of nonstandard physics in the early Universe (Iocco et al. 2009). However, the origin of the *cosmological lithium problem* (the factor of ≈ 3 difference between the ${}^7\text{Li}$ predictions and observations) is still a matter of debate (Fields 2011).

Cross-References

► Cosmic Background Radiation

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Bimolecular Reaction

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Two-body reaction](#)

Definition

A bimolecular reaction is a chemical process involving two reactants. Reactants may be electrons or

atoms and molecules existing in various combinations of charge states (neutral, anionic, or cationic). The most important reactant combinations for interstellar chemistry are ion-neutral, neutral-neutral, anion-neutral, electron-neutral, and electron-ion.

Cross-References

- [Anion](#)
- [Interstellar Chemical Processes](#)

Binary Stars, Young

Steven W. Stahlner

Department of Astronomy, University of California, Berkeley, CA, USA

Keywords

Star formation

Definition

Most stars are not isolated objects, but have an orbiting companion. This basic fact holds not only for mature stars but also for objects at an earlier stage of evolution. Indeed, several young star clusters have a higher fraction of binaries than do main-sequence stars generally. Young binaries exhibit a very broad range in separations and therefore orbital periods. In the widest pairs, the orbits are highly eccentric. Conversely, the tightest pairs are locked into circular orbits. Planet-forming disks are absent in these latter systems, apparently because of the disturbing influence of the companion.

Overview

Astronomers have long known that most stars have binary partners, that is, companions locked gravitationally into orbit. About 60% of solar-type, main-sequence stars have at least one such companion. The vast majority of these

multiple systems are binaries, but triples and even quadruples also exist. Binarity is also common for stars of other spectral types.

Some binary companions are so close together that one can detect the induced wobble in the stars' motion, through a periodic Doppler shift in the wavelength of spectral lines. Such spectroscopic binaries are relatively rare. Most systems are discovered because the two stars share a common spatial motion. This implies that their pairing is physical and not a chance superposition. Overall, the observed range of periods is vast, from less than a day to millions of years, corresponding to separations from 0.01 to 10,000 AU.

The fact that most mature stars have companions naturally leads us to wonder if this situation held further back in time. Are ► [pre-main-sequence stars](#), those too young to fuse hydrogen into helium, also preferentially found in binaries? What about even younger objects, those still gathering mass from their parent molecular clouds? Since the 1980s, many researchers have investigated the matter, and the answer is now clear. Pre-main-sequence stars are also very likely to have a binary companion. Indeed, the binary fraction in some young clusters is even greater than for main-sequence stars in the field.

The systems being found show a wide range in orbital separations. Some are tight enough to be detected as spectroscopic binaries. Most young binaries, however, are noticed because they exhibit a common spatial velocity within their parent stellar group. On the whole, pre-main-sequence binaries span a wide range of separations and periods, just as do main-sequence systems.

Many individual pre-main-sequence stars have planet-forming disks, as evidenced by their excess infrared and millimeter emission. The same is true for stars within binaries, but with a significant caveat: if the binary separation is less than about 100 AU, corresponding to a period of about 1000 years, then the excess emission is absent. Apparently, the relatively nearby companion star prevents formation of any circumstellar disk. For periods as low as a few days, the primary and its companion are locked into perfectly circular orbits.

Cross-References

► [Pre-Main-Sequence Star](#)

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Binding Constant

► [Affinity Constant](#)

Binding Energy

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Binding energy is the energy required to disassemble an entity into its constituent parts. This corresponds to the mechanical work which must be done in acting against the forces which hold the entity together. The binding energy of an atom is that required to disassemble an atom into free electrons and a nucleus, acting against the electromagnetic force. The nuclear binding energy is that required to disassemble a nucleus into its constituent neutrons and protons, acting against the strong nuclear force. The term is also used in other contexts, for example, for the

energy involved in attaching a gaseous molecule to an ► [interstellar dust](#) grain upon collision. In this case, the magnitude depends on both the physical nature of the molecule (e.g., polarizability) and of the grain surface. Binding energies for ► [physisorption](#) (through van der Waals bonding) are generally much lower than those of ► [chemisorption](#).

Cross-References

- [Chemisorption](#)
- [Interstellar Dust](#)
- [Physisorption](#)

Bioastronomy

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Definition

In current usage, bioastronomy is both a synonym for astrobiology (although the term was introduced before NASA coined “astrobiology”) and the title of the former Commission 51 of the International Astronomical Union (► [IAU](#)). IAU Commission 51 was established in 1982 as “Bioastronomy: Search for Extraterrestrial Life” was renamed simply “Bioastronomy” in 2006 and renamed again “Astrobiology” in 2015. From an early concentration on ► [SETI](#), the IAU Commission now defines its field of study to be the origin, evolution, and distribution of life in the universe (for more details, see the entry “Astrobiology (IAU Commission).”

Cross-References

- [Astrobiology](#)
- [Astrobiology \(IAU Commission\)](#)
- [IAU](#)
- [SETI](#)

Biobarrier

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In ► [planetary protection](#), a biobarrier is a mechanical barrier that protects clean elements of the spacecraft from contamination by other areas of the spacecraft that are less clean and/or an unclean local environment. Biobarriers may be hermetic, preventing fluid transfer as well as particulates and microbial contamination, or semi-permeable, allowing gases/vapors/liquids to pass (often important in, e.g., rocket launches to the vacuum of space) while preventing passage of microorganisms.

Cross-References

- [Planetary Protection](#)

Biobloc

- [Biostack](#)

Bioburden

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In planetary protection, the bioburden is the estimated total viable organisms on or in the spacecraft. The bioburden is managed by sterilization and cleanliness processes applied to the spacecraft

hardware, and characterized or enumerated by microbial assays.

Cross-References

- ▶ [Assay](#)
- ▶ [Planetary Protection](#)
- ▶ [Sterilization](#)

Bioburden Controlled Environment

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In planetary protection, a bioburden-controlled environment is an environment where the number of viable microorganisms, and therefore the potential for microbial contamination of space-flight hardware, is controlled or minimized. This includes clean rooms, laminar flow hoods or cabinets, and other temporary or permanent environments where the quantity of microorganisms and/or particulates is monitored and maintained below a specified level. Other characteristics of bioburden-controlled environments are the access controls on people and materials, and the use of clean room garments by operators in the bioburden-controlled environment, to prevent degradation of the cleanliness of the environment.

Cross-References

- ▶ [Assay](#)
- ▶ [Bioburden](#)
- ▶ [Planetary Protection](#)
- ▶ [Sterilization](#)

Bioburden Reduction

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

Bioburden reduction is the name given to processes designed to remove or destroy ▶ [microorganisms](#) that are performed in order to reduce ▶ [bioburden](#) levels on or in a hardware item of interest. Processes could involve cleaning and wiping with appropriate alcohols or other chemical solutions, dry heat microbial reduction (▶ [DHMR](#)), ultraviolet or γ -ray irradiation, or treatment with a gaseous sterilant.

Cross-References

- ▶ [Bioburden](#)
- ▶ [Planetary Protection](#)
- ▶ [Sterilization](#)

Biodetection System

- ▶ [Biosensor](#)

Biodiversity

Simon Tillier and Guillaume Lecointre
Département Systématique et Evolution, UMR
7138 CNRS-MNHN-UPMC-IRD, Muséum
National d'Histoire Naturelle, Paris, France

Keywords

Ecology · Ecosystem services · Environment ·
Evolution · Systematics · Taxonomy

Synonyms

[Diversity of life](#)

Definition

Biodiversity designates the condition of life on Earth in terms of its variation at all levels of biological organization, from genes to ► [ecosystems](#). By extension, it is used to designate life on Earth itself, most generally at the ► [species](#) level but often also at all organization levels altogether. The political impact of the term led to a definition adopted by the International Convention on Biological Diversity (Art.2): “Biological diversity” means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” (Convention on Biological Diversity [1992](#)).

History

Although first introduced in the end of the 1960s, the word biodiversity, as a contraction of biological diversity, has been coined by Walter G. Rosen while preparing a national US scientific forum held in Washington in 1986. The objective of this forum was to discuss the importance of the quality and variety of living organisms in relation with the threats constituted by ► [environment](#) degradation, species extinction, and potential losses of socioeconomic benefits (Wilson [1988](#)). In parallel, the convergence of interest from the scientific community, from the nature conservation organizations, and from the southern countries, who want to control the economic benefit from their living resources, led the United Nations Environment Programme (UNEP) to explore the need for an international convention on biological diversity. This approach led to an international legal instrument for the conservation and sustainable use of biological diversity: the Convention on Biological Diversity was opened for signature on June 5, 1992, at the United Nations Conference on Environment and Development, better known as the Rio “Earth Summit,” and was adopted by 168 countries within the next year. In terms of

scientific organization and programming, an international research program on biodiversity, named *Diversitas*, was established in 1991 jointly by UNESCO, SCOPE (Scientific Committee on Problems of the Environment or the International Council of Scientific Unions), and the IUBS (International Union of Biological Sciences) to “promote an integrative biodiversity science, linking biological, ecological and social disciplines in an effort to produce socially relevant new knowledge; and provide the scientific basis for the conservation and sustainable use of biodiversity.” Ten years after Rio, the second Earth Summit held in Johannesburg in 2002 set the so-called 2010 target: “to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on Earth.” Clearly the target has not been met, in the absence of instruments of measure as well as of effective policies.

However, the conjunction of scientific interest and social pressures has modified how ecologists, taxonomists, population geneticists, paleontologists, and social scientists of environment situate their own disciplines, toward an integrated vision where most see themselves as contributors to biodiversity research.

Overview

Biodiversity science is above all integrative. The central problem of biodiversity research is to understand how diversity of life, that is, the variation in quality *and* quantities of living things at any scale, relates to the functioning and evolution of ecosystems including the human populations and societies. In consequence, all population-level research may be relevant at any scale, from any local group of living organisms to all past, present, and future life. Taxonomists (or systematists, including paleontologists) explore and describe the patterns of biodiversity, present and past, proposing scenarios illustrating “how” – in terms of a suite of inferred historical events – biodiversity reached its present state at

the largest scales. Evolutionary biologists aim at understanding “how” – in terms of biological processes – biodiversity reached its present state at genetic and population levels. Ecologists explore the patterns of species interactions in ecosystems and the mechanisms of ecosystem functioning; and social scientists explore the relationships between human populations and societies and nonhuman biodiversity. Focus on socioeconomic benefits, which were already encompassed by the initial thoughts in the 1980s, has brought emphasis of the concept of ecosystem services, that is, the part of the ecosystem functions and products that is used by our species.

We understood as late as in the 1980s that the number of living species is probably tenfold the previous estimates, in the 10–40 million living species range, rather than 1–2 million (Erwin 1982 and subsequent papers). In parallel, it has become progressively evident that unprecedented losses and changes in biological diversity are taking place at the genetic, species, and ecosystem levels, particularly in nonmarine groups of organisms so far. Comparison with major extinction crises in the geological history of the Earth reveals that the current rate of extinction is at least in the same order of magnitude and several hundred times greater than the average between crises (Dirzo and Raven 2003). The present extinction crisis does not strike us because it is not catastrophic at the scale of the human lifespan, but rather in a time span of several millennia, which we do not perceive directly but is still a very short instant in the more than 3.5 billion year-long history of life on Earth. This crisis, sometimes referred to as the Sixth Extinction, is likely the direct result of human activities.

Understanding the patterns and processes of biodiversity loss and change is crucial for our species, not only because of the aesthetic, ethical, or cultural values attached to biodiversity but also because it could have numerous far-reaching consequences for our own life-support system. Even the chemical composition of the air we breathe and of seawater depends upon biological activity well beyond the increase of carbon dioxide in the

atmosphere and of acidity in the seawater, which results directly from human activities.

One of the likely consequences of man-induced changes in the environment is the reduction in the capacity of natural and managed ecosystems to deliver ecological services, such as the production of food and fiber, carbon storage, nutrient cycling and resistance to climate, and other environmental changes. Assessing the causes and consequences of biodiversity changes and establishing the bases for the conservation and sustainable use of biodiversity are major scientific challenges of our time. The major questions that research is facing are summarized in the *Diversitas* research program (Diversitas 2002, 2010).

How Did Biodiversity Evolve in Space and Time to Reach the Current State?

There are two kinds of sciences answering the “how” questions. The first one is focusing on the biological processes by which living matter diversifies its forms (see the entry *Evolution* (biological)). The way these scientists demonstrate their statements is close to that of chemistry or physics. By manipulating populations of organisms with very short generation times, it is possible to develop a hypothetico-deductive experimental approach to these “how” questions: population genetics is of first importance in the field. But there are also other experimental sciences like causal embryology or physiology that participate to the understanding of this “how,” though without any population approach.

The second approach is the historical “how.” A set of sciences like descriptive and comparative embryology and anatomy, paleontology, and systematics participate in a historical interpretation of how life arrived to its present state. The present distribution of organisms is explained by a suite or series of events, not necessarily linked to each other by causal relations. ► **Phylogeny** provides part of the information needed for the ordering of events through time. Other data, paleontological, stratigraphical, geological, etc., also participate in our knowledge of the history of biodiversity. The answer to the historical “how” has made decisive

progress in the last two decades through the association of the phylogenetic method introduced by Willi Hennig (Hennig 1966) with informatics and use of DNA sequences: phyloinformatics now allows processing large data sets, whether molecular or morpho-anatomical. Thanks to phylogenetic methods applied to molecular characters, our vision of the tree of life has been radically modified within the last 25 years and is still evolving. Within 25 years, our vision of the tree of life has shifted from five “kingdoms” to three main branches or clades, of which two are bacteria domains diverging from each other just as much as from ours, the eukaryotes (the organisms constituted by one to many cells with a nucleus). Convincing evidence has been brought to explain the origin of eukaryotes by multiple bacterial endosymbioses: our own cells, their mitochondria, and plasmids originate indeed from as many bacterial lineages. It is now admitted that lateral ► **gene** transfer (i.e., gene transmission between two otherwise independent lineages) is a relatively frequent phenomenon at least in bacteria and may well influence significantly their evolution.

At the ecosystem level, “how” is also a question from both points of view: from an ecological processes point of view, not only chance, that is, the initial conditions, but also species interactions doubtless shape the local communities in time, even though we are hardly able to understand and even less to predict the change when more than very few species interact. The historical “how” may be easier to grasp, thanks to both paleontological observations and, possibly, by combining the phylogeny of the species composing a community with the composition of the latter through time. An objective is to relate ecosystem change with causal factors such as climate change, entry of a clade into a new region, or the origin of innovations in a clade.

How Much Biodiversity Exists and How Does Its Change or Loss Affect the System as a Whole?

A prerequisite to the “how” is the “what,” that is, documenting biodiversity. Understanding how

little we know about the existing species implies that traditional methods and techniques are inappropriate, and new strategies are developed to increase the efficiency of field sampling, the quality and accessibility of collections for fieldwork, the collection and curation of voucher specimens, the technologies for imaging and DNA sequencing, the digitization of legacy data, and the development, maintenance, and connectivity of relevant databases. The need for rapid-capture technologies for identifying known species and discovering new ones has led to the development of the “Barcode of Life” initiative, which aims at providing IT tools for identifying species through short DNA sequences obtained from specimens identified by an expert and kept in legacy collections (Consortium Barcode of Life 2010; Golding et al. 2009). The need for access to the information on species occurrences and on the collections, which may well soon include the only remaining specimens of many species in view of the current rate of extinctions, has led to the constitution of the so-called GBIF (Global Biodiversity Information Facility 2010; Edwards et al. 2000), which is an international informatics infrastructure that allows the interoperability of the innumerable databases on collection specimens and species occurrences worldwide.

A serious problem for assessing species diversity is the uneven distribution of expertise among taxa and countries: groups of very high diversity and ecological importance, such as nematode worms, acarians, most insects, or microbes, in general, are notoriously understudied and very poorly known, whereas groups that are closer to us in terms of body organization, size, and appeal to imagination may even have more specialists than species, as is the case of birds or elephants. In parallel, expertise is located mainly in Western developed countries, principally in Europe and North America, whereas most megadiverse tropical countries have very few specialists and insufficient research infrastructures: biodiversity is in the South but expertise and infrastructures are in the North.

For their own biodiversity assessments and in response to the environmental concerns, which

are at the origin of environmental regulations, rich countries have developed observation networks that are feeding large observational databases, managing billions of observational data. These databases provide the basic tool for the application of environmental regulations regarding species and habitats but also constitute a tool for research when standardized and made interoperable, *inter alia*, thanks to the GBIF. Their weakness is that they necessarily concentrate on taxa for which there are a number of observers, that is, principally higher plants and vertebrates. However, when enough data have been collected in the medium and long term, it has been possible to show such phenomena as the decline of populations of common birds in Europe or the shift in distribution toward the north of bird and plant species as a consequence of global warming. In the domain of fisheries, fishing data collected since the end of the nineteenth century have allowed us to show that overfishing started at least more than one century ago, leading to constant diminution of tonnage and size of the fish at the world level and unpredictable consequences over the food web and equilibrium of the global ocean.

However, assessing is not enough in both scientific and societal terms: we want to be able to predict the change, for scientific reasons as well as for decision making in environmental policy. The solution lies in modeling, operationally based so far upon statistics on species distribution in terms of environmental parameters. This approach, called niche modeling, allows one to calculate an ecological envelope that can be projected on a map to delimit species' potential distribution in space. It is then easy to modify some environmental parameters, including climatic ones, to predict the consequences of changes on species occurrences and, to some extent, on the composition of communities. This approach has proved very powerful to define policies and strategies regarding invasive pest species in Mexico or the design of protected areas; but it is somewhat rudimentary by not taking into account ecological structures and processes, nor metapopulation dynamics, habitat fragmentation, etc. The ultimate goal is not just to understand but to predict biodiversity change, developing biodiversity scenarios that

predict biodiversity change at the landscape, regional, and global scales in response to various scenarios of how anthropogenic drivers will change in the future.

How Does Biodiversity Correspond to the Delivery of Ecosystem Functions and Services and What Is the True Value of These Commodities?

Over two decades of research in ecology have shown that the combination of abiotic (physical and chemical) factors together with biological interactions determines the limit of biodiversity in a community and that the composition of this community influences, in turn, the way it functions. A large number of experiments since the beginning of the 1990s have confirmed that generally the increase in biodiversity has a positive effect on ecosystem functioning.

Three mechanisms have been proposed to explain this positive effect. The first is a simple sampling effect: species-rich ecosystems would produce more biomass, simply because the probability for including a highly productive species is higher as the number of species is increased. The second is the functional complementarity of species resulting from a favorable pattern of traits in the community: by increasing diversity, one increases the number of effective ecological functions as more ecological niches are exploited. For example, two plant species having different root lengths extending down to the ground will better exploit resources in the soil and then produce more biomass together, than a single of them. Finally, interaction of two species, then called facilitation, may have a positive effect on production: for example, brambles in a meadow may create favorable conditions for smaller species that need moisture and shade, such as arum lilies, and doing so favors the increase in productivity of the system.

These mechanisms may be effective at any time and space scale, from bacteria and fungi in a piece of cheese to the entire tropical forests and oceans. However, for practical reasons, most experiments have been based on plant communities, including the two best known, the European BIODEPTH and the American Cedar Creek

experiments, which both have shown a positive effect of diversity upon biomass accumulation in the communities.

The relationship between diversity and stability of ecological communities has also been studied, showing at least theoretically that some species may have a key role for the persistence of the community when facing environmental disruption: roughly, having more species increases the chance of having at least one or a few able to develop under modified conditions and in so doing allow persistence of the community. Few experiments have tested this conclusion, but these few confirm so far the theoretical prediction of a relation between diversity and stability of ecosystem functioning.

However, most experiments neglect the trophic relationships between species, which we know are very complex in species-rich ecosystems, from predation and parasitism to mutual dependence such as in pollination processes. A starting point may be the top-down effect, through which a predator controls the density of prey, which themselves control production at lower trophic levels. Diminution in density at the top levels may allow an indirect increase in production at the lowest levels; but it may also have just the opposite effect when top levels participate significantly in nutrient recycling, which itself increases productivity: this may well be what happens as mankind clearly exploits and overexploits large predators.

Overall, we know now that diversity favors ecosystem resilience and biomass production. It is also suspected that diversity favors diversity. An illustration of this is, for example, the recent discovery of very high levels of horizontal or lateral transfers of DNA in microbial communities, in a way that genomes exhibit functional-environmental patterns as well as historical patterns. Horizontal heritage is far more important than previously thought, compared to “classical” vertical heritage. These networks of permanent DNA exchanges among a diversity of microbial “species” in a given environment (either marine, lacustrine, or terrestrial) stabilize the role played by these environmental communities in the biosphere. Generally speaking, the question of positive feedback of diversity is fundamental in

view of the present changes in ecosystems and still requires further research at various levels of ecosystem organization. If it is true, human activities endanger self-regulation of ecosystems, of which many are at risk of collapsing with unavoidably serious risk for our own species.

How Can Scientific Investigation Support Policy and Decision Making to Encourage More Sustainable Use of Biodiversity?

In view of the societal needs for a better understanding of the functions of biodiversity for human beings (and well-being where possible), communicating scientific results to relevant political levels is crucial. Researchers are trained in research and communication with other researchers, but not in communication toward decision makers, which results in numerous misunderstandings. This renders the formation of an ad hoc mechanism a necessity. Based on the example of the IPCC (Intergovernmental Panel on Climate Change), the United Nations and the G8 have endorsed in 2010 the creation of such a mechanism, called the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2010; Larigauderie and Mooney 2010) as initially proposed by France in 2005. The IPBES progresses at an intergovernmental pace, which is slower than species extinctions and ecosystem change, but will hopefully allow progress in the implementation of the necessary policies.

Key Research Findings

Since the beginning of the 1980s, a few points have been understood:

- First is a revolution in our vision of the tree of life and of the origin and diversification of eukaryotes. All eukaryotes are no more nor less than each of the two main “prokaryotic” clades (Bacteria and Archaea), fungi and animals now appear as originating from a common ancestor not shared with other groups, and humans are nothing more than the tip of a tiny twig among all mammals, which occupy

nothing more than a small branch of the small clade constituted by all animals in the tree of life.

- Next is the change of paradigm in both taxonomy and ecology: we now know that we know nothing about most living species and that the way we interact with biodiversity is not sustainable for the present ecosystems at any level, whether marine or land based.
- The whole biosphere is changing at all levels, possibly faster than ever, and surely through a process without precedent, which is provoked by our species: destruction of whole ecosystems and modification of others through anthropic activities including transport of species are realities that we have to face.
- In scientific terms, we understand better how biodiversity acts in the functioning of the whole ecosystems: biodiversity favors both production and stability of ecosystems and likely has a positive feedback on diversity itself.

Future Directions

On the purely scientific point of view, the main future direction to maintain our understanding of biodiversity is to keep all contributing sciences visible at the political level. The study of biodiversity is not merely a matter of counting the species that are found in a given area or proposing models predicting responses of ecosystems to anthropic perturbations. The future in studies and understanding of biodiversity must keep systematics and evolutionary biology as central disciplines along with inventories and ecological modeling.

Systematics is important in understanding the reasons why we classify living and fossil organisms as we do. Systematics provides the reason why the platypus is classified well apart among mammals. Phylogenetic systematics explains why the collection of traits exhibited by the platypus is so unique. If a decision has to be made concerning the preservation of the platypus, the ecological role of the platypus is going to have a negligible

weight compared to the argument from systematics. The platypus (or the coelacanth, choose the one you prefer) is negligible in terms of biomass, and its role in its environment could be replaced by another imported species. In terms of what organisms do in their environment, the platypus (or the coelacanth) can perfectly well be sacrificed. By contrast, phylogenetic systematics will provide the arguments to regard this species as a very important one. Phylogeny will show that the platypus is the product of a very ancient mammal lineage represented today by three species only. The characters exhibited by the platypus show this: it lays eggs and it has a bizarre anatomy of the temporal area. In parallel, the lineage gained characters on its own branch, such as a duck-like beak or venomous fangs on the posterior limbs. The combination of the whole set of properties makes the platypus a kind of unique evolutionary heritage – a rare combination of characters. Protecting species should therefore be considered in terms of what they *have* (systematics), not only through what they *do* (ecology).

Evolutionary biology is also important because we cannot pretend to understand and properly protect biodiversity without having a deep knowledge of the processes that generate biological diversity at all levels. This is going to be important because it is not sufficient to save the present state of nature as if it would not be going to change again. Life is continuously changing. It is important to protect the potential ability to get adapted to new conditions, so maintaining genetic variability and our knowledge about processes that generate it (and select it afterward) is of key importance.

The second relevant direction for our knowledge and action is to consider human societies and their products as parts of biodiversity. There is a philosophical tradition that keeps humankind separated from an undefined nonhuman “nature” or an undefined category of “animal” and that keeps culture separated from nature. In contrast, we are not only trying to change the world to save the diversity of this wonderful life but also to save the cultural-material heritage for the few next human generations.

Although the economics of biodiversity is a rapidly expanding field, and understanding the relationship between biodiversity and ecosystem functioning is still seen as a research priority, for practical reasons focus is presently made on observations and monitoring. Not only scientists but also all kinds of decision and policy makers need reliable information on what is happening and projections of what may happen, both locally and globally. Decreases of coral reefs and more generally ecological consequences of acidification of the oceans, changes in the composition of the atmosphere, invasion of exotic species, changes in the species distribution resulting from climate warming and transportation by humans, and destruction of habitats under anthropogenic pressures are all happening and hardly evaluated due to the lack of appropriate instruments. This observation calls for at least two lines for action from the scientific community:

- The first one is improving our capacity for the analysis and prediction of the change in biodiversity. Operational models based upon niche modeling that are already in use to assist decisions should be developed further. The predictive value of models could doubtless still be improved by incorporation of ecosystem functional parameters, as ambited by many ecologists; however, this development is impeded so far by the weakness of the concepts relating to ecosystem functions, which still requires a qualitative jump forward.
- Complementary and necessary for development of modeling is documenting what occurs and what happens, because without reliable data we may hardly hope to understand what is happening globally. Even local predictions require global data sets because, like in meteorology, operational modeling is based upon statistical approaches of which precision and reliability are in proportion to the amount of observations available. This need for data and monitoring is taken into account by the projected construction of the Global Earth Observation Biodiversity Observation Network (GEO BON), which is a

program for the coordination of observations on biodiversity promoted by Diversitas. GEO BON is a component of the Global Earth Observation System of Systems (GEOSS), an initiative led by the World Meteorological Organization (Scholes et al. 2008).

Clearly, biodiversity research is shifting from traditional fundamental questions on what is there, why it is there, and how it works to questions relating directly to societal concerns guided by the central question of where mankind is going in a context of radical ecological change at the global scale. So far, this shift is beneficial rather than detrimental to fundamental research; and indeed the questions raised by society regarding its own future as a constituent of biodiversity will not find their answers if progress is not going on in fundamental ecology, systematics, and evolutionary biology.

To conclude on a positive note, we are right to be concerned by the ongoing Sixth Extinction. However, life has to be considered in the very long term. The Sixth Extinction is a problem of our responsibility for the next 2 to some 200 human generations, but it is not a problem for life itself. Several drastic extinctions have taken place in the past million years; there will be others. Our theoretical framework allows us to predict that biodiversity will be recovered, as rich as ever or more, and life and Earth will continue to change together as time will continue going by.

Cross-References

- [Adaptation](#)
- [Domain \(Taxonomy\)](#)
- [Ecosystem](#)
- [Environment](#)
- [Evolution, Biological](#)
- [Gene](#)
- [Genome](#)
- [Lateral Gene Transfer](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Species](#)

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Biodiversity (Planetary Protection)

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

For ► [planetary protection](#), the biological diversity (biodiversity) in an environment is the inventory of types of ► [microorganisms](#) identified as being present. For microorganisms, the

identification depends also on the sensitivity and specificity of the ► [assay](#) which is used. For example, to prepare future missions to ► [Mars](#), space agencies are conducting studies in the clean rooms used for spacecraft assembly to establish the biodiversity of the spacecraft being built there.

Cross-References

- [Assay](#)
- [Planetary Protection](#)
- [Sterilization](#)

Bioenergetics

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Active transport · ATP · ATP synthesis · ATPase · Chemical energy · Electrical potential · Enthalpy · Entropy · Energy · Osmotic work · Photosynthesis · Proton motive force · Radiation · Respiration

Definition

Bioenergetics is the part of biochemistry dealing with ► [energy](#) flow through living systems. Life is dependent on energy transformation reactions. The ability to harness energy from a variety of metabolic pathways is a property of all living organisms.

Overview

Life and Energy

Life implies work. All life systems perform work: chemical work is needed for the synthesis of macromolecules, osmotic work is required for the maintenance of cellular concentrations, and

electrical work is necessary for the generation of ► **proton motive force**. Energy is the capacity to do work. Until the principle of the conservation of energy, the first law of thermodynamics, was enunciated in the middle of the nineteenth century, progress in bioenergetics was extremely slow.

The second law of thermodynamics establishes that in an isolated system, entropy (a measure of molecular disorder) can never decrease. The second law was enunciated for inanimate matter; however, a violation of this principle by living organisms has never been observed. Therefore, on empirical grounds, the validity of the second and first laws of thermodynamics for living organisms is generally accepted. Nevertheless, it must be kept in mind that living beings are open systems.

Not all processes permitted by the second law of thermodynamics can be used by living systems, for example, they cannot use the differences in temperature generated by combustion. The source of energy to perform biological work is chemical, and only few classes of chemical reactions can be used for these purposes.

The Earth is in a steady state. The intake of energy is just compensated by its loss. Energy intake and energy loss occur entirely through radiation. In a steady state, the entropy content of the Earth must be also constant. Entropy is gained in the form of solar radiation and loss as electromagnetic radiation. Entropy is also produced through irreversible processes. The rate of production of entropy must be equal to the net loss. Thus, in balance, the Earth emits entropy, and this entropic compensation is also operative in the biosphere. While organisms give just as much energy as they gain, the entropy associated with the energy released must exceed the entropy associated with the energy taken up. Organisms can develop if they interpose themselves into a gradient of entropy between incoming and outgoing energies.

Entropy is absorbed by live systems in the form of chemical substrates and radiation. In a chemical process, in ideal conditions, the sum of the entropies of the reacting chemical system and the environment remains constant all the time. In ideal

conditions, the process is carried out reversibly, but a small change in the parameters, for example, concentration, could reverse the direction of the process.

In living systems, work generated from chemical substrates is not produced by way of heat. Chemical energy is transformed into other forms of energy (e.g., ► **Proton Motive Force**, ► **ATP**) without passing through a heat stage. The small gradients of temperature that might exist within organisms are never used for work. In general, live systems work isothermally and isobarically.

In bioenergetics, the concept of free energy is very useful. The molar free energy, G , is defined as

$$G = H - TS$$

where H is the molar energy content, T is the temperature, and S the molar entropy content. Strictly, in an isobaric system, H should be called enthalpy and G free enthalpy. But in isobaric conditions, the volume changes are so small that the difference between enthalpy and energy disappears. The energetics of the reaction can be described in terms of the differences between products and reactants as

$$\Delta G = \Delta H - T\Delta S$$

The free enthalpy change ΔG has a negative value when the reaction is written in the direction in which it proceeds spontaneously, i.e., an exergonic reaction. In the opposite direction, the reaction is endergonic, and not spontaneous. The maximum work that can be obtained from a chemical reaction is given by ΔG , and it is obtained when the reaction is performed reversibly. But when a reaction has an irreversible component, some of the energy is dissipated as heat and then additional entropy is generated. While ΔH is mostly measured by calorimetry, ΔG and $T\Delta S$ are normally derived from measurements of chemical equilibrium. ΔG is related with the equilibrium concentrations of products ($c_{p1}, c_{p2}, \dots$) and reactants ($c_{r1}, c_{r2}, \dots$) and their actual concentrations ($c_{p1}^*, c_{p2}^*, \dots, c_{r1}^*, c_{r2}^*, \dots$):

$$\Delta G = -RT \ln \frac{c_{p1} c_{p2} \dots}{c_{r1} c_{r2} \dots} + RT \ln \frac{c_{p1}^* c_{p2}^* \dots}{c_{r1}^* c_{r2}^* \dots}$$

provided that activities can be replaced by concentrations. For physicochemical standard conditions (pH value 0), the value ΔG is called ΔG° . For physiological standard conditions (pH value 7), ΔG is by definition $\Delta G^{\circ'}$.

The equilibrium constant K is defined as

$$K = \frac{c_{p1} c_{p2} \dots}{c_{r1} c_{r2} \dots}$$

Therefore, for standard conditions,

$$\Delta G^\circ = -RT \ln K$$

and

$$\Delta G^{\circ'} = -RT \ln K'$$

As ΔG° (or $\Delta G^{\circ'}$) is a measure of the tendency for a reaction to occur in standard conditions, it is also known as the reaction affinity. The greater the affinity, the more exergonic the reaction and the more negative ΔG° (or $\Delta G^{\circ'}$). It has to be underlined that the exergonicity or endergonicity of a reaction, in a given condition, is not determined by the standard values (ΔG° or $\Delta G^{\circ'}$) but the values of ΔG . The work obtainable from a reaction is influenced by the actual concentrations, more exactly activities, of the reactants and the products.

As mentioned in the ideal case of reversible reactions, no entropy is generated. However, reactions cannot proceed fully reversible if they have finite velocities. Metabolism cannot be too slow. Therefore, full reversibility cannot be attained and entropy must be generated. Hence, entropy is certainly generated when organisms do external work.

Experimental work shows that antagonistic catabolic and anabolic processes always proceed along different pathways. Catabolic reactions are usually exergonic; thus, the corresponding anabolic reactions cannot proceed spontaneously, at least not in the same conditions. Therefore,

different pathways, which proceed at the expense of additional energy, are used for anabolism. In general, more energy in useful form is needed for anabolism than the energy obtained in catabolism. Often, no useful energy is obtained at all in the catabolic reactions of dynamic states. In this case, energy is dissipated as heat.

Active Transport

One of the most important dynamic states of the cell is the so-called active transport. Active transport is related with the transport of molecules and ions across the ► [cell membrane](#) against a concentration gradient. It requires osmotic work. To perform osmotic work, free energy is required. When the concentration of a solute in one side of the membrane is different from the concentration in the other side, diffusion to equilibrate the concentrations in both sides of the membrane occurs. The direction of the transport is given by the change in free energy:

$$\Delta G = RT \ln \frac{a_2}{a_1}$$

a being the thermodynamic activity, which as we mentioned before in most cases can be approximated to concentration. In diffusion ΔG is negative. In active transport ΔG is positive; this is the reason why osmotic work must operate to allow the solute to cross the membrane against a concentration gradient. If the solutes have a charge (ions), then an additional term related with the electrical potential must be considered.

Through active transport, large differences in concentration of molecules (i.e., glucose) and ions (i.e., H^+ , Na^+) can be set up between the cytoplasm and the environment or between different cell compartments in eukaryotic cells. Obviously if a difference in concentration across the membrane is generated by active transport, diffusion will operate in the opposite direction; thus, work must be performed all the time to maintain a steady state. Solutes are pumped across the membrane by specific mechanisms. Specificity is extremely important in active transport to ensure that the cell invests energy in transporting useful compounds. As has been pointed out, dynamic

states are very important for life systems. No organism is known to be able to develop without dynamic states. The complex mechanisms to maintain and regulate dynamic states are rather universal. One of the biggest surprises that is emerging from the analysis of whole-genome sequences is the high percentage of genomic information devoted to active transport, which underlines its importance.

Active transport is also the basis of cell bioenergetics. Most ► [energy conservation](#) reactions are directly or indirectly related with active transport systems. From an energetic point of view, active transport can be classified as transport reactions that generate useful energy for the cell (primary active transport) and those that require energy for its functioning (secondary active transport). Examples of primary active transport are ► [respiration](#), ► [photosynthesis](#), the transport of the fermentation products, and the ► [ATPase](#) activity, all of them coupled to the generation of ► [proton motive force](#). Examples of secondary active transport are the transport of nutrients to the cell, the maintenance of homeostatic ionic concentrations inside and outside of the cell, the bacterial flagellar movement produced, and the synthesis of ATP, all of them coupled to the dissipation of the ► [proton motive force](#).

In respiration (see ► [Respiration](#)), an electron donor gives electrons to an appropriated electron acceptor through the use of an electron transport chain located in the ► [cell membrane](#) in prokaryotes and in the mitochondrial membrane in eukaryotes. The passage of electrons through the chain promotes the translocation of protons, generating a gradient of protons between both sides of the membrane. The difference in potential energy (chemical energy) between the electron donor and the acceptor is transformed in proton motive force, a universal storage system of cellular energy.

In ► [photosynthesis](#), the photosynthetic reaction center is excited (oxidized) by radiation, and the excited electron is trapped by a constituent of an associated electron transport chain, and as in the respiration, the passage of the excited electron through the different components of the chain can promote (i) the translocation of protons producing

a gradient of protons (proton motive force) or (ii) the generation of cellular reducing power, depending of the type of photosynthesis. In the first case, the same excited electron goes back to the oxidized reaction center to reduce it to the ground state (cyclic ► [anoxygenic photosynthesis](#)). In the second case, an electron donor must donate an electron to the reaction center to bring it to the ground state (oxygenic photosynthesis, noncyclic anoxygenic photosynthesis), getting in both cases ready for another excitation reaction using radiative energy. In the photosynthesis, the source of energy is radiation and is transformed through a more or less complex system (depending on the type of photosynthesis) in cellular energy (proton motive force and/or reducing power).

Fermentation is the only bioenergetic system that does not make use of an electron transport chain to conserve energy (see ► [Fermentation](#)); instead cytoplasmic soluble enzymatic reactions are able to generate cellular useful energy (ATP) from chemical energy (reduced carbon substrates). Interestingly enough, because fermentation is the main source of energy for these organisms, an important amount of substrate must be fermented for growth, and as a consequence, a high concentration of fermentation products are produced (i.e., ethanol, organic acids). If the organism is able to couple the translocation of the fermentation products to the generation of a proton gradient, then the potential energy stored as a concentration gradient of fermentation products, which is not useful to fuel energy requiring cellular reactions, is transformed in proton motive force, a useful cellular energy source. In the absence of coupling between both transports, only diffusion applies and the potential energy is lost. It has been calculated that up to one third of the cellular energy used by fermentation organisms can be generated by this peculiar active transport system.

All these are examples of primary active transport systems because they can transform different ► [energy sources](#) in proton motive force. Once there is enough energy stored as proton motive force, it can be used to promote reactions that require work. The best-known example is the

translocation of cellular substrates (i.e., glucose) to the interior of the cell against a concentration gradient. Normally, organisms, especially prokaryotes, live in habitats with extremely low concentration of useful substrates to obtain energy. The required concentrations of these substrates inside the cell for metabolic reactions to proceed are several orders of magnitude higher than their concentration in the environment. Thus, very active transport system is required to concentrate these substrates inside the cell. To do this osmotic work, energy in the form of proton motive force is used. In this case, the translocation of a specific substrate is coupled to the dissipation (transport) of proton motive force.

Similarly, proton motive force can be used to maintain a high concentration of K^+ or a low concentration of Na^+ inside the cell. Due to simple diffusion, the high concentration of potassium stored inside the cell and required for an optimal performance of the different functional enzymatic activities leaks out because the concentration of this cation is rather low outside of the cells. To maintain a high concentration of potassium in the cytoplasm, an active transport is required, because it has to be performed against a concentration gradient. The coupling between the translocation of potassium to the interior of the cell with the dissipation of the proton motive force allows maintaining the optimal cellular potassium concentration. A similar situation can be found with the sodium concentration. In this case, the optimal cellular condition is a lower concentration of this cation in the cytoplasm than in the environment. In this case, simple diffusion leaks sodium to the cytoplasm, so the active transport required to pump sodium out of the cell can be performed using the energy stored as proton motive force through the coupling of both transport systems.

But energy stored in the form of proton motive force can be used for other cellular functions different than transport, like the bacterial movement of flagella. In this case the dissipation of the proton motive force is used to perform a mechanical work: the rotation of the flagella or the reverse transport of electrons in the electron transport chain to generate reducing power for

microorganisms that need it and cannot produce it by other means (many chemolithoautotrophs).

A special case of active transport that requires attention is related with a membrane enzymatic complex involved in the synthesis and hydrolysis of ATP (see ► [ATPase](#) and ► [ATP Synthase](#)). The membrane-bound synthesis of ATP from ADP and phosphate is an endergonic reaction that requires energy. This reaction, named ► [ATP synthase](#), can be fuelled by the use of the energy stored as proton motive force. In this case, it will perform as a secondary active transport system. But the same enzymatic complex can perform in the opposite direction: hydrolyzing ATP and using the released energy to promote the translocation of protons outside the membrane, generating proton motive force. In this case it is performing as a primary active transport system. The reversibility of this reaction is the core of the bioenergetic regulation of prokaryotic cells. Experimentally, it can be shown that there is a linear relationship between the intracellular concentration of ATP and the proton motive force. If the proton motive force measured as membrane potential corresponds to the concentration of ATP measured inside the cell, no activity can be detected. If the proton motive force is lower than the value that will correspond to a given concentration of ATP, then ATP is hydrolyzed to generate proton motive force until both systems are equilibrated. If the proton motive force is higher than the value that should correspond to the ATP concentration, then the proton motive force is dissipated to increase the ATP concentration until both systems reach equilibrium. With only one metabolic activity, prokaryotes can regulate in an efficient manner and with little genomic investment the bioenergetics of the cell.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [ATP](#)
- [ATP Synthase](#)
- [ATPase](#)
- [Cell Membrane](#)

- [Electrochemical Potential](#)
- [Energy](#)
- [Energy Conservation](#)
- [Energy Sources](#)
- [Metabolism](#)
- [Mitochondrion](#)
- [Oxidation](#)
- [Photosynthesis](#)
- [Proton Motive Force](#)
- [Proton Pump](#)
- [Reduction](#)
- [Respiration](#)

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Biofilm

Jana Kvíderová

Institute of Botany, Academy of Sciences of the Czech Republic, Trebon, Czech Republic

Keywords

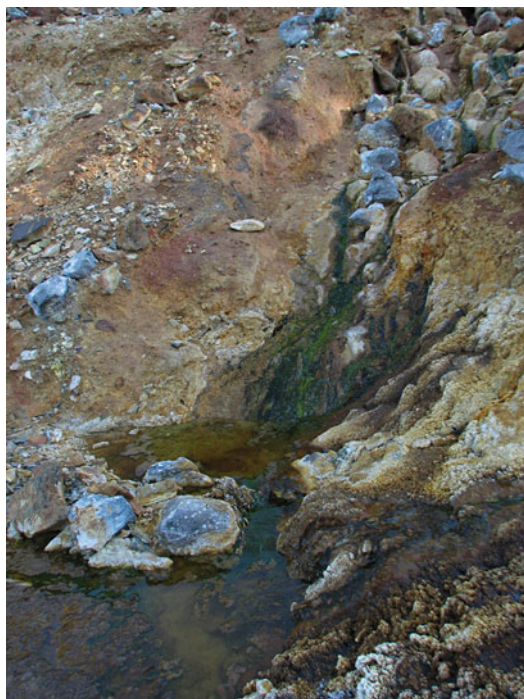
Adaptation · Biofilm · Biomarkers · Community · Extreme environment · Microorganisms · Species composition · Structure

Synonyms

[Microbial mats](#); [Periphyton](#)

Definition

Biofilm is a layer of microorganism(s) or microbial communities growing on a solid surface, usually of thicknesses ranging between several μm to



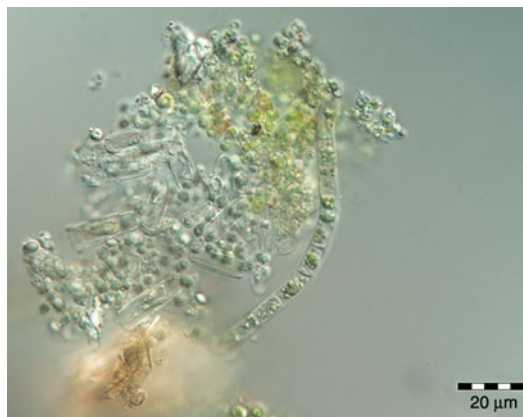
Biofilm, Fig. 1 Biofilms in the acidic waters of Río Tinto, SW Spain

several mm. The thicker biofilms are also referred as ► [microbial mats](#).

Overview

Biofilm communities are found in various aquatic and subaerial ecosystems or even in the human body (e.g., dental plaque) at liquid-solid or aerial-solid interfaces (Fig. 1). Typical biofilms develop on stones in streams and rivers or at the bottom of lakes. They participate in nutrient and energy cycling in the given ► [ecosystem](#) and could serve as a substrate for colonization by other species. Repeated sedimentation of inorganic material on the growing biofilm leads to layered structure resembling stromatolites (Krumbein et al. 2003).

Biofilms are usually formed by various microorganisms that include autotrophs as well as heterotrophs, eukaryotes, bacteria, and, in the most extreme conditions, archaea (Aguilera et al. 2007a). The organization level of the



Biofilm, Fig. 2 Example of a photosynthetic biofilm consisting in the association of unicellular red alga *Cyanidium caldarium*, filamentous green alga *Klebsormidium* sp., and pennate diatom *Pinnularia* sp. from Río Tinto, Spain

biofilm species can range from unicellular flagellates to multicellular filaments (Fig. 2). If the biofilm is formed by several layers of microorganisms, gradients of physical and chemical factors (e.g., light, pH, O₂) are established and influence its structure and species composition. The microenvironment within the mature biofilm could be different from that of the surroundings and could provide protection to more sensitive species (Ferris et al. 2005). For example, acidophilic red alga *Cyanidium* sp. is more tolerant to pH values above 3 than to those below 1, probably due to adaptation to elevated pH in biofilm interior (Kvíděrová 2012). It is possible that microorganisms within biofilms communicate by chemical signals. Such communication has been detected in biofilms of pathogenic bacteria, but in natural communities very little is known of this phenomena (Kellner and Surette 2006).

The development of a biofilm starts by accumulation of amorphous particles containing inorganic grains and bacteria. The cells divide, produce extracellular polymeric substances, form microcolonies, and provide substrate for further colonization by fungi and small eukaryotic heterotrophs like amoebas. The flagellates also participate at the initial formation. The sessile genera are observed later and could

require establishment of some organic matrix to be attached on. Filamentous microorganisms are last to appear. Small pieces of mature biofilm detach either due to internal signals or external factors, like water flow, and could colonize a new surface (Aguilera et al. 2007b).

Biofilms are the new microbial ecology frontier. Biofilms have not been studied in a systematic way until recently due to lack of appropriate methodologies. Confocal microscopy and in situ hybridization techniques allow to study intact biofilms and appreciate their complex structural diversity. For evaluation of photochemical performance of autotrophic biofilms, methods using variable chlorophyll fluorescence are applied in field (Gómez et al. 2011; Marteinson et al. 2013) and in detailed laboratory (Kvíderová 2012) studies.

An important part of microbial life on Earth is associated to biofilms. Biofilms and microorganisms from ► [extreme environments](#) are considered interesting astrobiological model systems (Aguilera et al. 2007b; Gómez et al. 2011; Kral et al. 2004), specially as biomarkers of extinct or extant life in habitable planets like Mars or on Galilean moons.

Cross-References

- [Colonization, Biological](#)
- [Concentration Gradients](#)
- [Ecosystem](#)
- [Extreme Environment](#)
- [Microbial Mats](#)
- [Microorganism](#)
- [Rio Tinto](#)
- [Stromatolites](#)

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Biofilms

- [Microbial Mats](#)

Biogenicity

Nicola McLoughlin
Department for Geology, Rhodes University,
Makhanda (Grahamstown), South Africa

Keywords

Biosignatures and traces of life · History and origins of life · Life detection

Synonyms

Biosignature

Definition

A BIOSIGNATURE IS A chemical OR morphological signatures THAT CAN BE preserved over a range of spatial scales in rocks, minerals, or ice that IS uniquely produced by past or present organisms. For example, elemental and isotopic signatures diagnostic of life that cannot be formed by purely abiotic processes. These may be accompanied by textural remains with shapes, orientations, and abundances that uniquely result from the growth, or decay of (once) living organisms. Further support for biogenicity can be shown if the distribution and abundance of this evidence are controlled by biologically significant primary variables such as light, temperature, and nutrient gradients.

Overview

Biogenicity criteria are used to assess the likelihood of a biological origin for candidate traces of life. Biogenicity criteria address observable and quantifiable features that can be broadly divided into three types: (1) the morphological complexity and size distribution of textural traces of life; (2) the elemental composition, bonding, symmetry, and isotopic composition of chemical traces of life; and (3) the environmental distribution or geological context of traces of life. These three approaches to investigating the biogenicity of candidate traces of life are mutually reinforcing and should be accompanied by efforts to falsify potential abiotic explanations for the observations. So-called ► “**dubiofossils**” or ► “**pseudofossils**” are features that are highly questionable traces of life and more likely explained by abiotic processes that can mimic life (Hofmann 1971).

Specific biogenicity criteria have been tailored for the different classes of biosignature found on earth and beyond AND HERE WE

WILL FOCUS ON EVIDENCE FOUND IN THE ROCK RECORD. For microfossils, biogenicity criteria have been proposed by SEVERAL AUTHORS, for example, Buick 1990 and Brasier et al. 2004. TO SUMMARISE THESE IN BRIEF these focus on the size distribution of the population OF CANDIDATE MICROFOS-SILS; morphological features such as branching, septation, evidence for cell walls, nuclei, or extracellular polymeric substances; their orientation especially evidence of colonial behavior, tiering, or phototaxis; and lastly evidence of primary environmentally controlled distribution and/or subsequent decay. The importance of such criteria has been highlighted by abiotic experiments that produce microfossil-like filamentous biomorphs in the laboratory, for example, (Garcia-Ruiz et al. 2003). These microfossil biogenicity criteria have also been adapted for meteorite sample, especially for those purported to contain fossilized magnetobacteria by, for example, (Thomas-Keprta et al. 2001).

For laminated sedimentary structures known as ► **stromatolites** found in carbonate rocks that form by the interaction of microbial mats and sediments, biogenicity criteria have been advanced by, for example, (Buick et al. 1981) and contrasted with abiotic artifacts by (McLoughlin et al. 2008). A primary sedimentary origin, along with complex laminated macro-morphology including domes, columns, and branches, is supportive of a biological origin for stromatolites. However, it is often the micro-fabrics of stromatolites, which preservation permitting, can be one of the best indicators of a biological origin, for example, (Hofmann 2000). For the related phenomenon of microbially induced sedimentary structures found in clastic rocks, biogenicity criteria have been formulated by (Noffke 2009). Lastly for micro-cavities produced by rock-dwelling organisms that tunnel into rock substrates, including carbonates, silicates, and volcanic glass, biogenicity criteria have been developed by, for example, (McLoughlin et al. 2007). For an up-to-date summary of biogenicity criteria please consult NASA's NfoLD (Network for Life Detection) database, which is a community effort to establish a

knowledge base to guide testing and evaluation of remote and in situ biosignatures (For an up-to-date <https://ldfknowledgebase.com/NASA> 2021).

Cross-References

- [Archaeal Traces of Life](#)
- [Biomarkers, Morphological](#)
- [Dubiofossil](#)
- [Endogenicity](#)
- [Endolithic](#)
- [Fossil](#)
- [Life](#)
- [Magnetotactic Bacteria](#)
- [Microbial Mats](#)
- [Microfossils](#)
- [Microbially Induced Sediment Structures \(MISS\)](#)
- [Pseudofossil](#)
- [Stromatolites](#)
- [Syngenicity](#)

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Biogeocentrism

Octavio A. Chon-Torres

Programa de Estudios Generales, Universidad de Lima, Lima, Perú

Definition

According to Chela-Flores (2001, 2009), this term refers to the way we understand life in the universe from the only reference we have, that is, life on Earth. In this notion, biogeocentrism is shown as the current model that prevails as long as we do not have, as yet, a confirmation of other forms of life in the universe. The way we understand life on Earth represents a conditioning factor to be able to detect it in other worlds. One of the challenges we face is, what would happen if, because we are conditioned to what we understand by life and how it behaves on Earth, we are overlooking different forms of extraterrestrial life?

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Biogeochemical Cycle of Nitrogen

► Nitrogen Cycle, Biological

Biogeochemical Cycles

David C. Fernandez-Remolar
State Key Laboratory of Lunar and Planetary
Sciences, Macau University of Science and
Technology, Taipa, China
CNSA Macau Center for Space Exploration and
Science, Macau, People's Republic of China

Keywords

Biogeochemistry · Biosphere · Earth systems ·
Ecosphere · Geobiology · Habitability ·
Homeostasis · Hydrosphere · Matter · Energy
fluxes

Acronyms

GOE Great Oxidation Event
IPB Iberian Pyrite Belt

Definition

The biogeochemical cycles are a theoretical concept that describes the transfer of matter and energy between the biosphere and the other active reservoirs of Earth – like the atmosphere, hydrosphere, and lithosphere (Schlessinger 1997). The main processes can be understood as the biosphere's storage or release of energy by uptaking or liberating molecular species with essential components for life, the so-called nutrients. The primary biogeochemical cycles involve different molecular species whose composition provides the essential elements for building polymeric structures and obtaining energy in cells. The biogeochemical cycles are activated when the biosphere interacts with some matter fluxes that specifically supply nutrients. They are sourced from specific sites or active centers on Earth (e.g., volcanic, hydrothermal systems) that are

essentially energy sources that maintain the supply of matter and energy to the Earth's surface. As the highest-level living structure, the biosphere has its energy transducers played by autotrophic organisms. Some geological systems (e.g., hydrothermal) can also act as energy transducers to recycle oxidized compounds ultimately uptaken by chemolithotrophs, which sustain the biological communities in deep regions of the oceans (Sutton and Milligan 2019). Therefore, the energy is transported as molecular compounds from the lithosphere to the different reservoirs of the Earth (Lovelock 2000). Such geochemical processes are likely intimately related to the pre-metabolic reactions that triggered the emergence of life on Earth (Varma et al. 2018). Furthermore, they are considered essential to make a planetary body habitable as they release energy in the form of compounds and sustain the chemical disequilibrium necessary for an emerging biosphere. The Earth's inner thermal factory is a major abiotic player in the biogeochemical cycles controlled by the biosphere. The reducing power of the internal activity of Earth (Richards 2015) is obtained through the production of diverse inorganic (e.g., reduced metals) and organic compounds (e.g., methane) (Schlessinger 2020). Such compounds are uptaken by chemoautotrophic organisms as electron donors sustaining the biogeochemical cycles in different habitats. The emergence of the photoautotrophic life (Lyons et al. 2014) diversified and increased the number of pathways to cycling matter and energy between the biosphere and the other terrestrial reservoirs. While matter and energy are produced in different sources, they transfer through different Earth fluxes to end in sinks that become unavailable, depending on the physical and/or chemical process (Schlessinger and Bernhardt 2020). For example, oxidation of organics plus sequestration of CO₂ in the oceans is a temporal or permanent sink for carbon. In turn, carbon is produced from many other sources, which supply rates are enhanced by different large-scale terrestrial events. Furthermore, the dynamic of the large-scale events also may change the distribution of sources and sinks. This is the case of the large sulfide deposits that were formed under the

Archean anoxic conditions, which sequestered a large amount of the total sulfur available in the terrestrial crust. However, the release of oxygen by chemoautotrophic life to the ocean and atmosphere during the GOE (Konhauser et al. 2011) sourced sulfur and other elements to the hydrosphere through the oxidation of the terrestrial crusts by acidic alteration. In this context, during the GOE the terrestrial sulfide orebodies that were sinks for sulfide became sources of sulfur after being mobilized by the oxidation event. The biosphere's ability to transfer energy among different chemical species results in the generation of intricate pathways involving diverse element cycles. For example, it is observed in an active chemolithotrophic community associated with different hydrothermal centers that sequestered a large amount of sulfur in the form of sulfides by the high organic supply in the form of plant debris (Fernandez-Remolar et al. 2018). The supply of organic carbon was released by a catastrophic event driven by regional volcanic activity that obliterated the late Devonian forests. The chemolithotrophic communities oxidized the organic carbon to CO_2 by reducing SO_4^- found in the seawater.

Overview

The biogeochemical cycles result from a complex network of interrelated pathways that are mediated by the biosphere with the different Earth's reservoirs. In this regard, the biogeochemical cycles are the different pathways that the biosphere at any scale uses to obtain nutrients and energy to persist. Different positive and negative feedback reactions emerge from such interaction that, to some extent, can control the physical and chemical properties of the environment (Margaleff 1968). The reservoir is the fundamental unit in biogeochemistry that corresponds with a physical container of the different components that are circulated through the biogeochemical pathways after its interaction with the biosphere. As emphasized in collapse the definition, the biogeochemical cycles emerge by different matter and energy fluxes are driven by the different

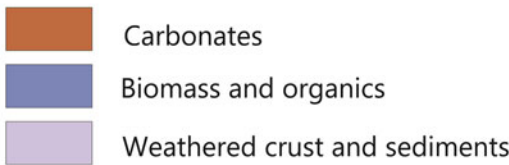
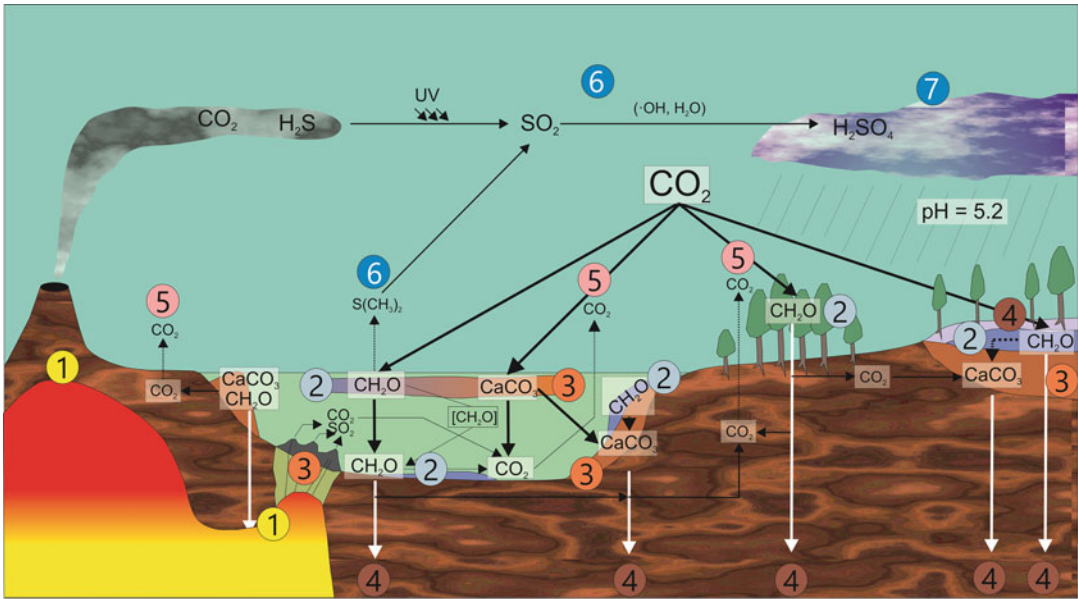
converter agents (Schlesinger and Bernhardt 2020). The converter agents are mainly the biological entities that transduce energy, transform, or store nutrients in reservoirs, which become newly available to the biosphere. Some of the active centers where the energy and nutrient converters occur have been considered to work as planetary organs to sustain the biosphere. It has been claimed that the destruction of the autotrophic centers producing oxygen would collapse the pathways sustaining the biochemical cycles and seriously compromise the biosphere itself (Lovelock 2000). However, it is uncertain if life on Earth will be fully terminated as the first living systems likely emerged from an anaerobic world. Although converters and transducers are mostly represented by living beings, there are some abiotic reactions that can initiate the biogeochemical cycles in different habitats as in the hydrothermal vents (McDermott et al. 2020) and the serpentinization systems (Schulte et al. 2008). In those habitats, the reducing power and chemical disequilibrium are obtained through the production of different reduced compounds that can provide energy to the chemosynthetic producers. Furthermore, the terrestrial reservoirs are partitioned in different lower units, which size can vary depending on the dimensions of the habitats that are associated with the biological and non-biological converter agents. While the reservoirs on earth (atmosphere, hydrosphere, biosphere, and geosphere) are partitioned in different regions matching the habitats, they also have particular parcels where the nutrients are partially removed from recycling. Significant environmental changes can, in turn, make them available, inducing large biogeochemical imbalances until a new equilibrium stage is reached. A good example is carbon release by global warming stored in deep oceans in the form of CO_2 and CH_4 , found as dissolved species or icy hydrates. A high rise of the temperature leads to a high supply of CO_2 to the atmosphere, triggering a positive feedback controlled by green housing and the production of carbonic acid. A same situation has been found in different thermal events that have been widely described to occur in different episodes of the Earth's history (Babila et al. 2018; Gehler et al.

2016; Kump 2018). In some extreme cases like during the late Permian, the atmospheric CO₂ reached a concentration of 3500 ppm (Saunders and Reichow 2009).

The biosphere stores and uses a wide range of nutrients, including those that are essential for building cellular and multicellular structures and provide energy through electron transfer or chemical bonding. Therefore, it has a large impact on the cycling of compounds (Fig. 1) that are bearing carbon, nitrogen, sulfur, or phosphorous (Brimblecombe 2014; Galloway 2014; Sundquist and Visser 2014; Ruttenberg 2014), which, in addition, were operating since the emergence of the biosphere more than 3.5 Ga ago. The nutrients can be exchanged with other reservoirs as volatiles, ions, or biominerals. As stated before, biomineral formation can eventually end in the elimination of nutrients from the biosphere through specific sites or sinks by driving them into other Earth's reservoirs.

One paradigmatic example is the limestone formation by unicellular planktonic algae and foraminifera, which biomineralize carbonate to form shells (Zondervan et al. 2001). After the microorganism's death, the carbonatic shells rain down continuously on the ocean floor, becoming the raw material leading to the global formation of sedimentary carbonates (Fig. 1). Later on, the global tectonics can transport the oceanic deposits from the sedimentary areas to the subduction zones where the carbonate is partially transformed back into CO₂ by thermal decomposition in deep areas of the lithosphere (Sundquist and Visser 2014). The CO₂ can then be returned to the atmosphere through exhalation of volatile compounds from the volcanic centers and geothermal systems. Some other nutrients like sulfide can be directly released into the atmosphere in the form of organic volatiles, which are lately transferred back to the hydrosphere and biosphere once they are oxidized by photochemical reactions. As shown by some organic compounds like dimethyl sulfide (Fig. 1), one of the main sources of sulfur in the biosphere, which is released into the atmosphere by phytoplankton, but returned to the hydrosphere in the form of sulfate after being oxidized by UV in the atmosphere (Brimblecombe 2014). The dimethyl sulfide (Fig. 1) becomes one of the primary sources

of the biosphere sulfur, released into the atmosphere by phytoplankton, but is returned to the hydrosphere in the form of sulfate after being oxidized by UV in the atmosphere (Brimblecombe 2014). Interestingly, the release of sulfur-bearing compounds into the atmosphere and their subsequent oxidation to sulfate is a crucial mechanism in nucleating clouds. It has a planetary impact on the thermal control of the Earth's temperature as it increases the albedo and, therefore, decreases the solar radiation affecting the Earth's surface (Charlson et al. 1987). Consequently, sulfur cycling by phytoplankton is an essential feedback mechanism to control climatic conditions on the planet. Other nutrients essential for life in low concentrations are released to the atmosphere following similar pathways as the iodine supplied to the atmosphere by marine phytoplankton in the form of different volatile compounds such as methyl iodide (Butler et al. 1981; Manley and de la Cuesta 1997). It is lately decomposed by photolytic reactions with oxidants in the troposphere to more oxidized forms of iodine. Finally, the iodine is returned to the lithosphere or hydrosphere by rainfall or simple influx from the atmosphere after being included in the aerosols, active cloud-nucleating agents on Earth (Baker 2005). The iodine and sulfur cycling are good examples of the emergence of feedbacks from the simple nutrient exchange between the different Earth's reservoirs that become essential homeostasis mechanisms that control the environmental conditions at a planetary scale (Charlson et al. 1987; Lovelock 2000). The homeostatic capabilities of the biosphere controlled through biogeochemical pathways are also observed at a local scale. Although it has been widely mentioned the physic and chemical control performed by different vegetal communities, some natural systems with astrobiological interest are controlled by chemical mechanisms that stabilize the environmental parameters. It is the case of the extreme hyperacidic environment of Rio Tinto, a 100-km long fluvial system that emerges from the low-pH solutions (<2.5) through the underground biooxidation of the IBP sulfide orebodies by chemolithotrophic communities. The underground microbial activity ends in the release of a solution enriched in Fe₃⁺, SO₄²⁻, and H⁺ (Fernández-Remolar et al. 2021)



- 1** Carbon sources in geothermal systems
- 2** Organic carbon reservoir (biosphere and organic by-products)
- 3** Inorganic carbon reservoir (carbonates)
- 4** Inorganic and organic carbon sinks
- 5** Geological cycle of carbon
- 6** Atmospheric branch of the sulfur cycle
- 7** Cloud nucleation by sulfuric acid generation

Biogeochemical Cycles, Fig. 1 Biogeochemical cycle of carbon coupled to the sulfur cycle. The diagram shows the main pathways and reservoirs integrating the whole carbon cycle and its interplays with the sulfur cycle. Volcanic centers and other geothermal-driven systems (e.g., hydrothermal systems) release carbon to the atmosphere (1) mainly in the form of CO_2 but also CH_4 and CO . The carbon is fixed as organic or inorganic carbon through the biosphere growth and organics (2) and the precipitation of carbonates (3), which can be produced by biomineralization, simple precipitation by biological mediation, oversaturation by abiotic mechanisms, or simple weathering. The carbon is removed from the crust by sediment burial of carbonates and organics (4); carbonate precipitations in the subsurface by biological uptake and weathering mechanisms are also effective processes to

remove carbon from the Earth's surface. The organic oxidation, thermal decomposition, or simple carbonate dissolution through diagenesis can cycle back into the atmosphere (5) the carbon as carbon dioxide to compensate the carbon loss through microbial uptake, carbonate precipitation, or simple weathering. Sulfur can be oxidized to sulfuric acid through complex photochemical reactions starting on hydrogen sulfide oxidation and ending on the sulfite hydration. Thus, sulfuric anion as a powerful nucleation agent of clouds (6) favors the supply of meteoric water to the surface that transports C-bearing gases and other volatiles to the crust, making the carbon available for its fixation as organic or inorganic compounds. Sulfur is released back to the atmosphere (7) as dimethyl sulfide supplied by algal activity

that thermodynamically favors the hydrolysis reaction through the ferric buffer ($\text{Fe}^{3+} + \text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})^{2+} + \text{H}^+$), maintaining the solution at an average pH of 2.3 for each year. Despite the extreme pH conditions, the emergence of such a homeostatic mechanism controlling the chemical conditions could be related to the high microbial diversity found in the Rio Tinto environment. Interestingly, the subsurface biooxidation of the orebody by diverse chemolithotrophic life links the nitrogen cycle with the iron and sulfur cycles. Such microorganisms obtain this nutrient as different molecular species like NH_4^+ , NO_2^+ , and NO_3^+ from the host rock which were sequestered by hydrothermalism (Fernández-Remolar et al. 2021). In this regard, the nitrogen cycle is initiated by redox coupling with the different iron and sulfur ions released from the orebody by the microbial attack. The acidic biooxidation that sustains the homeostatic conditions in the surface habitat also favors the fast release of different nutrients, including sulfur, iron, nitrogen, and phosphorous.

The last part in biochemical cycling corresponds with the transport agents, which act as natural carriers to distribute to the different Earth's reservoirs. Most of them are activated by simple physical gradients powered by local or regional changes in temperature, density, pressure, or gravity. Although potential energy plays an essential role in fluvial transport, most transporting agents are driven by the latitudinal difference in temperature. In this regard, it is worth mentioning that the hydrological cycle on Earth contributes to nutrient exchange between the different Earth's reservoirs. The interaction between the transport and the biogeochemical agents control the element fluxes that strongly affect the residence times in the different reservoirs (Schlessinger and Bernhardt 2020). The rates of the biogeochemical fluxes.

Basic Methodology

Biogeochemistry, the discipline that studies the interplay between the biosphere and the different Earth reservoirs, emerges from the interaction of

experimental sciences like physics, chemistry, biology, and geology. Thus, it uses a diverse suite of methodologies and techniques. The biogeochemical cycles are powered by matter and energy exchanges experimentally measurable by different rates, which are quantifiable in mass units per unit of time. In this sense, reaction kinetics (metabolic and chemical) and thermodynamics are essential concepts in describing how biogeochemical cycles operate (Schlessinger and Bernhardt 2020). Furthermore, system modeling is an essential tool deeply rooted in linear and nonlinear mathematics that has increased our understanding of cycling dynamics. It has also integrated the local and regional biogeochemical cycling of single nutrients with other compounds on a larger range, which provides a better comprehension of the biogeochemical processes at a planetary scale (Sellers et al. 1997). Building up system models requires the collection of accurate quantitative data to build consistent models. In this regard, spectral satellite data analysis has significantly advanced the biogeochemical process at regional or planetary scales (Frouin et al. 2018; Graham et al. 2015). However, the satellite data quantification demands a ground truth approach to calibrate it locally through sampling air, water, sediments, soils, or rocks. It can be done through different in situ analytical techniques such as spectrophotometers, visible and infrared spectroscopy, chromatography, and mass spectrometers (Viollier et al. 2003). Accurate gas analysis is frequently based on careful sampling processes that use pressurized sampling cells to collect the volatile phases. The quantification and determination of volatile fluxes in water masses, soils, or sediments are characterized by sophisticated systems that integrate the sampling cell and the instrumentation system (Heyer and Berger 2000).

Furthermore, inferring the rates of biogeochemical fluxes requires collecting samples at different time spans. It can be done from a planetary scale using successive satellite images with different collection dates to a very local scale, which can deal with the seasonal variation of nutrient concentration in a lacustrine system. Nutrients in

minerals or dissolved ions can be analyzed using various techniques that characterize their organic composition, such as atomic absorption, thermal fluorescence, and mass spectrometers. Some complex instrument suites, like ToF-SIMS and NanoSIMS, can recognize the biogeochemical processes in modern and ancient environments to characterize the distribution of organics, inorganic compounds, and isotopes in soil and rocky samples (Fernández-Remolar et al. 2018, 2021; Herrmann et al. 2007).

Key Research Findings

Some of the quintessential findings in science that life derived from Earth and are intimately integrated into the matter and energy cycles of Earth were indeed done by biogeochemistry's father Vernadsky in the early 1900s (Vernadsky 1998). Interestingly, such scientific discoveries linked prebiotic systems with particular geochemical cycles (e.g., C, S, and Fe) that have been considered as early stages of premetabolic systems (Drobner et al. 1990; Gorham 1991; Varma et al. 2018). Furthermore, chemical stoichiometry linking molecular compounds with the different terrestrial reservoirs identified the biogeochemical mechanisms to control the climatic activity and the earth's crust composition. (Garrels et al. 1975; Lovelock 1972). In this context, the study of the biogeochemical cycles in the modern earth has been essential to understand how human activity is affecting the climatic conditions on Earth (Bianchi et al. 2021). On the other hand, the characterization of the biogeochemical cycles through chemical reactions has led to the conceptual building of the different biogeochemical cycles on Earth and perform the quantitative evaluation of the element pools in natural and anthropic systems (Parton et al. 1993). The application of different techniques as the geochemistry of stable isotopes has led to the monitoring of the metabolism evolution and the biosphere composition (Nealson and Rye 2014), but also the changes in the dynamics of the biogeochemical cycles over time in close relation with the climate

and ocean evolution (Sutton et al. 2018; Sundquist and Ackerman 2014).

Applications

Given that the biogeochemistry emerges from the interaction of several disciplines, it can consequently have countless applications. For example, from environmental to agronomic sciences, biogeochemical cycles are in the central core to foresee climatic extremes or minimize the impact of crops on the environment. Regarding astrobiology, the study of the biogeochemical cycles is the core of its essential question for search life in the universe whether or not a planetary body can sustain life (Nisbet and Fowler 2014). The four main ingredients – liquid water, nutrients, energy sources, and chemical disequilibrium – that enable a planet to become potentially habitable are the same key elements that initiate and maintain the biogeochemical cycles operated by a hypothetical extraterrestrial biosphere. The chemical disequilibrium, among all ingredients, emerges as essential to fuel the matter and energy transfer that maintains the cycling. Several attempts exist to visualize how biogeochemical cycling could operate in modern planetary bodies sustained by redox disequilibrium maintained through photochemical reactions that supply oxidizing and reducing compounds to the planetary surface. For Mars, a planet covered by a thin CO₂-rich atmosphere, the radiolysis of methane has been suggested as a mechanism to provide H₂ as an electron donor for microbial life in the subsurface (Blair et al. 2007; Weiss et al. 1999). Interestingly, accurate geochemical calculations from Mars meteorites show that the deep underground oxidative processes like radiolysis affection sulfide orebodies can sustain a deep biosphere sustained by chemolithotrophs through producing H₂ and SO₄²⁻. Similar cycling for carbon is proposed for Europa (Chyba and Phillips 2001), an icy satellite of Jupiter with no atmospheric cover exposed to a heavy bombardment of ionized particles like Na⁺. Furthermore, a similar scenario to the

Mars radiolytic biosphere has also been envisaged in Jupiter's icy satellite (Altair et al. 2018).

Future Directions

It is widely discussed that biogeochemistry can play an essential role in foreseeing severe environmental issues like climate change and contamination (Bianchi et al. 2021). In this regard, it is needed to understand better the attributes of the different components in the biogeochemical cycles, particularly the biological side, which will also improve the environmental modeling (Bianchi et al. 2021). However, studying the biogeochemical cycles can not only foresee how the Earth systems will operate in the future. Such improvement will also assist in understanding the biosphere's emergence, its coevolution with Earth, and its potential emergence in other planetary bodies. As discussed above, it touches on essential questions about how the origin of life was linked to the early geochemical cycles operating in the Hadean to early Archean Earth (Keller et al. 2014). Such research also poses crucial information about the emergence of life in other planetary bodies, showing earlier evolutionary stages or following different biogeochemical pathways. The Perseverance rover is collecting a set of samples that, in the following years, might provide some clues about the geochemical cycles operating in a young terrestrial planet. Perhaps, this information will be the basis to understand how life emerged on our planet whether it did not occur on Mars or, on the other hand, reached a prebiotic stage (Clark et al. 2021). In this context, the revelation of the biogeochemical cycles involved in the emergence of life in the Solar System's terrestrial planets will also provide essential information for detecting it in some exoplanets (Seager 2014). However, the lack of knowledge of the global cycles in other terrestrial planets of the Solar System (Witze 2020) also poses questions about detecting biosignatures in exoplanets. Thus, it is a long way until we can fully understand the molecular compounds produced by the planetary geochemical cycles, which can be very unexpected as the phosphine case on

Venus or the release of methane to the Mars atmosphere (Moores et al. 2019). Such a lack of knowledge is a common issue in terrestrial planets and the geochemical cycles in icy bodies (Hörs 2017). The combination of the future exploration of the Solar System with the research of the very early geochemical systems on Earth will provide a complete picture of the critical processes linked to the emergence of the prebiotic systems that evolved to the first living forms. Such information will likely shed light on the habitability and potential emergence of prebiotic systems or biospheres in other regions in the Universe.

Cross-References

- ▶ Autotrophy
- ▶ Biosphere
- ▶ Carbon Cycle, Biological
- ▶ Carbon Dioxide
- ▶ Gaia Hypothesis
- ▶ Heat Flow, Planetary
- ▶ Heterotroph
- ▶ Homeostasis
- ▶ Hydrosphere
- ▶ Hydrothermal Environments
- ▶ Lithosphere, Planetary
- ▶ Nitrogen Cycle, Biological
- ▶ Nitrogen Fixation
- ▶ Sulfur Cycle

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Bioindicators

► Biomarkers (Atmosphere)

Bioindice

► Biomarkers

Bioinformatics

Ugo Bastolla

Unidad de Bioinformática, Centro de Biología Molecular “Severo Ochoa,” CSIC-UAM, Madrid, Spain

Keywords

Algorithms · Databases · Drug design · Gene networks · Macromolecules · Molecular evolution · Protein folding · Sequence analysis · Structural bioinformatics · Systems biology

Synonyms

Computational biology

Definition

Bioinformatics, also called computational biology, is a recent discipline whose aims are to store, retrieve, classify, and organize information about biological systems, to detect their evolutionary and functional patterns, to suggest laws of biological organization through statistical analysis, and to predict the results of new experiments by extrapolating experimental data with

the help of evolutionary or physically inspired reasoning.

History

One can say that bioinformatics originated with the need to compare protein sequences in an objective and automatic way in the early 1960s, inspired by the recent discipline of information theory, which led to the proposal of the molecular clock in ► [protein](#) evolution. Since then, sequence analysis has become more complex, addressing the comparison of the first complete genomes in the 1990s. Anfinsen experiments in the 1950s–1970s motivated the holy grail of computational biology: to predict protein structures from physical principles (Anfinsen 1973). While this dream did not materialize yet, it attracted many physicists to the field and stimulated a very rich and fruitful dialogue with statistical mechanics. Bioinformatics is nowadays a kind of two-headed animal, trying to combine the historical approach of evolutionary theory with the universality of physical laws. This hectic field is benefiting from the open-access mentality in which scientists all over the world freely share their algorithms and databases through the Internet.

Overview

The scope of bioinformatics is rapidly evolving. Currently, its main fields are the following:

1. Sequence analysis: alignment and comparison of macromolecular sequences to predict structural and functional relationships; algorithms for fast search of related sequences in large databases, like Blast; statistical models of sequence families (hidden Markov models); and analysis of splice variants in different tissues and organisms
2. Structural bioinformatics: macromolecular structure alignment and classification; analysis of structural evolution; prediction of secondary, tertiary (protein and RNA folding), and quaternary (protein-protein and protein-nucleic acid interactions) structure; prediction of folding stability upon mutation; prediction of the protein propensity to misfold and form amyloid fibrils or amorphous aggregates, involved in diseases; analysis and prediction of conformation changes upon molecular binding; and prediction of naturally disordered regions of a protein
3. Computational drug design: virtual screening of candidate drugs by predicting their affinity to target ► [proteins](#) through protein-drug docking or other techniques
4. Analysis, classification, and prediction of protein function
5. Molecular evolution: reconstruction of evolutionary patterns and phylogenetic trees and simulations of evolutionary processes
6. Gene expression analysis: statistical analysis of mRNA levels measured through microarrays and other techniques to detect co-regulated genes and compare different cell types and tissues in health and disease
7. Proteomic analysis to detect gene expression by measuring protein content
8. Analysis and prediction of gene networks: DNA regulation through transcription factors; post-translational modifications of proteins, in particular phosphorylation; protein-protein interaction networks; and biochemical pathways
9. Algorithm improvement
10. Database management and integration
11. Last but not least, literature mining to retrieve information about biological systems of interest

Points 6–8 also belong to systems biology, an interdisciplinary field that focuses its study on the interactions between the components of biological systems, while mathematical modeling of evolutionary processes has been demonstrated to have a rigorous formal analogy with statistical physics. Bioinformatics and its sister disciplines are more and more central in a dialogue with experimental biology, both as tools for predictions and information retrieval and as a conceptual framework to look for general organizational and evolutionary principles that help us to better understand living matter.

Cross-References

- [Evolution, Molecular](#)
- [Genome](#)
- [Genomics](#)
- [Nucleic Acids](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Protein](#)
- [Proteins, Primary Structure](#)
- [Proteins, Quaternary Structure](#)
- [Proteins, Secondary Structure](#)
- [Proteins, Tertiary Structure](#)
- [Proteome, Proteomics](#)

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Biological Efficacy

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

The biological efficacy of a process is used to describe the effectiveness of a specified process at affecting biological organisms. Efficacy refers

to an expected result. For instance, the biological efficacy of the ► [DHMR](#) is described by the measured reduction of the ► [bioburden](#).

Cross-References

- [Bioburden](#)
- [DHMR](#)
- [Planetary Protection](#)

Biological Evolution

- [Evolution, Biological](#)

Biological Indicator

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In planetary protection, as well as medical sterilization procedures, biological indicators are used to establish the efficacy of a bioburden reduction process. A well-characterized preparation of microorganisms (usually spores) is subjected to the bioburden reduction or sterilization protocol and a pass/fail analysis is conducted after the protocol by attempting to grow the microorganisms from the biological indicator. Failure of growth from the biological indicator indicates success of the bioburden reduction process. A number of biological indicators are commercially available in the form of a population of spores generated from a species of microorganism with known levels of resistance to a particular bioburden reduction process.

Cross-References

- [Bioburden](#)
- [Bioburden Reduction](#)

- [Microorganism](#)
- [Planetary Protection](#)
- [Spore](#)
- [Sterilization](#)

Biological Networks

Emma Hart
School of Computing, Edinburgh Napier
University, Edinburgh, UK

Keywords

Biological network · Graph · Hub · Motif ·
Power law · Scale-free network

Synonyms

[Metabolic networks](#); [Protein-protein interaction networks](#); [Transcription networks](#)

Definition

A biological network is an abstract representation of a biological system as a graph in which nodes in the graph represent components in the system (genes, cells, molecules) and links between the nodes represent interactions between components. Links may be weighted to represent strength of interactions. The resulting graph has a particular topology which can be used to understand function.

Overview

Recent advances in technology have resulted in an explosion in the amount of data that can be collected from biological systems. Techniques such as mass spectrometry, yeast two-hybrid assays, and other high-throughput methods have enabled significant advances in the identification of components, expression patterns,

and interactions within biological systems. Analyzing such vast data sets is challenging. Furthermore, the data sets are often incomplete and perhaps inaccurate. However, by considering the biological system as a network or graph in which entities in the network are represented by nodes, with links between nodes representing interactions, the essential properties of the system can be captured in an abstracted form with definite topological structure which can be linked to functional properties of the system. This abstraction enables the applications of tools developed in fields such as complex network theory, statistical physics, and sociology to be applied to biological networks, greatly facilitating their analysis (Wuchty et al. 2003; Barabási and Oltvai 2004; Barabási and Albert 1999). It further enables the comparison of biological systems to engineered systems which are traditionally described in network form (e.g., as a flowchart) and thereby enables the identification of shared principles such as robustness, fragility, tolerance, and modularity (Alon 2003).

Many biological systems have been studied from the perspective of network theory (Zhu et al. 2007), for example:

- ► [Transcription factors](#): Data obtained from chromatin immunoprecipitation (ChIP) followed by probing of genomic microarrays and from ► [DNA sequencing](#) has been used to assemble networks describing transcription factor binding sites in yeast and mammalian cells.
- *Protein-protein interactions*: Such interactions represent the most readily available biological networks to date. Data is generated from techniques such as two-hybrid assays and other high-throughput techniques such as purification and mass spectrometry. In such networks, nodes represent proteins with edges denoting physical interactions between proteins (Jeong et al. 2001). Examples of particular protein interaction networks studied include *Saccharomyces cerevisiae* (yeast), *Helicobacter pylori*

(► [bacteria](#)), as well as those in *Drosophila* and humans.

- *Metabolic networks*: Biochemical data has enabled the construction of *metabolic networks* (e.g., ► [glycolysis](#)) which describe the metabolic and physical processes that determine the physiological and biochemical properties of cells, usually focusing on the basic chemical pathways that generate the essential components used in biochemical reactions. Nodes in such networks generally represent enzymes, with edges denoting interactions between them (Jeong et al. 2000).
- *Immune networks*: The mammalian immune system can be considered as a number of interacting networks operating at different levels separated in both time and space. Within cells, *gene networks* link genes and transcription factors controlling gene expression; intracellular signaling networks link surface receptors on cells to gene-regulatory events; other cells of the immune system such as *B-cells* and *T-cells* communicate via mediators such as cytokines and hence form cellular networks (Callard and Stark 2007).
- *Neuronal networks*: The brain consists of intricately organized networks of cortical connections; these connections can be modeled by networks in which nodes are brain regions or areas and edges represent fiber connections between them (Kepes 2007).

The examples above provide a brief insight into the diversity of biological systems that can be modeled using a network approach. Despite the obvious differences between the systems listed, the network approach provides a common framework in which these systems can be analyzed and therefore compared. Such comparisons have revealed many similarities between networks, not only those derived from biological systems but also social systems (e.g., friendship networks) and engineered systems (e.g., the World Wide Web) (Barabási and Albert 1999). This tends to indicate generic principles of organization which can be exploited to gain further understanding and will ultimately enable systems biology to combine the numerous details about molecular interactions

into a single framework, thereby offering a means to address the structure of the ► [cell](#) as a whole.

Basic Methodology

Network topology plays a key role in understanding the architecture and function of biological networks. A number of measures are commonly used to describe the structure of a biological network:

- *Degree*: The degree of a node defines the numbers of links the node has to other nodes and is the most basic measure used. The average degree $\langle k \rangle$ can be calculated; however, a more useful measure is the degree distribution $P(k)$ which describes the number of nodes in the network having k links. A Poisson-shaped degree distribution indicates that there are no highly connected nodes; in contrast, a power-law degree distribution indicates the presence of a few highly connected nodes known as *hubs*.
- *Mean shortest path*: The shortest path is a measure of the navigability of a network and describes the mean shortest distance between any two nodes in the network. Biological networks (e.g., protein interaction networks and transcriptional networks) exhibit a *small-world* property in which the mean shortest path is very small.
- *Clustering coefficient*: This measures the average probability in a network that two nodes which have a mutual parent are also connected (Watts and Strogatz 1998); using social network terminology, this can be interpreted as “the friend of your friend is likely to be your friend.” The clustering coefficient reveals important information regarding network structure. $C(k)$ measures the average clustering coefficient of nodes with k links; if $C(k)$ is independent of k , the network is either homogeneous or it is dominated by numerous small tightly linked clusters. On the other hand, if $C(k)$ follows $C(k) \sim k^{-1}$, the network has a hierarchical architecture meaning that sparsely connected nodes are part of highly clustered

regions with communication between the different regions maintained by a few hubs (Wuchty et al. 2001).

These properties can be used to classify the topology of a network into a number of *models*. Biological networks tend to be *scale free* in that they are characterized by a degree distribution which follows a *power law* $P(k) \sim k^{-\gamma}$, i.e., most nodes in the network participate in very few interactions, but a small number participate in many and therefore function as *hubs*. Many biological systems are intrinsically *modular*, i.e., functionality is achieved via a set of physically or functionally linked modules which work together. Modularity is accounted for in *hierarchical network models* which assume that clusters can combine together in an iterative manner to generate a hierarchical or layered structure (Barabási and Oltvai 2004).

Key Research Findings

The application of network analysis techniques to biological systems, made possible by the abstraction of biological systems as networks, indicates:

- Power-law degree distributions emerge as a universal law characterizing cellular networks (Barabási and Albert 1999).
- Many biological networks have the same topological scaling properties as complex non-biological systems such as social networks or the World Wide Web, despite obvious differences in their components and structure, and furthermore show striking similarities to the inherent organization of nonbiological systems (Barabási and Albert 1999).
- Integrity and robustness of biological networks are facilitated by structures which contain a few highly connected hubs, e.g., genes which can integrate multiple signals or trigger widespread attacks (Wuchty et al. 2003; Jeong et al. 2001); this ensures robustness against random failures but at the same time makes them vulnerable to targeted attacks. This is consistent with experimental data suggesting that most mutations have little phenotypic effect but that networks are extremely vulnerable to attack at certain critical genes.
- The observed modularity found in biological networks via network analysis supports the notion that evolution acts over multiple levels (Wuchty et al. 2003); organisms can increase in complexity via copying and reuse of existing modules over time; furthermore, modules can be readily reconfigured to adapt to new conditions through evolution (Gerhart and Kirschner 1997).
- Many different biological systems contain common *motifs* – subgraphs of a network which are overrepresented when compared to a randomized version of the same network. For example, triangular motifs which have feed-forward functionality are found in both transcription-regulatory and feed-forward networks. Data obtained from yeast transcription networks points to the evolutionary conservation of key motif patterns with distinct functionalities.

Applications

Understanding the underlying structure of biological networks may eventually enable a complete description of the biological networks of a complete cell to be elucidated, promising great benefits to medicine in the future. The identification of hubs – the highly connected nodes in a network – leads to the possibility of being able to identify potential targets for drug design. The ability to target the high-degree proteins in a network could lead, for example, to new strategies for therapeutic mediation of signaling pathways in cancer. Interactions in metabolic networks are closely related to the ► *gene* functions and therefore have great potential for immediate applications in the interpretation of gene roles. Identification of unknown pathogenic genes might help shed light on disease pathogenic mechanisms (Zhu et al. 2007). Advancement in our understanding of cytokine connectivity architectures has already demonstrated that immune cells do not function merely as individual clones but work in innately integrated and hierarchical collectives, shedding new light on immune-body systems organization and our

understanding of the role of the immune system in wound healing and angiogenesis (Frankenstein et al. 2006). Manipulating the cytokine network has led to novel approaches in treating acute and chronic diseases, including cancer (Vilcek and Feldmann 2004).

Future Directions

Advancements in technology will increasingly extend our abilities to accurately collect vast quantities of data. This will be coupled with advancements in theoretical tools and methods which will continue to drive forward understanding of the complex interactions occurring *within* cells, extending our understanding to intercellular networks and eventually extending it to cellular networks of complete organisms.

The science of complex networks has already played a significant role in increasing understanding of the *structural* aspects of biological networks. Future research will additionally need to take account of the *dynamic* aspects of cellular networks, including temporal and spatial aspects of activity and interactions within biological networks. Development of a novel framework in which the function of biological networks can be interpreted heralds a new era of understanding of biology, disease pathologies, and medicine in the future.

Cross-References

- [Bioinformatics](#)
- [Cell](#)
- [Evolution, Biological](#)
- [Metabolism](#)
- [Protein](#)
- [Scale-Free Networks](#)

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Biological Radiation Effects

- [Ionizing Radiation, Biological Effects](#)

Biological Safety Level

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Synonyms

[BSL](#)

Definition

The biological safety level (BSL) is used in the USA to describe a set of specifications for the precautions required to isolate potentially hazardous biological agents in a containment facility at a specified stringency, ranging from BSL-1, which indicates the least strict containment, to BSL-4, which is the containment required for the most hazardous human pathogens. A similar scale is used in the European Union using the abbreviation P1-P4, where P indicates either pathogen or protection. For instance, a BSL-4 laboratory (P4 in Europe) is under reduced pressure relative to atmospheric pressure, the exhaust air is filtered, and all wastes including water and any hardware leaving the high-containment area are sterilized chemically or by heating. Trained personnel work inside the area in protective suits, overpressurized by air pumped in from outside through a dedicated system. The exterior of the suit is chemically disinfected when workers leave the area.

Biological Sensors

► [Biosensor](#)

Biomarker

► [Isotope Biosignatures](#)

Biomarkers

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Keywords

Chemical fossils · Molecular fossils ·
Morphological fossils

Synonyms

[Bioindex](#); [Biosignature](#); [Chemical fossil](#); [Molecular biomarkers](#); [Molecular biosignatures](#); [Morphological fossil](#); [Trace of life](#)

Definition

Biomarkers, biosignatures, and traces of life are three different terms or expressions related to the search for life in the Earth's rock record or beyond the Earth. However, they have different meanings, depending on the field of research where they are used or depending on the “philosophy” of the user.

Overview

Biomarkers or “markers of life” or “traces of life” include chemical, morphological, sedimentary, or isotopic processes or structures that are biogenic and could be detected to infer the past or present presence of life.

However, in practice, astrophysicists use “biomarkers” for gases of possible biological origin that could be detected in a planetary atmosphere. Geochemists use “biomarkers” for ► [molecular fossils](#) (fossil molecules such as steranes and hopanes). Paleontologists use “biomarkers” for morphological and biosedimentary fossils. Some scientists would use “biomarkers” for all possible traces of life. The term “biosignatures” is very common in the literature as a general term for all possible traces of life. However, astrobiologists now realize that discriminating possible traces of life from unambiguous traces of life is extremely difficult in the early Earth rock record and even more challenging in an extraterrestrial context. Detecting life requires a set of multidisciplinary approaches and criteria and a large (and always improving but never completed) understanding of natural processes. Therefore, rather than using the term “signatures” or “biosignatures,” the expression

“traces of life” or even better “indices of life” or “bioindices” should be favored.

Cross-References

- Biogenicity
- Biomarkers, Morphological
- Biomarkers, Spectral
- Biomineralization
- Dubiofossil
- Earth's Atmosphere, History of the Origins
- Endogenicity
- Fossil
- Fossilization, Process of
- Molecular Fossils
- Pseudofossil
- Syngenicity

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Biomarkers (Atmosphere)

John Lee Grenfell¹ and Sébastien Lebonnois²

¹Institut für Planetenforschung, Extrasolare Planeten und Atmosphären, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany

²Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, CNRS, Paris, France

Synonyms

Bioindicators

Definition

In exoplanet science the term “biomarker” or “bioindicator” refers to an indication (or “hint”) that life as we know it could be present – but in order to decide more definitively, additional information would be required.

Overview

The detection, e.g., of atmospheric methane in an exoplanetary atmosphere would constitute a biomarker because additional information is needed in order to determine whether or not the source is biological. This, in the case of methane, can be tested, e.g., by comparing the ratio of its outgassing amount with other outgassed species such as H₂ (see, e.g., Oze et al. 2012) and/or by determining the carbon isotope ratio (as discussed in the review of Etiope and Sherwood Lollar 2013). In contrast, the term “biosignature” refers to a robust signal that is strongly suggestive of life. For example, the atmospheric detection of an Earth-like amount of nitrous oxide (N₂O) for an Earth-like planet orbiting a sun-like star would constitute a biosignature because according to current knowledge, such a signal could not be produced by anything other than microbes. In other words, the known atmospheric abiotic sources (for an overview see, e.g., Kaiser and Röckmann 2005) for this gas are much too slow to “mimic” life in such a case.

The boundary between a biomarker and a biosignature is not strictly defined. Strong (technological) biosignatures indicative of advanced life have been suggested, e.g., the detection of emitted electromagnetic waves similar to those on Earth or the atmospheric detection of (industrially produced) chlorofluorocarbons. In such cases, it is unforeseeable as to how these signals could arise without (intelligent) life.

The detection of O₂ (hence O₃ from which it is formed) would immediately initiate a debate as to the origin – biotic or otherwise – of such signals. Any process which produces significant

atomic oxygen (O), e.g., via CO₂ photolysis (potentially important in thick, Venus-like atmospheres) and/or H₂O photolysis (potentially important in hot, steam atmospheres), can, via the self-reaction of O, lead to abiotic O₂ production in the atmosphere. Selsis et al. (2002) discuss these issues. To address the question whether *Earth-like amounts* of atmospheric O₂ and O₃ could constitute a biosignature, would therefore benefit from more theoretical studies to improve understanding of the associated range of abiotic sources.

Vegetation on Earth produces simple organic molecules such as chloromethane (CH₃Cl) (Hewitt and Jackson 2009), but again each case in hand would need to be investigated by applying theoretical studies adapted to the particular conditions (e.g., stellar flux, spectrum, etc.) in order to determine the (in situ abiotic) gas-phase sources. In this process of elimination, life is the “last man standing.”

Cross-References

- [Biomarkers Atmospheric, Evolution over Geological Time](#)
- [Biomarkers, Spectral](#)
- [False Negative](#)
- [False Positive](#)

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Biomarkers Atmospheric, Evolution over Geological Time

Lisa Kaltenegger

Cornell University, Ithaca, NY, USA

Definition

The spectrum of the Earth has not been static throughout the past 4.6 billion years. This is due to the temporal variations in atmospheric molecular abundances and temperature structure and in the surface morphology and ► [albedo](#). Observations of Earth-like planets at different geological ages will certainly help us understand the diversity and some common features of terrestrial planets, including ours. For our own planet, models show varying biomarkers over geological times that could be detected in the spectrum (see, e.g., Schindler and Kasting 2000; Pavlov et al. 2000; Traub and Jucks 2006; Kaltenegger et al. 2007) to characterize it in terms of habitability and the possible presence of life.

Cross-References

- [Albedo](#)
- [Atmospheric Retrieval for Exoplanets](#)
- [Biomarkers \(Atmosphere\)](#)
- [Biomarkers, Spectral](#)
- [Habitability of the Solar System](#)
- [Habitability, Role of the Atmosphere](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)

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Biomarkers, Morphological

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Keywords

Biominerals · Biosignatures · Fossils ·
Microfossils · MISS · Stromatolites · Traces of
life

Synonyms

[Biosignature](#); [Trace of life](#)

Definition

Morphological biosignatures comprise objects or structures of biological origin. They include body fossils, biominerals, and microbially influenced sedimentary structures preserved in carbonates (such as ► [stromatolites](#)), in siliciclastics (such as MISS), or other rock types.

Overview

Body fossils include microfossils and macrofossils of various compositions and modes of fossilization. Microbially influenced sedimentary structures include stromatolites (laminated carbonate rocks precipitated or trapped by microorganisms), thrombolites (unlaminated carbonate rocks precipitated or trapped by microorganisms), oncolites (small carbonate spheres with concentric laminations precipitated by

microorganisms), and MISS (a range of sedimentary structures produced by the presence and activity of ► [microbial mats](#) in siliciclastic sediments). Biominerals can be passively produced or actively produced by the organisms, and the frontier between a biological or abiological origin is tenuous. Ichnofossils or fossil traces of activities such as burrows, trails, and tracks are sometimes considered as morphological biomarkers. Abiotic processes can produce structures resembling microfossils (► [Pseudofossil](#)). Chemical precipitates can look like stromatolites. Minerals can self-assemble into complex structures that resemble body fossils or biominerals. Deciphering the ► [biogenicity](#) of an object or a structure is thus very difficult even using cutting-edge in situ techniques. Several criteria have been proposed in the literature in order to test their biogenicity. Most of them underline the importance of proving the endogenicity, the syngeneity, and the biogenicity of the structures in question in a well-characterized geological context. An additional falsification approach is required to exclude all possible abiotic hypotheses before a biological origin can be accepted.

Basic Methodology

Geobiological investigations in recent and past environments have determined the criteria for biogenicity of macroscopic and microscopic morphological signatures of life.

Laboratory studies including artificial cell degradation, bioalteration of minerals, and mineralization experiments might reveal biotic patterns and preservable properties, although these studies may not reflect the full complexity of natural environmental conditions. Documentation of abiotic patterns and morphologies is also essential, but is difficult outside the lab on our biological planet.

When trying to understand the origin of a possible morphological biomarker, three main aspects need to be considered: (1) The preservational environments: what conditions preserve cells with varying biochemical properties?

(2) The taphonomy: how do processes of degradation and preservation retain, alter, or erase original biological properties? (3) The criteria for biogenicity: how can we tell biological from nonbiological?

Key Research Findings and Applications

Body Fossils

A body fossil is any morphological remain of an organism after its death. It can have various sizes (microscopic to macroscopic) and composition (organic or mineral) and may represent a whole organism, part of an organism, or colonial organisms. Body fossils can have a variety of morphologies and chemical composition, depending on their original properties and the conditions in which they are preserved. The organic composition may be transformed to various extents or erased by the complex processes of fossilization. The mineral composition may be primary (produced or precipitated by the organism) or secondary (the original carbonaceous or mineral walls or envelopes being in that case partially or completely replaced by other minerals). Body fossils may also be preserved as molds. In that case, the fossils are first dissolved then the hole in shape of the fossil is filled with a secondary mineral.

It is difficult to prove the biogenicity of microscopic body fossils in absence of carbonaceous material. Microscopic cellular casts and molds formed by various minerals can preserve or obscure the presence of a sheath and/or significantly alter the size of the microbes. For example, bacterial cells preserved by silicification (replaced by silica) are difficult to discriminate from chemical precipitates. The organic composition of a structure does not prove its biogenicity. The term “organic” just indicates the presence of molecules with carbon and hydrogen. Organic matter is common in the universe and occurs in interstellar medium and in meteorites or is produced abiotically by chemical reactions in hydrothermal conditions on Earth. Therefore, more criteria are required to assert the biogenicity of carbonaceous material.

Microscopic and microchemical analyses of fossils isolated from shales or embedded in various rocks are needed to demonstrate a range of preservable biological properties, as well as to determine the taphonomic processes specific to the preservational environment and to the original biology. The microfossils can be characterized by their preserved walls (structure and ultrastructure) or sheaths, pigment and biopolymer composition, morphology (regular cellular shape, complex shape, ornamentation, structured organic matter), abundance (population) and distribution in the rock, orientation recording behavior and motility of benthic organisms (e.g., mats with vertical filaments erected toward light), or passive sedimentation of planktonic cells, pattern of cellular division, and, very importantly, their taphonomy (producing features such as collapsed folded flexible hollow vesicles, sinuous segmented filamentous shape, and pigmented surfaces of colonies).

Biominerals

Biominerals are minerals formed by organisms. Biominerals can be passively produced or actively produced by the organisms, and the frontier between a biological or abiological origin is ambiguous. Biologically induced mineralization (BIM) includes biominerals formed through the metabolic activity of microorganisms. Biologically controlled mineralization (BCM) includes biominerals whose formation is genetically controlled by microorganisms. Associations of biological tissues with minerals like bones or macroscopic and microscopic shells or plates are easy to consider as body fossils and are examples of BCM. Microscopic mineral precipitates onto cells or sheaths or coated streamers or filament bundles are more difficult to interpret in absence of the cell or filament and can be BIM or BCM. These precipitates may or may not form in absence of the microorganisms. The controversy regarding the magnetite minerals found in the Martian meteorite ALH84001 is a good illustration of the problem. Observations in natural settings and experiments in the laboratory can help determine criteria for biogenicity.

Microbially Induced Sedimentary Structures (MISS) and Stromatolites

These structures are produced by the interaction between a microbial mat and the surrounding sedimentary environment. They can be preserved in carbonates or in siliciclastics. They include a variety of laminated or unlaminated precipitates and/or trapped and bound mineral grains. ► [Stromatolites](#) are found in the rock record since the early Archean. They reach large sizes around 2.7 Ga when their biogenicity is not questioned. Criteria such as rock fabrics, presence and distribution of carbonaceous material or cells or filaments, unevenness of laminae, angle of repose of laminae, etc., are investigated to prove or disprove the biogenicity of these carbonate structures.

The process controlling the genesis of stromatolites is not yet well understood, although the association of macroscopic morphology with water energy is clear. Other structures indicating the presence of microbial mat interacting with the sediment include particular fabric in sandstone, pinnacles, and other irregular mat surface morphologies. Again, observations in natural settings and experiments in the laboratory can help determine criteria of biogenicity. The presence of body fossils strengthens the biogenicity of the ► [microbially induced sedimentary structures](#).

Future Directions

Defining morphological (and other) biosignatures is not a simple task. The taphonomic processes differ depending on the preservational environments and the original biology, leading to bias in fossil diversity and morphology, often preventing identification or even recognition. A better understanding of these environments and their particular fossilization processes will help to make predictions of the types of biosignatures to search for in possible past or present extraterrestrial habitats (where and what to look for), important when deciding landing sites and instrumentation for exobiological missions in situ and for returned

samples. Characterizing the taphonomic processes and the criteria for recognition of biogenicity will help interpret future observations in early Earth and extraterrestrial records.

However, the early Archean record of stromatolites and of microscopic biosignatures is still actively debated, illustrating the difficulty (or impossibility) of defining unambiguous traces of life in very old rocks, much less on another planet where knowledge of the geological background is limited. Therefore, when searching for traces of life in ancient and extraterrestrial materials, a multitude of complementary studies and biomarkers or bio-indices (not only morphological biomarkers) should be used. All possible abiotic explanations should be considered and discarded before reaching an acceptable level of reliability in any interpretation of biogenicity. Nevertheless, the conclusions will always be limited by our current understanding of the natural processes involved.

Cross-References

- [Biomarkers](#)
- [Biomineralization](#)
- [Dubiofossil](#)
- [Fossil](#)
- [Fossilization, Process of](#)
- [Mars](#)
- [Microbial Mats](#)
- [Microbially Induced Sedimentary Structures](#)
- [Microfossils, Analytical Techniques](#)
- [Pseudofossil](#)
- [Rio Tinto](#)
- [Stromatolites](#)

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and characterize a planetary environment. Here we concentrate on characterizing a habitable planet using spectroscopy and discuss which features could point toward a biological origin (see also ► [Habitable planet, characterization](#); [Habitability, effects of eccentricity](#); ► [Habitability, effects of stellar irradiation](#); ► [Habitability of the solar system](#)).

History

Sagan et al. (1993) analyzed a spectrum of the Earth taken by the Galileo probe, searching for signatures of life, and concluded that the large amount of O₂ and the simultaneous presence of traces of CH₄ are strongly suggestive of biology. After a decade rich in giant exoplanet detections, observational techniques have now reached the ability to find planets of less than 10 M_{Earth} (so-called ► [Super-Earths](#)) that may potentially be habitable.

Overview

We discuss how we can read a planet's spectrum to assess its habitability and search for the spectral signatures of a biosphere. To characterize a planet's atmosphere and its potential habitability, we look for absorption features in the reflection and transmission spectrum of the planet. On Earth, some atmospheric species exhibiting noticeable spectral features in the planet's spectrum result directly or indirectly from biological activity: The main ones are O₂, O₃, CH₄, and N₂O. CO₂ and H₂O are in addition important as greenhouse gases in a planet's atmosphere and potential sources for high O₂ concentration from photosynthesis. Future remote-sensing characterization of planetary environments can be used to test our understanding of the factors that contribute to planetary habitability. To detect such features remotely with first-generation spectroscopy mission that will not resolve the planet, the atmosphere has to show such chemical features globally.

Biomarkers, Spectral

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Keywords

Biomarkers · Extrasolar planets · Habitability · Habitable zone · Planetary atmospheres · Spectroscopy

Definition

The spectrum of a planet can contain signatures of atmospheric species that can remotely indicate habitable conditions. Some of the chemical species can indicate habitable conditions and some (combinations) can indicate biota on a planet. It is their presence and abundance along with other atmospheric species, in a certain context (e.g., the properties of the star and the planet), that can explore the underlying physics

Introduction

Dedicated future space missions will have the explicit purpose of detecting other Earth-like worlds, analyzing their characteristics, determining the composition of their atmospheres, investigating their capability to sustain life as we know it, and searching for signs of life. This can set our own planet, the only known habitat, in context with other rocky worlds and expand our statistics of 3 for rocky planets that could potentially support life. Searches will concentrate on planets in the so-called ► [habitable zone](#) (HZ) where water could remain liquid if present and gases produced by biota could easily exchange with and influence the atmosphere. The HZ is defined for surface conditions only.

Our search for signs of life is based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth, in that it requires liquid water as a solvent and has a carbon-based chemistry (see, e.g., Brack 1993; Des Marais et al. 2002). Life on the basis of a different chemistry is not considered here, because the vast range of conceivably possible life-forms might produce signatures in their atmosphere that are so far unknown. Therefore, we assume that extraterrestrial life is similar to life on Earth in its use of the same input and output gases and that it exists out of thermodynamic equilibrium (Lovelock 1975). “Biomarkers” here refer to detectable species or a set of species, whose presence at significant abundance strongly suggests a biological origin (e.g., couple $\text{CH}_4 + \text{O}_2$ or $\text{CH}_4 + \text{O}_3$ (Lovelock 1975)). A bioindicator is maybe indicative of biological processes but can also be produced abiotically.

Chemoautotrophic life, whose metabolism does not depend on the stellar light, can still exist outside the HZ, thriving in the interior of the planet where liquid water is available. Such metabolisms (see Extremophile) rely on very limited sources of energy (compared to stellar light) and electron donors (compared to H_2O on Earth). They mainly catalyze reactions that would occur at a slower rate in purely abiotic conditions, and they are thus not expected to modify a whole planetary environment in a way detectable remotely.

Basic Methodology

Atmospheric Features of a Habitable Planet

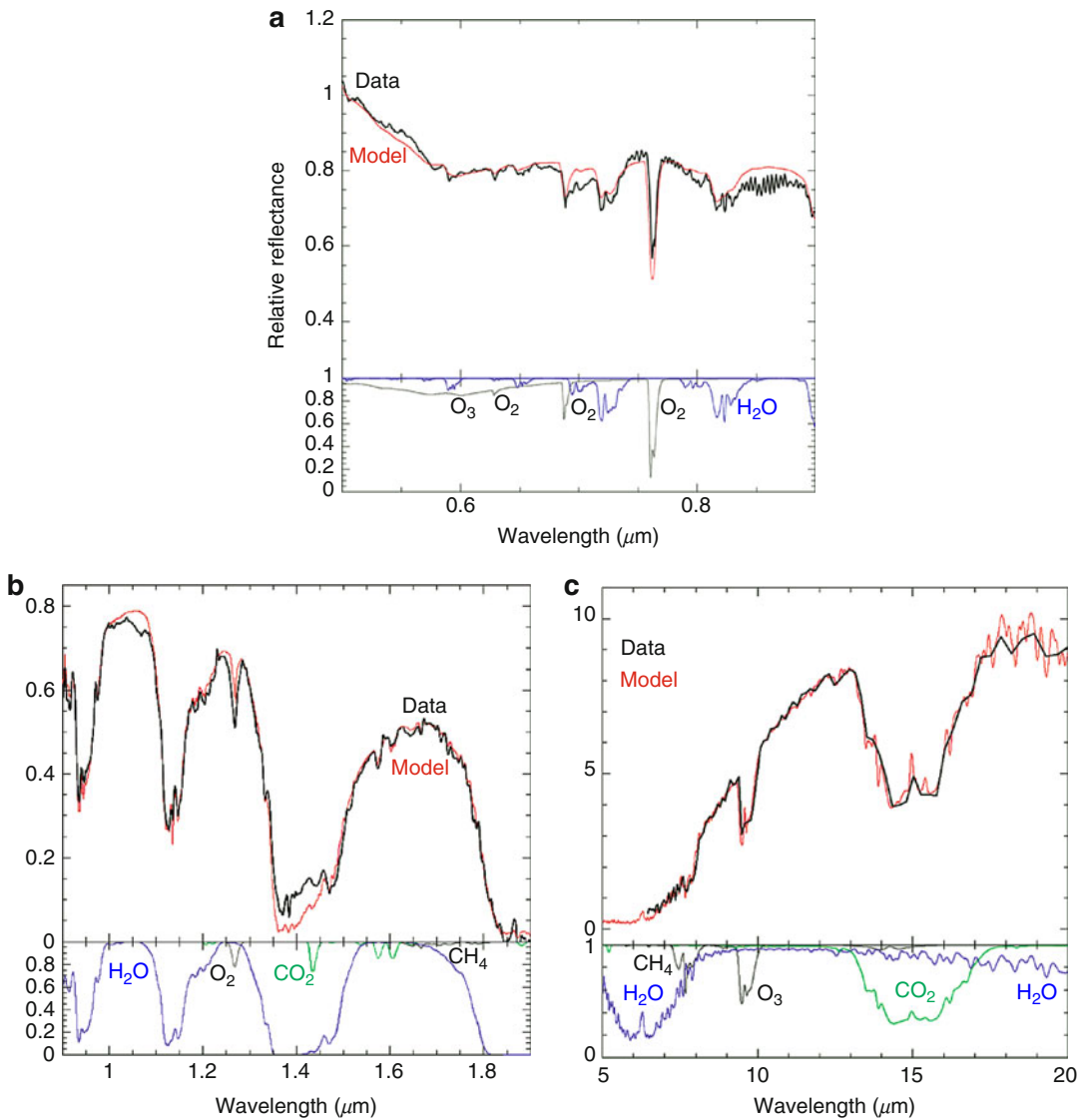
A planet observed remotely is a very faint, small object close to a very bright and large object, its parent star. The Earth is about a million times fainter than the Sun in the mid-infrared and about a billion times fainter than the Sun in the visible. Suppressing the starlight to that degree allows collecting the planet’s light and characterizing its atmosphere.

Key Research Findings

Spectra of Earth in Reflection, Emission, and Transmission

Figure 1 shows observations and model fits to the spectra of the Earth in three wavelength ranges, the visible and near infrared represent the reflected starlight, while the infrared (IR) spectrum is generated by the emitted heat flux of the planet (Kaltenegger et al. 2007). For the data shown in Fig. 1 (a) is the visible earthshine spectrum (Woollf et al. 2002), (b) is the near-infrared earthshine (defined as light from the Sun reflected from the Earth to the Moon and back again) spectrum (Turnbull et al. 2006), and (c) is the thermal infrared spectrum of the Earth as measured by a spectrometer en route to Mars (Christensen and Pearl 1997). The data are shown in black and the Smithsonian Astrophysical Observatory model in red. In each case, the constituent gas spectra in a clear atmosphere are shown below, illustrating how each molecule contributes to the overall spectrum.

Figure 2a shows observations (Iriarte 2002) and model fits to transmission spectra of the Earth (Kaltenegger and Traub 2009) that represent the transit of the Earth. The data are shown in blue and the model in red. A transmission spectrum gives the apparent radius of a planet versus wavelength. Different molecules in the planet’s atmosphere absorb part of the stellar light and make the planet appear bigger than its solid radius at characteristic wavelengths, depending on the molecule. This is shown here as effective height in the atmosphere. The



Biomarkers, Spectral, Fig. 1 Observed reflectivity spectrum in the visible (Woolf et al. 2002) (a) and near infrared (Turnbull et al. 2006) (b) and emission spectrum in the infrared (IR) (Christensen and Pearl 1997) (c) of the

integrated Earth, as determined from earthshine and space, respectively. The data are shown in black and the Smithsonian Astrophysical Observatory model in red. The reflectivity scale is arbitrary

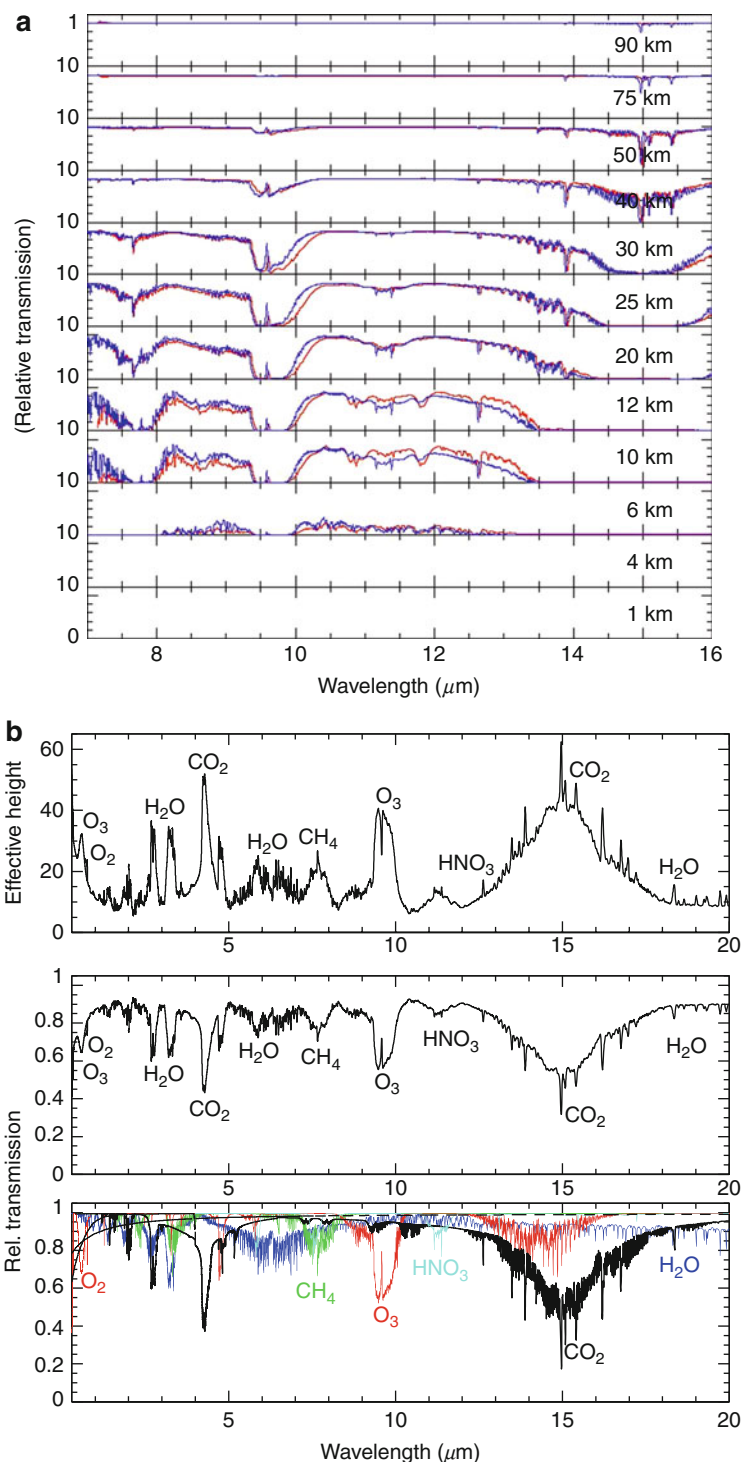
atmospheric features are indicated. For details on the Earth's transmission spectrum during a lunar eclipse, see Palle et al. (2009) and Vidal-Madjar et al. (2010).

Both spectral regions contain the signature of atmospheric gases that may indicate habitable conditions and, possibly, the presence of a biosphere: CO_2 , H_2O , O_3 , CH_4 , and N_2O in the

thermal infrared and H_2O , O_3 , O_2 , CH_4 , and CO_2 in the visible to near infrared in reflection (Fig. 1) and transmission spectra (Fig. 2). The presence or absence of these spectral features (detected individually or collectively) will indicate similarities or differences among the atmospheres of terrestrial planets and their astrobiological potential.

Biomarkers, Spectral,

Fig. 2 Synthetic transmission spectra of the Earth from UV to IR (Kaltenegger and Traub 2009) for a cloudless atmosphere based on shuttle data (Irione 2002) and calculated for a line of sight at the tangent height indicated on the right (a). A transmission spectrum gives the apparent radius of a planet versus wavelength. Different molecules in the planet's atmosphere absorb the stellar light and make the planet appear bigger than its solid radius at characteristic wavelengths, depending on the molecule. This is shown here as effective height in the atmosphere (b). The atmospheric features are indicated below

**Characterizing Planetary Environments**

It is relatively straightforward to remotely ascertain that the Earth is a habitable planet, replete

with oceans, a greenhouse atmosphere, global geochemical cycles, and life – if one has data with arbitrarily high signal-to-noise ratio and

spatial and spectral resolutions. The interpretation of observations of other planets with limited signal-to-noise ratio and spectral resolution, as well as absolutely no spatial resolution, as envisioned for the first-generation instruments, will be far more challenging. This implies that we need to gather information on the planet's environment to understand what we will see. We can then test if we have an abiotic explanation of all compounds seen in the atmosphere of such a planet. If we do not, we can work with the exciting biotic hypothesis.

O₂ and O₃ in combination with a reducing gas like CH₄ are good biomarker candidates. Reduced gases and oxygen have to be produced concurrently to be detectable in the atmosphere, as they react rapidly with each other. Thus, the chemical imbalance traced by the simultaneous signature of O₂ and/or O₃ and of a reduced gas like CH₄ can be considered as a signature of biological activity (Lovelock 1975). These species can be detected by a low-resolution spectrograph (O₂ in the visible with a resolution <100, O₃ and CH₄ in the infrared with a resolution <50). Note that if the presence of biogenic gases such as O₂/O₃ + CH₄ may imply the presence of a massive and active biosphere, their absence does not imply the absence of life. Life existed on Earth before the interplay between oxygenic photosynthesis and carbon cycling produced an oxygen-rich atmosphere.

Temperature and Radius of a Planet

Knowing the temperature and planetary radius is crucial for a general understanding of the physical and chemical processes occurring on the planet (e.g., tectonism, atmosphere, escape). In theory, spectroscopy can provide some detailed information on the thermal profile of a planetary atmosphere (see atmospheric structure). This, however, requires a spectral resolution and a sensitivity that are well beyond the performance of a first-generation spacecraft. Generally, the surface temperature of a planet at a specific distance from its star depends on its ► [albedo](#) and on the greenhouse warming by atmospheric compounds. However, even with a low-resolution spectrum of the thermal emission, the mean effective temperature can be obtained from the peak of the

blackbody curve in the infrared (IR). The measured IR flux can directly be converted into a brightness temperature that will provide information on the temperature of the atmospheric layers responsible for the emission. The overall flux of the planet in the IR is determined by the surface area of the planet and its effective temperature; therefore, the radius of the emitting surface (e.g., ground or cloud layers; see ► [Clouds](#)) of the planet can be obtained.

The ability to associate the spectrum with a surface temperature relies on the existence and identification of spectral windows probing the surface or specific atmospheric levels. Such identification is not trivial. For an Earth-like planet, there are some atmospheric windows that can be used in most of the cases, especially between 8 and 11 µm. This window would, however, become opaque at high H₂O partial pressure (e.g., in the inner part of the habitable zone (HZ) where a lot of water is vaporized) and at high CO₂ pressure (e.g., a very young Earth or the outer part of the HZ). The accuracy of the radius and temperature determination will depend on the quality of the fit (and thus on the sensitivity and resolution of the spectrum), the precision of the Sun-star distance, the cloud coverage, and also the distribution of brightness temperatures over the planetary surface. Assuming the effective temperature of our planet were radiated from the uppermost cloud deck at about 12 km would introduce about 2% error on the Earth's radius derived from emergent and/or transmission spectra. For transiting planets, the accuracy of the radius of the planet depends on how well the host star is characterized.

Potential Biomarkers

Owen (1980) suggested searching for O₂ as a tracer of life. Oxygen in high abundance is a promising bioindicator. Oxygenic photosynthesis, the by-product of which is molecular oxygen extracted from water, allows terrestrial plants and photosynthetic bacteria (cyanobacteria) to use abundant H₂O, instead of having to rely on scarce supplies of electron donors like H₂ and H₂S to reduce CO₂. With oxygenic photosynthesis, the production of the biomass becomes limited only by nutrients and no longer by energy (light in this

case) nor by the abundance of electron donors. Oxygenic photosynthesis at a planetary scale results in the storage of large amounts of radiative energy in chemical energy, in the form of organic matter. For this reason, oxygenic photosynthesis had a tremendous impact on biogeochemical cycles on Earth and eventually resulted in the global transformation of the Earth's environment. Less than 1 ppm of atmospheric O_2 comes from abiotic processes (Walker 1977). Cyanobacteria and plants are responsible for the biotic production by using solar photons to extract hydrogen from water and using it to produce organic molecules from CO_2 . This metabolism is called oxygenic photosynthesis. The reverse reaction, using O_2 to oxidize the organics produced by photosynthesis, can occur abiotically when organics are exposed to free oxygen or biotically by both eukaryotes and certain prokaryotes using O_2 and consuming organics.

Due to a balance in the above processes, the net release of O_2 in the atmosphere actually depends on the burial of organics in sediments. Each reduced carbon buried results in a free O_2 molecule in the atmosphere. This net release rate is also counterbalanced by the weathering of fossilized carbon when exposed to the surface. The oxidation of reduced volcanic gases such as H_2 and H_2S also accounts for a significant fraction of the oxygen losses. The atmospheric oxygen is recycled through respiration and photosynthesis in less than 10,000 years. In the case of a total extinction of the Earth's biosphere, the atmospheric O_2 would disappear in a few million years.

The spectrum of the Earth has exhibited a strong infrared signature of ozone for more than 2 billion years and a strong visible signature of O_2 for an undetermined period of time between 2 and 0.8 billion years (depending on the required depth of the band for detection and also the actual evolution of the O_2 level; Kaltenegger et al. 2007). This difference is due to the fact that a saturated ozone band appears already at very low levels of O_2 (10^{-4} ppm), while the oxygen line remains unsaturated at values below the present atmospheric level (Segura et al. 2003). The depth of the saturated O_3 band is determined by the temperature difference between the surface-to-clouds

region (producing the spectral continuum) and the ozone layer.

N_2O is produced in abundance by microbial life but only in negligible amounts by abiotic processes. Nearly all of Earth's N_2O is produced by the activities of anaerobic nitrifying and denitrifying bacteria. N_2O would nevertheless be hard to detect in the Earth's atmosphere with low resolution, as its abundance is low at the surface (0.3 ppmv) and falls off rapidly in the stratosphere. Spectral features of N_2O would become more apparent in atmospheres with more N_2O and/or less H_2O vapor. Segura et al. (2003) have calculated the level of N_2O for different O_2 levels and found that its abundance decreases together with O_2 .

The methane found in the present atmosphere of the Earth has a biological origin, except for a small fraction produced abiotically in hydrothermal systems where hydrogen is released by the oxidation of ferrous iron by H_2O and reacts with CO_2 . Depending on the degree of oxidation of a planet's crust and upper mantle, such non-biological mechanisms can produce large amounts of CH_4 under certain circumstances. Therefore, the detection of methane alone cannot be considered a sign of life, while its detection in an oxygen-rich atmosphere would be difficult to explain in the absence of a biosphere. Note that methane on Mars has been suggested (Mumma et al. 2009), while the atmosphere of Mars contains 0.1% of O_2 and some ozone. In this case, the amounts involved are extremely low, and the origin of the Martian O_2 and O_3 is known to be photochemical reactions initiated by the photolysis of CO_2 and water vapor. If confirmed, the presence of methane could be explained by subsurface geochemical process, assuming that reducing conditions exist on Mars below the highly oxidized surface. The case of NH_3 is similar to the one of CH_4 . They are both released into the Earth's atmosphere by the biosphere with broadly similar rates, but the atmospheric abundance of NH_3 is orders of magnitude lower due to its very short lifetime under UV irradiation. The detection of NH_3 in the atmosphere of a habitable planet would thus be extremely interesting, especially if found with oxidized species. The detection of H_2O and CO_2 are important in the search

for signs of life not as biosignatures themselves but because they are raw materials for life and thus necessary for planetary habitability.

There are other molecules that could, under some circumstances, act as excellent biomarkers; for example, the manufactured chlorofluorocarbons (CCl_2F_2 and CCl_3F) are observed in our current atmosphere in the thermal infrared wave band, but their abundances are currently too low to be spectroscopically observed at low resolution.

Applications

Low-Resolution Spectral Information in the Visible to Near IR

In the visible to near infrared, one can see increasingly strong telluric H_2O bands at 0.73, 0.82, 0.95, and 1.14 μm . The strongest O_2 feature is the saturated Fraunhofer A-band at 0.76 μm . A weaker feature at 0.69 μm cannot be seen with low resolution. O_3 has a broad feature, the Chappuis band, which appears as a broad triangular dip in the middle of the visible spectrum from about 0.45 to 0.74 μm . The feature is very broad and shallow. Methane at present terrestrial abundance (1.65 ppm) has no significant visible absorption features, but at high abundance it has strong visible bands at 0.88 and 1.04 μm , readily detectable, for example, in early Earth models. CO_2 has negligible visible features at present Earth abundance, but in a high CO_2 atmosphere of 10% CO_2 , like in an early Earth evolution stage, the weak 1.06- μm band could be observed. In the UV, O_3 shows a strong feature that is not discussed here. The red edge of land plants due to chlorophyll developed about 0.44 Ga. It could be observed on a cloudless Earth or if the cloud pattern is known.

Low-Resolution Spectral Information in the Mid-IR

In the mid-IR for Earth, the detectable signatures of biological activity in low resolution are the combined detection of the 9.6- μm O_3 band, the 15- μm CO_2 band, and the 6.3- μm H_2O band or its rotational band that extends from 12 μm out into the microwave region (Selsis 2003). The 9.6- μm O_3 band is highly saturated and is thus a poor

quantitative indicator but an excellent qualitative indicator for the existence of even traces of O_2 . CH_4 is not readily identified using low-resolution spectroscopy for present-day Earth, but the methane feature at 7.66 μm in the IR is easily detectable at higher abundances (e.g., 100 $\times$ on early Earth; Kaltenegger et al. 2007), provided that the spectrum contains the whole band and a high enough signal-to-noise ratio. Taken together with molecular oxygen, abundant CH_4 can indicate biological processes (see also Sagan et al. 1993; Segura et al. 2003). Although methane's abundance is less than 2 ppm in the Earth's atmosphere, the 7.75- μm band shows up in a medium-resolution ($\text{Res} = 100$) infrared spectrum. Three N_2O features in the thermal infrared are detectable at 7.75 and 8.52 μm and at 16.89 μm for levels higher than in the present atmosphere of the Earth.

Abiotic Sources of Biomarkers

Abiotic sources of biomarkers are very important to assess, so that we can identify when they might constitute a ► “false positive” for life. CH_4 is an abundant constituent of the cold planetary atmospheres in the outer solar system. On Earth, it is produced abiotically in hydrothermal systems where H_2 (produced from the oxidation of Fe by water) reacts with CO_2 in a certain range of pressures and temperatures. In the absence of atmospheric oxygen, abiotic methane could build up to detectable levels. Therefore, the detection of CH_4 cannot be attributed unambiguously to life.

O_2 also has abiotic sources, e.g., (a) the photolysis of CO_2 , followed by recombination of O atoms to form O_2 ($\text{O} + \text{O} + \text{M} \rightarrow \text{O}_2 + \text{M}$), and (b) the photolysis of H_2O followed by escape of hydrogen to space. The first source results in a steady state maintained by photodissociation by the stellar UV radiation but with a constant elemental composition of the atmosphere, while the second one is a net source of oxygen. In order to reach detectable levels of O_2 (in the reflected spectrum), the photolysis of CO_2 has to occur in the absence of outgassing of reduced species and in the absence of liquid water, because of the wet deposition of oxidized species. Normally, the detection of the water vapor bands simultaneously with the O_2 band can rule out this abiotic mechanism (Segura

et al. 2007), although one should be careful, as the vapor pressure of H₂O over a high-albedo icy surface might be high enough to produce detectable H₂O bands. In the infrared, this process cannot produce a detectable O₃ feature (Selsis et al. 2002). The loss of hydrogen to space can result in massive oxygen leftovers: More than 200 bars of oxygen could build up after the loss of the hydrogen contained in the Earth's oceans. However, the case of Venus tells us that such oxygen leftover has a limited lifetime in the atmosphere (because of the oxidation of the crust and the loss of oxygen to space): We do not find O₂ in the Venusian atmosphere despite the massive loss of water probably experienced in the early history of the planet. Also, such evaporation-induced buildup of O₂ should occur only closer to a certain distance from the star and affect small planets with low gravity more dramatically than more massive planets. For small planets ($<0.5 M_{\text{Earth}}$) close to the inner edge of the habitable zone, there is a risk of abiotic oxygen detection, but this risk becomes negligible for big planets further away from their star. The fact that on the Earth oxygen and indirectly ozone are by-products of the biological activity does not mean that life is the only process able to enrich an atmosphere with these compounds. The question of the abiotic synthesis of biomarkers is crucial, but only very few studies have been dedicated to it (Rosenqvist and Chassefiere 1995; Leger et al. 1993; Lagrange et al. 2009; Selsis et al. 2002).

Cryptic Worlds

On the Earth, photosynthetic organisms are responsible for the production of nearly all of the oxygen in the atmosphere. However, in many regions of the Earth, and particularly where surface conditions are extreme, for example, in hot and cold deserts, photosynthetic organisms can be driven into and under substrates where light is still sufficient for photosynthesis. These communities exhibit no detectable surface spectral signature. The same is true of the assemblages of photosynthetic organisms at more than a few meters depth in water bodies. These communities are widespread and dominate local photosynthetic productivity on Earth. Such worlds could be very interesting Earth analogues that could

be habitats but cannot exhibit a biological surface feature, such as that due to chlorophyll, in the disk-averaged spectrum (Cockell et al. 2009).

Summary

Dedicated future space missions will have the explicit purpose of detecting other Earth-like worlds, analyzing their characteristics, determining the composition of their atmospheres, investigating their capability to sustain life as we know it, and searching for signs of life. These searches for signs of life will be based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth, in that it requires liquid water as a solvent, has an energy source, and has a carbon-based chemistry. Life on the basis of a different chemistry is not considered here, because the vast possible range of conceivable life-forms might produce signatures in their atmosphere that so far are unknown. We have identified some remotely detectable biomarkers whose presence at significant abundance would strongly suggest a biological origin (e.g., the couples CH₄ + O₂ or CH₄ + O₃ (Lovelock 1975) or N₂O). In addition to searching for signs of life, we need to understand how the observed atmosphere physically and chemically works.

Future Directions

Models of habitable worlds with different parameters (e.g., age, mass, size, composition, temperature, and biota) expand our knowledge of how a habitable planet's spectrum could appear and how robust our definition of biomarkers is. We are just starting to learn how to characterize habitable planets remotely. The results of a first-generation mission will most likely result in an amazing scope of diverse planets that will place our own planet in an overall context.

Cross-References

- [Albedo](#)
- [Atmosphere, Structure](#)

- ▶ Biomarkers Atmospheric, Evolution Over Geological Time
- ▶ Clouds
- ▶ Greenhouse Effect
- ▶ Habitability of the Solar System
- ▶ Habitability, Effect of Eccentricity
- ▶ Habitability, Effects of Stellar Irradiation
- ▶ Habitable Planet, Characterization
- ▶ Habitable Zone
- ▶ Habitable Zone, Effect of Tidal Locking
- ▶ Mars
- ▶ Super-Earths
- ▶ Venus

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Biomineralization

Karim Benzerara

Institut de Minéralogie et de Physique des Milieux Condensés, UMR 7590, CNRS, Sorbonne Université & Muséum National d'Histoire Naturelle, Paris, France

Keywords

Biologically controlled biomineralization ·
Biologically induced biomineralization ·
Biosignature · Bioprecipitate

Synonyms

Bioprecipitation

Definition

Biomineralization is the process by which organisms form minerals, which are called biominerals. It is a widespread phenomenon induced or controlled by a huge diversity of eukaryotes, bacteria, or archaea. There is a very large diversity of chemical compositions and structures for biominerals, including carbonates (e.g., aragonite, calcite), silicates (e.g., opal, authigenic Mg-silicates such as talc), and Fe and/or Mn oxides. Biominerals can be used in the search for traces of ancient terrestrial or extraterrestrial life. They can be used as recorders of paleoenvironmental conditions, especially in paleoclimatology (e.g., corals,

foraminifers). Finally, their unique properties can inspire mimetic strategies intending to design nanomaterials for new advanced technologies.

Overview

Organisms can impact mineral formation at several steps:

1. Organisms can modify actively or passively solution chemistry in their vicinity, by changing pH or the activity of any chemical species. This may raise supersaturation with a mineral phase in the surrounding solution or inside the cells and makes conditions thermodynamically favorable to mineral precipitation.
2. Organisms can impact nucleation, that is, the formation of very small and unstable mineral seeds. They can indeed stabilize these nuclei by providing large surfaces (e.g., cell walls, extracellular polymers) with lower surface tension.
3. Finally, organisms can impact mineral growth. Traditionally, growth takes place layer by layer. Organisms can inhibit crystal growth in certain directions by the production of poisoning molecules, forming minerals with particular shapes. Alternatively, nuclei may aggregate, forming mesocrystals, sometimes with the mediation of an organic matrix (e.g., Sethmann et al. 2006). This mechanism has been increasingly identified in biomineralizing systems, but exact molecular mechanisms remain unknown.

Three types of biomineralization processes have been distinguished in the literature (Dupraz et al. 2009):

1. *Biologically controlled biomineralization* refers to cases in which a specific cellular activity directs the nucleation, growth, morphology, and final location of a mineral, involving specific genes. Many eukaryote biominerals result from this process. Formation of intracellular magnetites in magnetotactic bacteria (Lefèvre

- and Bazylnski 2013) and intracellular carbonates in several cyanobacteria (Benzerara et al. 2014) and *Achromatium oxaliferum* are additional examples.
2. *Biologically induced biomineralization* results from the indirect modification of the chemistry of the environment by biological activity. Several types of microbial metabolism can, for example, modify solution chemistry and induce carbonation, that is, precipitation of carbonate minerals, including photosynthesis, sulfate reduction, urea degradation, ammonification, or denitrification (Castanier et al. 2000).
 3. *Biologically influenced biomineralization* is defined as passive mineralization of organic matter, whose properties influence crystal morphology and composition. Polysaccharides and proteins have been shown to impact biomineralization in many cases (e.g., Obst et al. 2009). The term organomineralization is sometimes used, encompassing biologically influenced and biologically induced biomineralization.

The morphology, structure, and chemistry of prokaryote biominerals have frequently been proposed as potential biosignatures (e.g., Konhauser 1998) and used to infer the presence of traces of life in ancient terrestrial or extraterrestrial rocks such as the Martian meteorite ALH84001 (McKay et al. 1996). For further reading, reviews on various biomineralizing systems can be found (e.g., Bäuerlein 2000; Mann 2001; Weiner and Dove 2003; Benzerara and Menguy 2009; Benzerara et al. 2019).

Cross-References

- Biomarkers, Morphological
- Bioprecipitation
- Mineral

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Biomorphs

Juan Manuel García-Ruiz

Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, Armilla, Granada, Spain

Keywords

Biomimetic · Self-organization · Life detection · Early life · Barium carbonate · Calcium carbonate

Definition

Biomorphs are abiotic mineral structures displaying morphology characteristics of living organisms, i.e., shapes described by fractal branching and continuous curvature. They must form under plausible geochemical conditions of the Earth or other planets and moons through natural physicochemical processes without life intervention. Biomorphs may emulate amazingly well the morphology of early life forms and some of the oldest remnants of life on our planet. They are, therefore, relevant to the problem of life detection on Earth and elsewhere.

History

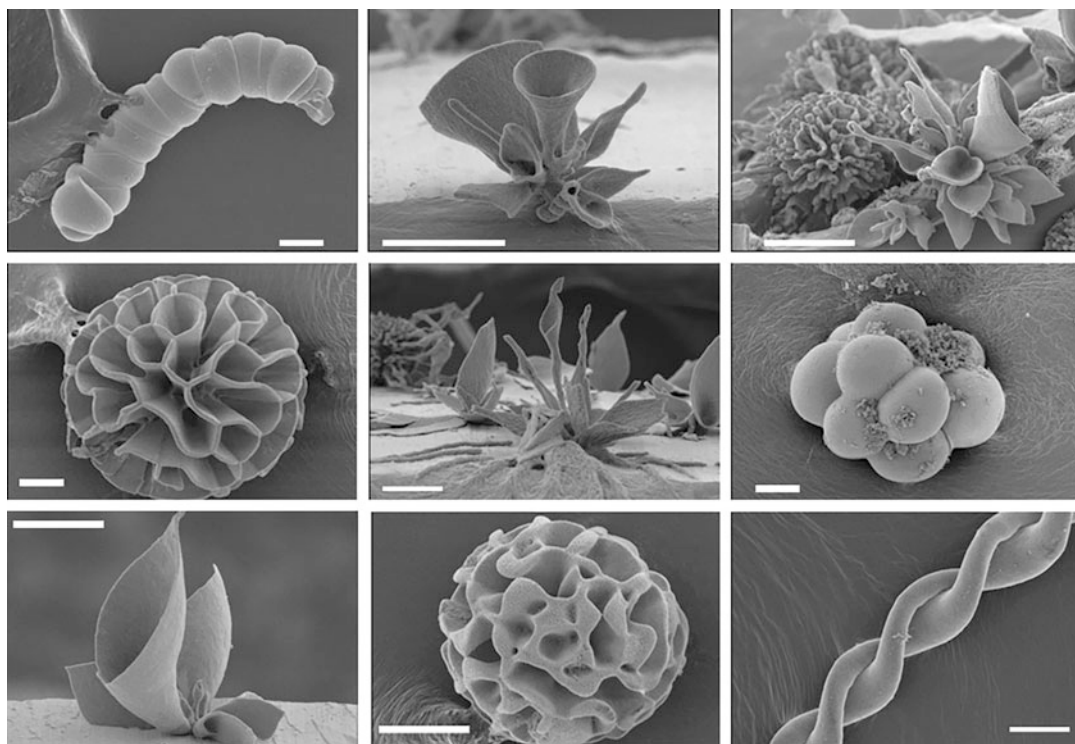
The term was coined by García-Ruiz to describe biomorphic polycrystalline structures of barium carbonate and silica (García-Ruiz 1994). “Biomorph” means abiogenic mineral patterns that share with life morphology. The name was inspired by the paintings of Desmond Morris and the virtual entities devised by Richard Dawkins in the book “The blind watchmaker.”

Overview

The ability of living systems to engineer complex shapes has led us to believe in the existence of a boundary separating the realm of biology from the realm of inorganic minerals. Such a belief profoundly influences the use of morphology as a critical criterion for biogenicity in primitive life detection studies (Buick 1990; Schopf 1993). However, bizarre as it might seem, purely inorganic processes can also yield self-assembled complex structures with non-crystallographic symmetry that mimics extremely well the shape of early living organisms (Fig. 1) (García-Ruiz 1999; Brasier and Wacey 2012). The most interesting of these processes in terms of morphological emulation and geochemical plausibility is the one leading to the precipitation of alkaline-earth carbonate from

alkaline silica-rich solutions. The synthesis is straightforward, requiring only a source of carbonate ions (e.g., atmospheric CO₂), strong alkaline aqueous solutions, silica, and alkaline-earth cations (Ba and Sr, Ca). Under these alkaline conditions, the precipitation of alkaline-earth carbonates (witherite, strontianite, or monohydrocalcite/aragonite) is coupled to silica interactions yielding crystal aggregates made of thousands of nanocrystals exhibiting self-assembled noncrystallographic morphologies (García-Ruiz et al. 2009). These structures share with life complexity, morphology, hierarchy, and self-organization. Their morphologies are highly reminiscent of the shape of primitive organisms, but the precipitates are purely inorganic in origin and form without the involvement of biological compounds or living organisms. This is the reason why they were named silica-carbonate biomorphs. The extreme conditions of pH and silica concentration required for silica-carbonate self-organization are rare but occur in contemporary environments such as those linked to serpentinization hydrochemistry and soda lakes (García-Ruiz et al. 2017). However, these nowadays bizarre geochemical conditions are thought to be widespread in early states of the history of the Earth, particularly during the Hadean (Saladino et al. 2019; García-Ruiz et al. 2020). However, so far, silica-carbonate biomorphs have not been clearly identified in rocks.

Silica biomorphs emulate the shape of primitive organisms to such a degree that for many years they were questioned based on possible biological contamination of the experiments to synthesize them. Nowadays, it is widely accepted that silica-carbonate biomorphs are formed by pure inorganic mechanisms (Kellermeier et al. 2012), and that they do so under geochemical conditions similar to those leading to chert precursors, where the putative Archean microfossils were embedded (García-Ruiz et al. 2003). The existence of silica biomorphs has questioned the use of morphology as an unambiguous criterion for the detection of primitive life remnants. More precisely, the claim

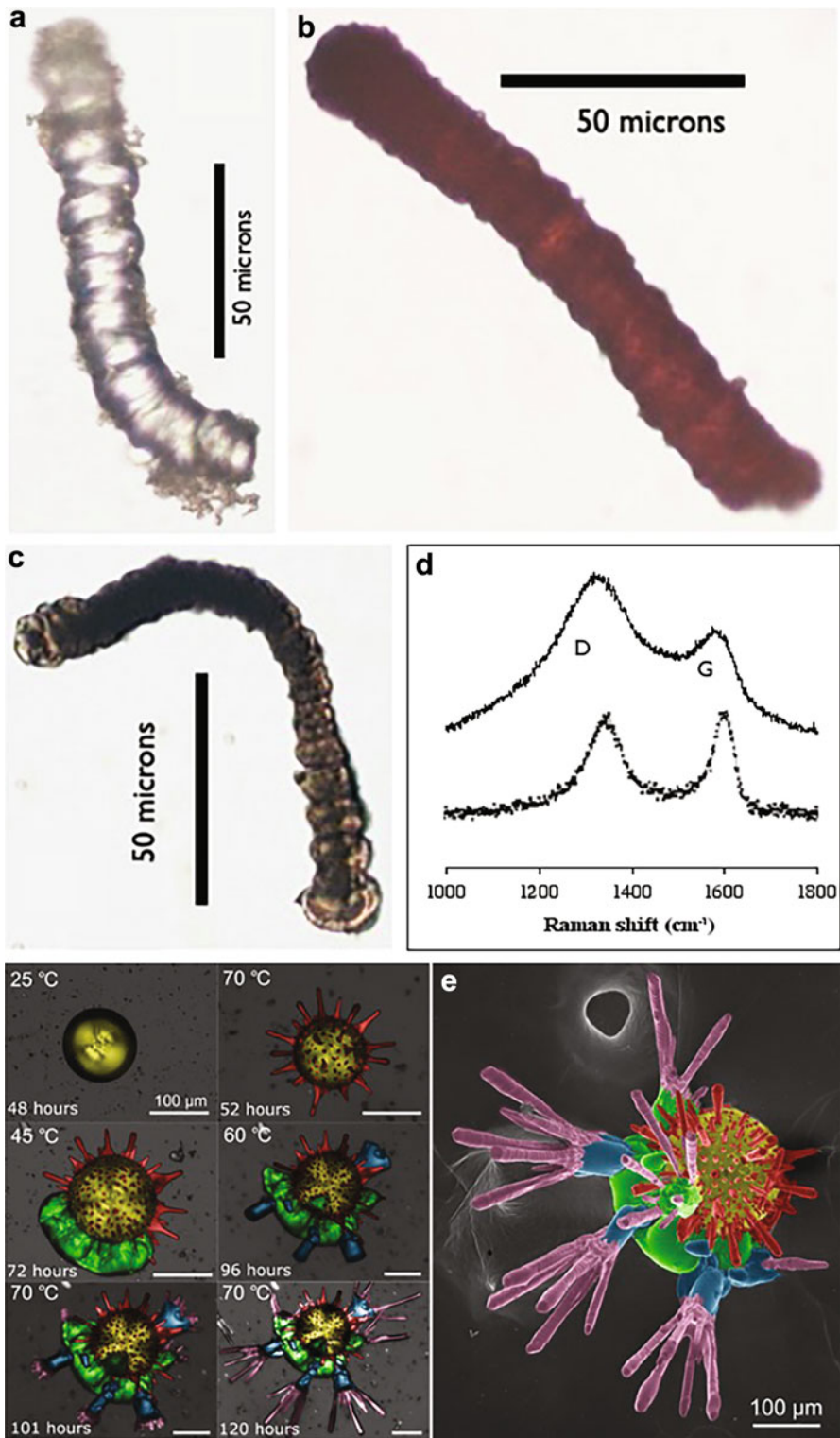


Biomorphs, Fig. 1 A selection of scanning electron micrographs of silica-witherite biomorphs. (Adapted from Camerup 2007 Scale bars = 15 microns)

is that morphology does not contain definitive information on morphogenesis (García-Ruiz et al. 2002). This assertion could come as a shock to biologists who used to identify fossils by their morphologies, so different from the morphology of minerals and rocks. However, it must be remembered that what we use to identify fossils of ammonites, trilobites, or dinosaurs as remnants of life is not morphology but comparative anatomy, an idea introduced by Cuvier in the nineteenth century. When looking for the oldest remnants of life, the problem is that they are tiny pieces of rock, with poor or no compartmentalization at all, namely microspheres, microrods, tubules, septated tubular shapes, simple helicoids, discoid shapes, and a few other simple shapes. Therefore, it is impossible to apply comparative anatomy to these putative fossils of early life. Thus, when identifying the physical structures of possible oldest remnants of life on this planet or in extraterrestrial bodies, we

have nothing else than morphology. This made the unambiguous differentiation of actual life remnants from inorganic biomimetic counterparts a task that must be performed with caution (van Zuilen et al. 2002; Rouillard et al. 2018; Javaux 2019). The study of silica biomorphs has revealed a new morphogenetic mechanism capable of creating crystalline materials with positive or negative constant curvature and biomineral-like textures, which lead to the design of new pathways toward concerted morphogenesis and bottom-up self-assembly created by a self-triggered chemical-coupling mechanism. The potential interest of these fascinating structures in Earth Sciences has never been fully explored, mostly because of their complexity and multidisciplinary nature (Fig. 2).

While the term “biomorphs” was coined for the above-described carbonate precipitation induced by silica, the trend in paleontological and astrobiological studies nowadays is to call



Biomorphs, Fig. 2 Optical micrographs of silica-witherite biomorphs before and after exposure to organic species, all taken under identical illumination: (a) inorganic biomorph as synthesized; (b) biomorph after

biomorphs to any abiotic mineral shapes that may be an alternative explanation to biological remnants of early life (Cosmidis and Templeton 2016; Dodd et al. 2017).

Cross-References

- Abiogenesis
- Abiotic
- Apex Chert, Microfossils
- Biomarkers, Morphological
- Dresser Formation, Traces of Life
- Dubiofossil
- Fossil
- Microfossils
- Self-Assembly
- Sulfur

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Biooxidation of Sulfur

- Sulfide Oxidation

Biomorphs, Fig. 2 (continued) hydrothermal adsorption of organics; (c) cured biomorphs produced by baking the sample that was preexposed to the organic mixture [as in (b)]; (d) upper curve: Raman spectrum of heat-cured biomorphs (similar to c) compared with kerogen-like

Raman spectrum reported by Schopf et al. (2002) (lower curve), collected from a microfilament in the Archean Warrawoona chert. (Adapted from García-Ruiz et al. 2003) and; (e) tailored biomorphs of calcium carbonate (monohydrocalcite) (Adapted from Zhang et al. 2018)

Biopan

René Demets

ESTEC (HSF-USL), Noordwijk, The Netherlands

Keywords

Exposure experiments · Radiation biology

Definition

Biopan is a pan-shaped exposure facility for experiments in the domains of astrobiology, radiation biology, and radiation dosimetry (Demets et al. 2005). Externally mounted on unmanned recoverable satellites of the Foton type, Biopan flies 2-week missions in low Earth orbit at 63.0° inclination, allowing exposure of biological samples to the harsh space conditions. Six flights have been completed between 1992 and 2007 with up to ten different experiments per flight. Biopan carries its experiment packages (total mass 4 kg max.) on two mounting plates (total surface area 1080 cm²).

Overview

In orbit, the hinged lid of Biopan is opened by telecommand whereupon the experiments are freely exposed to the space environment. At the end of the flight, the lid is hermetically closed and locked. During reentry into the atmosphere, Biopan and its contents are protected against the frictional heat by an ablative heat shield. Biopan is equipped with a variety of sensors to monitor and record the environmental history of the test samples. Included are ultraviolet (UV) sensors, a radiometer, and a set of eight thermistors to measure the experiment temperatures. The sensor data are stored on board and retrieved after landing. The temperature profile of the experiments is selectable. A noncontrolled mode can be chosen with temperatures freely oscillating between ≤ -20 °C and $\geq +10$ °C, in sync with the alternating periods of solar illumination and shadowing in orbit. Alternatively, by using electrical heaters and thermal blankets, a stable temperature can be provided with a fixed set point

in the 10–25 °C range. Organic molecules, bacterial spores, ► [archaea](#), plant seeds, ► [lichens](#), and tardigrades have been exposed in Biopan to a combination of solar UV, space vacuum, space radiation, wide temperature fluctuations, and weightlessness. Biopan carries reference samples, which are kept under identical conditions but shielded against UV. Additional control samples are maintained on ground. The typical operational cycle of Biopan includes experiment integration at 1 week before launch, 2 weeks of orbital flight, and return of the experiments to the investigators at 4 days after landing. Biopan was designed and built for ESA by Kayser-Threde (Munich, Germany) with Kayser Italia (Livorno, Italy) responsible for the flight software and the electronics. The heat shield is manufactured by TsSKB-Progress (Samara, Russia).

Cross-References

- [Exposure Facilities](#)
- [Foton Capsule, Spacecraft](#)

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Biopoiesis

- [Origin of Life](#)

Biopolymer

Lucas J. Stal

Department of Marine Microbiology, Royal Netherlands Institute of Sea Research (NIOZ), Yerseke, The Netherlands

Keywords

Biopolymer · Cellulose · Chitin ·
Exopolymers · Heteropolymer ·

Homopolymer · Nucleic acid · Peptidoglycan ·
Polyhydroxyalkanoate · Polypeptide ·
Polyphosphate · Polysaccharide · Protein ·
Silicate · Starch

Synonyms

Natural polymer

Definition

Biopolymers are mostly organic molecules that are composed of repeating monomers and produced by living organisms. Homopolymers are such molecules that are composed of one type of monomer, while heteropolymers are composed of more than one type of monomer. Such ► [polymers](#) may either be a repeating unit of two or more monomers or may be more heterogeneous, complex, and often branched.

Overview

There is a wealth of examples of biopolymers important for the organisms that produce them and for the ecosystems they inhabit. Polynucleotides and polypeptides are the key to life. Polynucleotides (deoxyribonucleic acid, DNA, and ribonucleic acid, RNA) are the carriers of information in cells and are responsible for the translation of this information into polypeptides. Polypeptides are proteins and enzymes that are composed of amino acids that are polymerized through peptide bonds. Enzymes catalyze most metabolic reactions in the cell. Glycogen, chrysolaminaran, and starch are examples of branched and linear polyglucoses that serve as carbon and energy storages in a variety of organisms. Polyhydroxyalkanoates (PHA), such as polyhydroxybutyrate (PHB), also serve as reserve compounds in many bacteria. These compounds have found application as biodegradable plastics. Cyanophycin is a polymer also known as multi-L-arginyl-poly-[L-aspartic

acid]. It serves as nitrogen storage, and although it was first discovered in cyanobacteria (therefore the name), it also occurs in other bacteria. This polymer has found application as a pharmaceutical. Chitin is a linear homopolymer of *N*-acetylglucosamine. Chitin and cellulose (a glucose polymer) share a similar structure. Chitin is a component of the cell walls of arthropods and most fungi and is also synthesized by some diatoms, but is not known in bacteria or archaea. Cellulose is a typical plant ► [cell wall](#) component but is also synthesized by some bacteria, notably by cyanobacteria. Peptidoglycan (murein) is a biopolymer of *N*-acetylglucosamine and *N*-acetyl-muramic acid, which serves as the main cell wall component in bacteria and some archaea (the latter possess a slightly different polymer known as pseudo-peptidoglycan). Polyphosphate is an inorganic polymer of orthophosphate and occurs in all three domains of life. In bacteria, polyphosphates may serve as storage of phosphorus and/or energy. Silicate is a mostly inorganic polymer of silicon although it is normally associated with organic matter. Silicate is the main component of the frustules of diatoms. Probably the most diverse and complex biopolymers are exopolymers. These are complex polymeric carbohydrates with associated glycolipids, proteins, and nucleic acids, as well as a variety of uronic acids, pyruvate, sulfate, and carboxylic groups. They may serve as the sheath of microorganisms or be extruded as mucilage in the outer environment and have a variety of functions.

Cross-References

- [Cell Wall](#)
- [Exopolymers](#)
- [Nucleic Acids](#)
- [Peptidoglycan](#)
- [Polymer](#)
- [Polynucleotide](#)
- [Polypeptide](#)
- [Polysaccharide](#)
- [Protein](#)
- [Refractory Organic Polymer](#)

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Bioprecipitation

Karim Benzerara
Sorbonne Université, Muséum National
d'Histoire Naturelle, UMR CNRS 7590, Institut
de Minéralogie, de Physique des Matériaux et de
Cosmochimie (IMPMC), 4 Place Jussieu, Paris,
France

Synonyms

[Biomineralization](#)

Definition

Bioprecipitation refers to the process of formation of mineral phases (bioprecipitates or biominerals) by organisms. Cells or associated extracellular polymers can serve as nucleation surfaces and/or alter the chemical composition of fluids and raise the supersaturation of the solution with a mineral phase. Alternatively, bioprecipitation has been used in meteorology to refer to the nucleation of ice by bacteria in clouds resulting in snow or rainfall.

Cross-References

► [Biomineralization](#)

Biosensor

Laura M. Lechuga
Nanobiosensors and Bioanalytical Applications
Group, Institut Català de Nanociència i
Nanotecnologia (ICN2) CSIC and CIBER-BBN,
Barcelona, Spain

Keywords

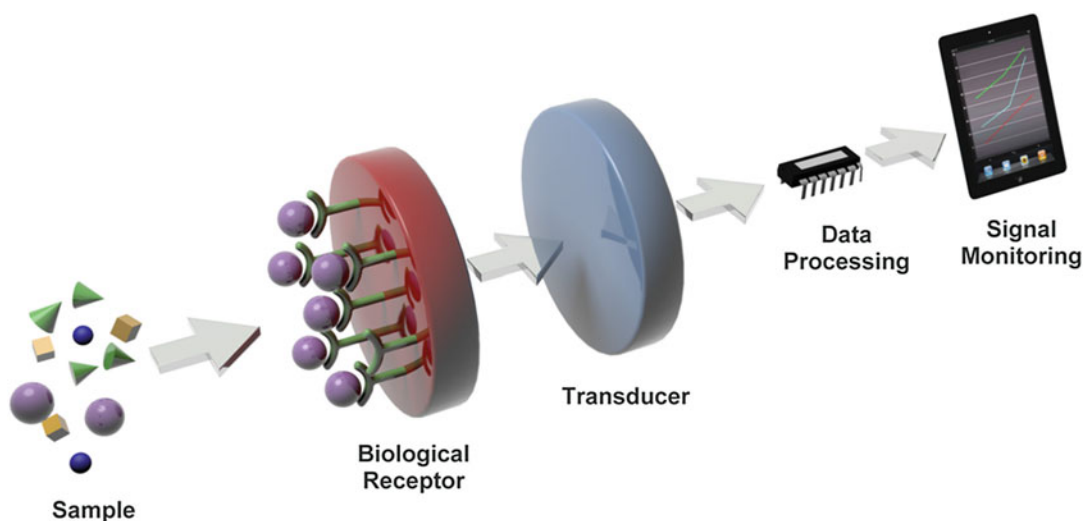
Transducer · Bioreceptor layer · Optical
biosensor · Electrochemical biosensor ·
Acoustic biosensor · Plasmonic sensors ·
Label-free detection · Lab on a chip

Synonyms

[Biodetection system](#); [Biological sensors](#); [Lab on a chip](#)

Definition

A biosensor is a compact hybrid device incorporating a biological receptor in direct contact with a transducer (the term “biosensor” derives from this combination). The biological element specifically recognizes a substance (chemical or biological) in a sample, thereby inducing a change in the transducer, which delivers a signal proportional to the concentration of the substance (see Fig. 1). The main advantages of biosensors are the selectivity and sensitivity of the analysis. In addition, biosensors can supply real-time and online information. Biological elements employed can be enzymes, antibodies, DNA, whole cells, or tissues, for example. Depending on the physical change observed, transducers could be electrochemical, optical, piezoelectric, acoustic, magnetic, or nanomechanical.



Biosensor, Fig. 1 Scheme of a biosensor device

Overview

Biosensor is a general term for a wide range of analytical devices that measure the presence or concentration of biological or chemical molecules in complex samples by translating a biomolecular interaction at the transducer surface into a quantifiable physical signal. When the biospecific interaction takes place, a physicochemical change is induced, as, for example, a redox, mass, resonant frequency, absorption, or refractive index change. The aim of a biosensor is to produce discrete or continuous signals that are proportional to the concentration of a single analyte or a related group of analytes. The biological element is capable of sensing the presence, activity, or concentration of the substance in a solution. Substances capable of being analyzed with biosensors range from protein biomarkers, toxins, antigens, drugs of abuse, pesticides, peptides, proteins (IgG, albumin, insulin, etc.), hormones, vitamins, antibiotics, organic molecules (glucose, lactose, cholesterol, urea, etc.), DNA and DNA single mutations, RNA, microRNA, epigenetic marks, cancer cells, pathogenic microorganisms, and many others.

The first demonstration of a biosensor dates from 1962, when enzyme electrodes for glucose sensing were developed by L. C. Clark (USA). Since then, an intensive effort has been focused on biosensor research and development, a significant output of which was the commercial launch of the glucose biosensor in 1975. The glucose biosensor has become a landmark in the diagnostics field, thereby allowing millions of diabetics to test, in any place and at any time, their glucose level in the blood. Substantial work on achieving reliable biosensors began in the 1980s, and since then, many developments have been demonstrated. Biosensing technology has been a very active research field both in academic and in industrial laboratories during the last decades. But, until now, only a limited number of biosensors have achieved the stringent requirement for being commercialized. This is mainly due to the poor stability of the biological receptor once it is in contact with the transducer, as it must be stable under variable conditions of pH, temperature, humidity, and ionic strength.

The use of biosensor devices has clear advantages in analytical chemistry. The main characteristics of biosensors are high sensitivity and

selectivity. In addition, biosensors can provide rapid, direct, and cost-effective analyses, ease of operation, high accuracy, and wide detection range using a minimum volume of sample and reagents. This technology avoids the expensive, complex, and time-consuming procedures typically employed in standard analytical evaluation.

In order to obtain reliable biosensor devices, there are two crucial steps: (i) the design and fabrication of a highly sensitive physical transducer, that is, a device capable of efficiently transforming the biomolecular reaction into a measurable signal, and (ii) the stable and reliable biofunctionalization of the physical transducer with the appropriate, selective, biological receptor (protein, DNA, cell, aptamer, etc.). The biosensor research and development area is highly multidisciplinary because several aspects need to be considered to successfully achieve the device, such as the transduction modality used, fluidic design (most of the biosensing analyses are performed in liquid), surface biofunctionalization, detection format (direct, indirect, sandwich-type, competitive binding), and data processing and analysis.

Basic Methodology

The possible combinations of different bioreceptors and transducers result in a vast range of biosensor types. Depending on the bioreceptor, the transducer, or the type of detection, biosensors can be classified into different types and subtypes. It is important to point out that the selection of the most suitable combination of bioreceptor/transducer/type of detection is dictated by the application itself, which depends on the type of substance to be detected and the complexity of the sample which contains the substance to be evaluated.

Types of Detection

Two main types of detection can be employed: “label” and “label-free.” In the “label-free” scheme, the original and unmodified analyte is detected in a direct manner. In the “label” approach, the analyte is tagged with a label which acts as an indirect indicator of the presence

of the molecule. In general, the “label” approach results in a higher sensitivity of analysis, while the “label-free” approach is direct, is rapid, and avoids the manipulation or degradation of the analyte. Each detection method has advantages and disadvantages and the method employed should be selected according to the foreseen application.

Classification by Bioreceptor Layer Type

Depending on the bioreceptor, biosensors can be divided into two main types: catalytic biosensors and affinity biosensors. In catalytic biosensors, the receptors are able to recognize (bio)chemical species and transform them into a product. This type of biosensor is mostly represented by enzymatic biosensors, but whole cells or tissue receptors also fall under this category. Affinity biosensors use the specific capabilities of an analyte to bind to a biorecognition element. Immunosensors (based on specific interactions between an antibody and an antigen) or DNA biosensors (based on the affinity between complementary oligonucleotides) are the main examples of affinity biosensors. Biomimetic receptors based on engineered molecules as aptamers or molecular imprinted polymers have emerged during the last years as an attractive alternative to biological receptors, although they have not achieved yet the same specificity than the natural receptors and they are only suitable for some specific applications.

Classification by Transducer Type

Depending on the transducer employed, biosensors can be divided into the following main types: electrochemical biosensors, optical biosensors, piezoelectric biosensors, magnetic biosensors, and nanomechanical biosensors. Electrochemical biosensors are based on changes in electrical currents or potential across electrodes when the biosensing reaction involves redox changes. They are the simplest and most developed biosensors. They can be amperometric (based on the measurement of the current resulting from the electrochemical oxidation or reduction of electroactive species), potentiometric (based on the determination of the potential difference between an indicator and a reference electrode (such as ISFET devices)), or conductometric (based on a change in conductance (such as measured by

interdigitated electrodes)). Piezoelectric biosensors are based on the piezoelectric effect: the frequency of a resonating crystal changes when molecules are adsorbed on top of the crystal. Surface acoustic wave systems and quartz crystal microbalances are the main examples of piezoelectric devices.

In optical biosensors, the biorecognition event results in a change in optical properties such as a variation in the emission properties (luminescence), in the absorption coefficient, or in the refractive index. This variation induces a change in some of the characteristics of light (wavelength, intensity, polarization, phase velocity) which can be detected using techniques as emission, absorption, fluorescence, evanescent wave detection, or polarimetry. Many optical biosensors have been developed because they frequently exhibit higher sensitivity than other transducer types. One of the most successful label-free and commercially accepted optical biosensors is the surface plasmon resonance (SPR) sensor that is based on an evanescent wave interaction. Localized surface plasmon resonance (LSPR) based on metal nanostructures has gained attention in the last years. Other optical biosensors make use of optical waveguides as the basic element for light transmission, such as optical fibers or integrated optics-based waveguides, including interferometers (Mach-Zehnder, Young, bimodal interferometers), microcavities (as microring resonators), and grating- and photonic crystal-based structures. Other optical biosensors include those based on porous silicon, silicon photonic wires, or resonant bicells.

In nanomechanical sensors, the specific biorecognition on the cantilever surface results in a nanomechanical response, which produces a cantilever bending of few nanometers and a shift in the resonant frequency. In this way, microcantilevers translate the molecular reaction into a nanomechanical motion, which is commonly detected using optical or piezoresistive readout. Nanomechanical sensors achieve a high level of sensitivity and are amenable for array multiplexing and integration in compact platforms.

Biofunctionalization

Biofunctionalization is the process of immobilizing the receptor biomolecules onto the transducer surface to provide the required

biospecificity of the biosensor. The bioimmobilization process must maximize the sensitivity and must supply a reproducible layer and must ensure optimal coverage density of the receptor, proper receptor orientation for efficient kinetics, minimal background and nonspecific adsorption, and long-term stability. Amongst the various bio-immobilization approaches, the most commonly used are physical adsorption, covalent binding, and affinity-based (as avidin/biotin, His-Tag systems, protein A/G for antibodies) entrapment (physical or covalent) within host matrices (e.g., polymers, polymeric hydrogels, and sol-gels). Usually, covalent binding to the substrate is the preferred route for most bioreceptors through the use of self-assembled monolayers, but the most suitable technique depends on the bioreceptor type and the sample to be evaluated.

Whatever the immobilization technique employed, a previous chemical activation of the sensor surface is mandatory. Silicon-, silicon oxide-, and silicon nitride-based surfaces can be functionalized using the well-known silane chemistry. Gold surfaces are normally functionalized using thiol chemistry.

Applications

The fields of application for biosensors are almost endless. Applications for these devices include clinical diagnostics (including personal health monitoring), basic research in life sciences, drug research in the pharmaceutical industry, online screening of water quality for both household and industrial use, control of industrial processes, veterinary diagnostics, quality control in the food and beverage industry, detection of harmful substances, military and homeland security or environmental monitoring, and many others. The most significant applications are related to the clinical diagnostics field, mainly due to the great success of glucose biosensors since their invention. Indeed, glucose biosensors account for about 85% of the entire biosensor market. In the astrobiology area, biosensors are useful tools for detecting biomarkers or biosignatures of extant or extinct life which could be produced in biotic or abiotic processes (such as bacteria strains, cells,

extracellular materials, isolated macromolecules or biomarkers, etc.).

Future Directions

The ultimate aim in biosensor technology is the achievement of a fully integrated, low-cost, portable, and reliable lab-on-a-chip platform, able to simultaneously detect and identify hundreds of substances in real time with high sensitivity, even at the single molecule level and connected through a wireless scheme to a central operational station or hospital database. Therefore, the major future objectives in biosensor technology will be to achieve higher sensitivity, to reduce sample volume and reagents by miniaturization at the micro-/nanoscale, to increase the number of substances detected within the same sample, to develop devices of high multiplexing capabilities for analyzing an elevated number of substances in parallel, and to develop wearable biosensors and biosensors suitable for implantation in the human body. Other important aspects to be considered in the future are issues associated with the commercialization of biosensors for relevant applications, which still face significant technological hurdles. Development cycles tend to be long and commercial success remains limited. The main issues in biosensor technology, such as the stability and reliability of the biorecognition layer, still need to be surpassed.

Cross-References

- ▶ [Aptamer](#)
- ▶ [Hybridization](#)
- ▶ [Molecular Recognition](#)
- ▶ [Surface Plasmon Resonance](#)

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Biosignature

- ▶ [Biogenicity](#)
- ▶ [Biomarkers](#)
- ▶ [Biomarkers, Morphological](#)

Biosignatures, Effect of Metamorphism

Sylvain Bernard

Laboratoire de Minéralogie et de Cosmochimie
du Muséum (LMCM), Paris, France

Keywords

Burial · Chemistry · Degradation · Diagenesis ·
Fossilization · Isotopes · Metamorphism ·
Microscopy · Organic molecules ·
Preservation · Spectroscopy · Structure

Synonyms

[Fossilization processes](#)

Definition

Biosignatures are molecular, mineral, or isotopic patterns that can be unambiguously interpreted as evidence of extant or extinct life (Slater 2009). However, fossilized biosignatures are not immutable but prone to degradation during diagenesis and ► [metamorphism](#) and may become difficult to distinguish from signatures of abiogenic compounds (e.g., García-Ruiz et al. 2003; Pasteris and Wopenka 2003; McCollom and Seewald 2006). Nevertheless, from the multiscale characterization of organic-rich ► [metamorphic rocks](#) using advanced synchrotron-based micro ► [spectroscopy](#) techniques, Bernard et al. (2007, 2010) have shown that high-grade metamorphism might not totally erase structural and chemical bio-features, at least at the sub-micrometer scale.

Overview

Understanding the physical and chemical evolution of life relies on the ability to decipher preserved evidence in the rock record, a.k.a. fossilized biosignatures (Seckbach and Walsh 2008; Slater 2009). However, the combination of biological, chemical, and physical factors during taphonomic

processes and deep burial inevitably alter the chemical, structural, and isotopic fidelity of such fossilized biosignatures (Schiffbauer et al. 2007). In addition, abiogenic processes may form disordered carbon-dominated precipitates displaying morphologies and signatures quite similar to biogenic objects (García-Ruiz et al. 2003; Pasteris and Wopenka 2003; McCollom and Seewald 2006). Therefore, unambiguously identifying biosignatures within metamorphic rocks has been generally believed to be extremely difficult, if not impossible, except in very rare cases such as the exceptionally well-preserved Burgess Shale ► [fossils](#) which experienced greenschist facies metamorphism (Powell 2003). Recently, the analytical improvements of microspectroscopy techniques in general and synchrotron-based techniques in particular (see Templeton and Knowles 2009 for a review) have allowed the chemical and structural characterization of metamorphic organic matter down to the nanometer scale. Altogether, these studies have shown that even high-grade metamorphic rocks may retain morphologically and geochemically recognizable traces of life, depending notably on the original biochemical nature of the ► [biopolymer](#) (Bernard et al. 2007, 2010).

In the long term, physical biosignatures have a greater chance of preservation than complex organic markers. Metamorphic degradation of ► [organic molecules](#) is associated with an aromaticity increase, mainly by the release of heteroelement-containing functional groups as CO₂, N₂, and H₂S and by the elimination of aliphatic groups as CH₄. Organic molecules which have undergone restructuring during early diagenesis to become resistant cross-linked aliphatic or aromatic macromolecules (a.k.a. geopolymers) and those which have been closely associated to minerals (such as carbonates, sulfates, and clays) will have a greater chance of long-term preservation. The isotopic composition of organic compounds is relatively stable, to the extent that basic molecular skeletons are preserved. Otherwise, the effect of thermal metamorphism on organic matter is to form isotopically lighter volatile species and isotopically heavier residual refractory solids. In conclusion, although biosignatures might be partially preserved during metamorphism, a great

deal of caution must be implemented and multiple lines of evidence (morphological, ultrastructural, as well as geochemical) must be sought during their analysis and interpretation.

Cross-References

- [Abiotic](#)
- [Absorption Spectroscopy](#)
- [Biomarkers](#)
- [Biomarkers, Morphological](#)
- [Biomarkers, Spectral](#)
- [Biopolymer](#)
- [Carbon Cycle, Biological](#)
- [Complex Organic Molecules](#)
- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)
- [Fischer-Tropsch-Type Reaction](#)
- [Fossil](#)
- [Fossilization, Process of](#)
- [Infrared Spectroscopy](#)
- [Isotope](#)
- [Isotope Biosignatures](#)
- [Isotopic Exchange Reaction](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Ratio](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Metasediment](#)
- [Microfossils](#)
- [Microfossils, Analytical Techniques](#)
- [Molecular Fossils](#)
- [Organic Molecule](#)
- [Origin of Life](#)
- [Raman Spectroscopy](#)
- [Spectroscopy](#)

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Biosphere

David C. Fernandez-Remolar
State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Taipa, China
CNSA Macau Center for Space Exploration and Science, Macau, PR China

Keywords

Biocenosis · Biogeochemistry · Ecosystem · Homeostasis

Acronyms

GOE Great Oxidation Event

Synonyms

Ecosphere, Gaia

Definition

The biosphere is a concept initially created by the prominent geologist Edward Suess to define the upper part of the Earth's lithosphere intricately associated with life (Smil 2003). Later on, the Russian biologist Vladimir Vernadsky realized the actual dimension of the impact of life on Earth and linked the biosphere to a natural entity intimately associated with global geochemical cycling of matter and energy within the terrestrial crust (Vernadsky 1998). According to this last conception, the biosphere can be understood as a complex, natural entity resulting, at a global planetary scale, from the interactions between all life forms and the different reservoirs of matter and energy like the geosphere, hydrosphere, and atmosphere (Smil 2003). Based on this concept, the British scientist James Lovelock envisaged the biosphere as an organism of planetary scale, Gaia, which rules the planet's main physical and chemical parameters through a series of intricate feedback mechanisms (Lovelock 2000).

Overview

Under a formal ecological approach, the biosphere can be defined as a global biological system that arises from the integration of all biocenosis (Lévêque 2003), ranging from those sustained by autotrophs that can range from primary photosynthesizers to chemolithotrophic producers as found in deep crustal regions or in the hydrothermal systems. In this sense, the ecosphere would include the biosphere as the biotic component of the planetary ecosystem, as in the same way, biocenosis accounts for ecosystem (Huggett 1999). As the biosphere merged early in time with the geochemical cycles that are operating in our planet, sometimes it is challenging to separate the living

systems from the different nonbiological planetary reservoirs such as the atmosphere, the hydrosphere, and the geosphere. The complex pathways of exchanging matter and energy between the biosphere and the planet led to the emergence of feedback mechanisms that control the environment's physical and chemical variables at regional and global scales. One paradigmatic example is the temperature and pH control in the oceans (Orr et al. 2005; Knoll et al. 1996) through the uptake and sequestration of CO₂ that is transformed into biomass and carbonates, and which is later buried in the form of organic matter, or the carbonates themselves. The same kind of global feedback is controlled by the cycling of compounds bearing nitrogen and sulfur, which induce physical and chemical changes in the Earth's atmosphere by photochemical reactions occurring in the troposphere (Seinfeld and Pandys 2006). They regulate the thermal conditions on the Earth's surface by controlling the planetary albedo through the release of dimethyl sulfide that oxidizes to SO₂. Interestingly, the biosphere also controls the environmental conditions by controlling the thermal and hydric balance in a region. It commonly happens through the structure and composition of the large communities of terrestrial woodlands, which interact with the water cycle to modify the thermal and hydric conditions at regional and, therefore, global scales (Rodríguez-Iturbe and Porporato 2004). The GOE driven by the photosynthesizers activity during the Late Archean-Early Proterozoic resulted in, at a greater scale, a global process of environmental control. As a result, the biosphere becomes more diverse and takes control of new Earth regions through the oxygen cycle that has a large impact on the Earth's crust. The emergence of the oxygen cycle led to large-scale ecological succession starting with a few low-specialized colonists and ending in the formation of different diverse ecosystems sustained by very specialized organisms adapted to a wide variety of niches. Consequently, microbially-mediated oxygenation combined with global geological events (Knoll 2003) triggered diversity and environmental changes that affected the ocean habitats and led to the colonization and

environmental control of the early Earth's continental areas. The total biosphere biomass has been estimated of being around 550 gigatons (Gt) of carbon ($1 \text{ Gt} = 10^{15} \text{ g}$), where plants hold about 450 Gt, which equals the 80% of the total biomass on Earth (Bar-On et al. 2018). Some biomass estimates for the Paleozoic woodlands show that they stored a similar magnitude of carbon as the Amazonas and Congo tropical forests (Fernández-Remolar et al. 2018). If those calculations are right, it suggests that by the end of the Devonian (about 360 Ma), the total terrestrial biomass was comparable to the biomass stored by the modern biosphere.

Cross-References

- ▶ [Algae](#)
- ▶ [Archaea](#)
- ▶ [Autotroph](#)
- ▶ [Biogeochemical Cycles](#)
- ▶ [Biotope](#)
- ▶ [Carbon Cycle, Biological](#)
- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Ecosystem](#)
- ▶ [Gaia Hypothesis](#)
- ▶ [Greenhouse Effect](#)
- ▶ [Habitat](#)
- ▶ [Heterotroph](#)
- ▶ [Homeostasis](#)
- ▶ [Hydrosphere](#)
- ▶ [Nitrogen Cycle, Biological](#)
- ▶ [Oceans, Chemical Evolution of](#)
- ▶ [Oxygenation of the Earth's Atmosphere](#)
- ▶ [Sulfur Cycle](#)
- ▶ [Symbiosis](#)

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Biostabilization

Nora Noffke
Old Dominion University, Norfolk, Virginia,
USA

Synonyms

[Microbial sediment fixation](#)

Definition

Biostabilization is the fixation of clastic sediment by biofilms, microbial mats, and their extracellular polymeric substances (EPS) in natural aquatic settings (Paterson 1997). Three main effects of biostabilizations can be distinguished (Noffke 2010). Type 1 – microbial reduction of sediment

erodibility. Type 2 – allowing the flexible deformation of a sediment surface composed of loose grains that without the presence of a biofilm-matrix, would disintegrate upon pressure. Type 3 – smoothing and sealing of the sedimentary surface reducing gas and fluid exchange between sediment and atmosphere or water. Biostabilization is one of four mechanisms that lead to the formation of microbially induced sedimentary structures (MISS) such as gas domes, roll-ups, and mat chips.

History

Biostabilization of clastic deposits by microbial mats was studied in tidal flats of the North Sea. Führböter and Manzenrider (1987) used a portable flume chamber placed on microbial mats to quantify the resistance of the microbenthos against erosion by water current. Paterson (1997) conducted laboratory experiments that showed the mechanics of microbial stabilization.

Cross-References

- [Biofilm](#)
- [Microbial Mats](#)
- [Microbially Induced Sediment Structures \(MISS\)](#)
- [Stromatolites](#)
- [EPS](#)

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Biostack

Gerda Horneck
DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Biological radiation effects · Cosmic rays · Heavy ion hits · HZE particles · Nuclear track detectors

Synonyms

[Biobloc](#)

Definition

The Biostack concept allows studying the biological effects of single heavy ions of cosmic rays. Each Biostack device is composed of a stack of visual track detectors (e.g., nuclear emulsions, cellulose nitrate, and polycarbonate) with layers of biological objects in resting state sandwiched between them. After exposure to the outer space, the track detectors are developed, the trajectory of each heavy ion is localized relative to the site of the biological object, and the physical data of each particle are correlated with the observed biological effects along its path.

History

The Biostack program has been developed in the late 1960s under the auspices of the Council of Europe within the Working Group on Space Biophysics and has been performed in international cooperation by scientists from Europe, Russia, and the USA. Biostack experiments were flown on the NASA missions Apollo 16 and 17 (1972), Apollo-Soyuz Test Project (1975), and the ► [Long Duration Exposure Facility](#) (1984–1990), on ESA/NASA missions Spacelab

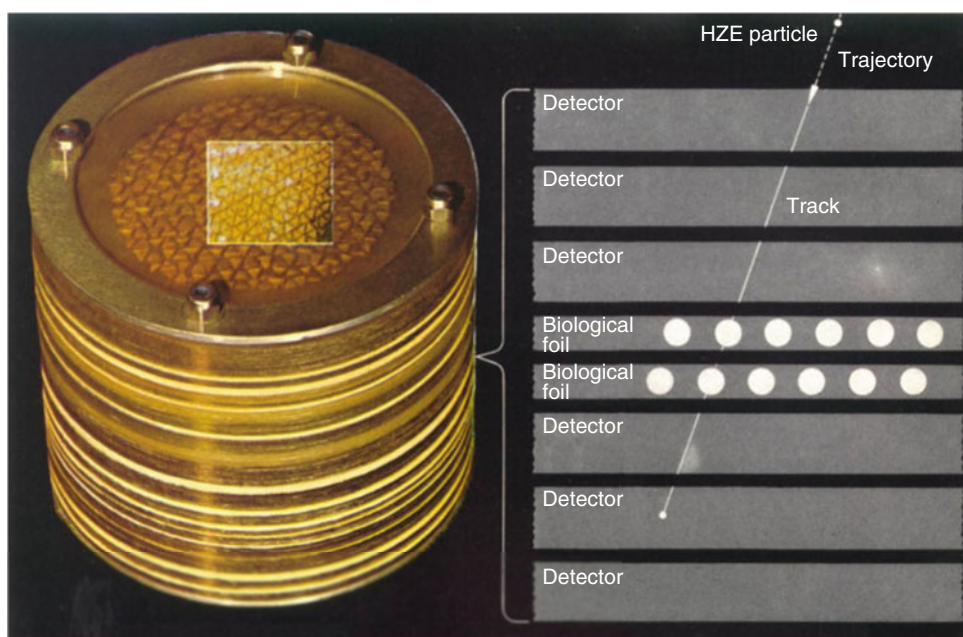
1 (1983) and Spacelab IML-2 (1994), on the German/NASA mission Spacelab D2 (1993), on the ESA mission ► **EURECA** (1992–1993), and on ESA/Russian missions of the Biocosmos and Foton series (1992–1994). The Biostack program was managed by Horst Bücker and Günther Reitz, both from the German Aerospace Center (DLR), Germany.

Overview

With the beginning of human space flight, health effects from exposure to cosmic rays became a concern, and radiation protection guidance has been required. The heavy ions of cosmic radiation, the so-called ► **HZE particles**, i.e., particles of high (H) atomic number (Z) and high energy (E), are of special concern. To understand the ways by which single particles of cosmic radiation interact with biological systems, the Biostack concept was developed to precisely localize the trajectory of an HZE particle relative to the biological object and to correlate the physical

data of the particle relative to the observed biological effects along its path (Fig. 1). A large variety of biological specimens, such as viruses, bacterial ► **spores**, plant seeds and animal eggs, and cysts, allowed the evaluation of radiation effects at different levels of biological organization and at different radiation sensitivities. The following biological effects were ascribed to the passage of a single HZE particle:

- In seeds of *Arabidopsis thaliana* or *Nicotiana tabacum*, hit by an HZE particle in their shoot meristem, development was significantly disturbed, as demonstrated by up to 90% loss of germination (early lethality) or embryo lethality. Seedling abnormalities, such as hypertrophy or deformation of cotyledons, hypocotyl, or root, or chlorophyll deficiency, occurred with high frequency as a consequence of a passage of a single HZE particle close to the shoot or root meristem. In *Lactuca sativa* seeds, hit by an HZE particle, multiple chromosomal aberrations developed at high frequencies. *Zea mays* seeds, flown on ASTP,



Biostack, Fig. 1 The Biostack concept to localize biological effects produced by single HZE particles of cosmic radiation; Biostack experiments were flown onboard of

Apollo 16 and 17; ASTP; Spacelab 1, D2, IML-1, and IML-2; LDEF; Cosmos 1887 and 2004; and EURECA (Photo credit DLR)

developed large yellow strips in all leaves as somatic mutation.

- In 90% of the mosaic eggs of the brine shrimp *Artemia salina* hit by an HZE particle, hatching, characterized by release of a free-swimming nauplius, was inhibited. Anomalies of the body or extremities appeared approximately ten times more frequently than in the ground controls. Likewise, hatching of the Indian stick insect *Carausius morosus* from eggs, hit by a cosmic HZE particle, was significantly reduced. Malformations were increased in individuals having developed from eggs hit. They were characterized by a curved abdomen, fused segments, or shortened legs.
- Spores of the bacterium *Bacillus subtilis* were inactivated well beyond 1 μm from the HZE particle trajectory, whose distance would roughly correspond to the dimensions of a ► [spore](#), thereby pointing to a long-ranging effect of HZE particles.

Quantifying various genetic and developmental disturbances caused by individual HZE particles of cosmic radiation, the Biostack data are of relevance for assessing the radiation risks for astronauts, especially during exploratory missions, as well as for estimating the likelihood of ► [lithopanspermia](#), i.e., the interplanetary transfer of microorganisms within rocks.

Cross-References

- [Apollo Mission](#)
- [Cosmic Rays in the Heliosphere](#)
- [EURECA](#)
- [Foton Capsule, Spacecraft](#)
- [HZE Particle](#)
- [Ionizing Radiation, Biological Effects](#)
- [Linear Energy Transfer](#)
- [Lithopanspermia](#)
- [Long Duration Exposure Facility](#)
- [Panspermia](#)
- [Radiation Biology](#)
- [Space Environment](#)
- [Spore](#)

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Biosynthesis

- [Anabolism](#)

Biotic Crisis

- [Mass Extinctions](#)

Biotic Isotope Fractionation

- [Isotope Biosignatures](#)

Biotic Mineral Alteration

- [Fungal Weathering](#)

Biotic Mineral Dissolution and Complexation

► [Fungal Weathering](#)

Biotope

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Environment](#); [Habitat](#)

Definition

A biotope is an area of homogeneous environmental conditions providing living space for a specific assemblage of organisms. Biotope is almost synonymous with the term habitat, but while the subject of a habitat is a species or a population, the subject of a biotope is a biological community.

Cross-References

► [Colonization, Biological](#)

Bipolar Flow

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Molecular flow · Star formation

Definition

Bipolar flows are a phenomenon associated with young stars still embedded in their parent ► [molecular clouds](#). There are two kinds of flows – jets and molecular outflows. The first represent high-speed stellar wind gas, ejected into two narrow streams. The second are broader cones of more slowly moving cloud gas. Each molecular outflow is driven by a jet running down its central axis. What is seen most prominently in the jets are shock waves created when the wind runs into either ambient cloud gas or slower gas ejected earlier. Neither the launching of the wind nor its collimation into jets is well understood.

Overview

It has long been known that massive stars emit strong winds that drive back nearby gas. Since these objects are all relatively young, there is often such a gaseous environment, the remnant of the cloud that formed the star itself. In the 1980s, astronomers were surprised to discover that even young stars of solar mass and below drive vigorous outflows. Each outflow appears as two opposite streams (hence “bipolar”) emanating from the central object. In the youngest examples, the star is so embedded in ambient dusty gas that it is optically invisible. Even in such cases, however, bipolar outflows are present. The flows probably play a key role in clearing away remaining material in star-forming molecular clouds. Despite extensive study, the physical mechanisms underlying both their launching and collimation remain mysterious.

Flows generated by young stars have two components – jets and molecular outflows. Both have bipolar morphologies. Otherwise, their properties are very different, undoubtedly reflecting their distinct origins. Stellar jets consist of gas emitted at high speed into a narrow opening angle. A typical jet speed is 300 km/s, which is also the magnitude of the escape velocity from the stellar

surface. The gas has a temperature of 10,000 K. What we observe most prominently are shock waves created when this high-speed gas rams into other material. These shock waves, which radiate in a variety of spectral emission lines, are called Herbig-Haro objects. Discovered in the 1950s, the shocks appeared as isolated, glowing patches. Thirty years later, astronomers detected narrow, faint strands linking the bright knots and leading back to a young, embedded star. Each arm of a stellar jet has a length of about 0.1 pc. Individual Herbig-Haro objects can be detected much farther out, up to several parsecs from the driving source.

Molecular outflows are broader swathes of much slower and cooler gas. They exhibit the same bipolar morphology and axis orientation as jets. Indeed, it is now believed that every molecular outflow has a jet running down its center. Gas in the broader outflows moves at speeds of typically 10 km/s, and most of its mass has a temperature of about 10 K. Since this temperature also characterizes molecular clouds, the broader outflows are thought to represent cloud material being pushed outward by the jet. This relatively cold gas is observed through the radio emission of molecules in the cloud. The dominant species, molecular hydrogen, is a weak emitter at these low temperatures, so astronomers generally utilize CO, which has a strong spectral line at a wavelength of 2.6 mm. Smaller amounts of much warmer gas have been detected using other tracer molecules, such as ammonia.

Since stellar jets glow mainly at optical wavelengths, they are easily obscured by dust in the molecular clouds that lie near the driving stars. To see a jet, the star must be near the surface of the cloud. Sometimes, the cloud has been partially ablated by ultraviolet radiation from a nearby massive star, revealing the young, low-mass star and its jet. The millimeter radio emission used to detect molecular outflows, however, easily penetrates interstellar dust. Thus, these broader flows are relatively easy to find, and hundreds of examples exist. In contrast, there are still only a few dozen clear detections of stellar jets. The red-

shifted arm of the jet, which is penetrating back into the molecular cloud away from the observer, is often considerably fainter but has been detected in most cases.

The high-speed material in stellar jets must represent the actual wind being emitted by the star or the inner portion of its circumstellar disk. The rough match of the wind speed and the stellar escape velocity occurs in other examples of winds from stars over a broad range of masses and ages. How the wind is launched in this particular case is not clear. The wind from our Sun is pushed outward by the hot gas at the base of the solar corona. The mass transport rate in a young stellar jet is higher by 6 orders of magnitude, and thermal pressure is inadequate. It is generally agreed that the wind is tapping rotational energy. The star, which is indeed rapidly rotating, also contains a strong magnetic field. The wind could be flung out along the magnetic field lines, a process which also occurs in our Sun. If this is the basic process, then the jet is also carrying off angular momentum, causing the star to slow its rotation. The outflow could also facilitate accretion of inner disk material onto the star.

The bright knots (Herbig-Haro objects) observed along jets mark locations where high-speed gas encounters material moving at lower velocity. But what exactly is this target material? In a few cases, it is clear that wind gas is impacting the ambient molecular cloud. There are some well-documented examples, however, of the knots being spaced symmetrically around the central star. No external cloud could possess such a high degree of symmetry. Hence, most shocks must arise in a different way.

An important clue comes from observing the space motion of Herbig-Haro objects; images taken a few decades apart show a marked shift, indicating speeds of several hundred kilometers per second. This speed is similar to that detected in the main body of the jet, which we have said represents stellar wind material. On the other hand, the spectral emission lines from the knots indicate that the shocked material is largely neutral so that gas enters the shock front at speeds of only about 30 km/s.

The explanation is that incoming material is hitting not a static environment but one already in motion. That is, the shocks arise when relatively fast wind gas encounters slower gas that was emitted earlier. Thus, the pattern of knots effectively constitutes a record of temporal wind variations, and the symmetrical patterns observed are neatly explained. The inferred fluctuations in wind speed are of order 10%, with associated periods ranging from decades to millennia.

The most mysterious aspect of stellar jets is their remarkable degree of collimation. Most jets have an aspect ratio (length to width) of about 100 to 1. One popular idea is that the rotating wind material twists up in its internal magnetic field. A twisted field exerts an inward force along the central axis. Perhaps this force keeps the jet from diverging. On the other hand, twisted magnetic fields created in the laboratory are unstable to reconnection. So are the twisted flux loops that protrude from the solar surface; their reconnection gives rise to X-ray flares. Researchers are using numerical simulations to see if the more vigorous outflows along interstellar magnetized jets are more stable.

An alternative notion is that the expanding jet creates shocks in the surrounding molecular gas. These so-called reflecting shocks effectively bend the flow back toward the axis. The converging flow then creates another pair of shocks and diverges outward once more. Alternating pairs of reflecting shocks are commonly seen in supersonic flows on Earth, such as the exhaust of a rocket.

It is clear, in any case, that the jets interact strongly with molecular gas. The outflows are observed to be clumpier than normal cloud gas. Their speed also increases closer to the jet axis. Terrestrial jets create not only a sequence of shocks but also a collar of turbulent gas that widens until the central jet terminates. An analogous process could be occurring near young stars. Here, turbulence might be induced by jet material spewing out transversely from each shock. Indeed, careful observation of Herbig-Haro shocks does show material ejected in this manner, with the hot spray of ionized gas creating a cocoon surrounding the shock. This spray could also be responsible for stirring up the surrounding cloud gas and dragging it forward as a molecular outflow.

However, interstellar jets can extend far beyond the turbulent, clumpy outflow. Astronomers have detected a number of stellar jets extending over a parsec from the central star, with little or no molecular gas. These long chains of Herbig-Haro objects are gently curved, reflecting the rotation or perhaps precession of the underlying jet source. The period of rotation is of order 10,000 years. Despite the fact that they are traveling through nearly empty space, the shocks are slowing down. It is possible that momentum is being continually deposited in the lateral spray of gas. Indeed, small clumps of gas are sometimes observed off to the side of the main jet flow.

While much of the underlying physics is still murky, the phenomenon of bipolar flows has clear importance in the process of star formation. First, solar-type stars form inside relatively small molecular clouds called dense cores. Since only about a third of the core mass winds up in the star, the rest must somehow be dispersed. Winds are the obvious candidate. On a larger scale, stars are born not as isolated objects but in groups. Initially, these clusters are embedded within large molecular clouds. Many such primitive groups have been detected by infrared telescopes. When the group first appears in optical light, the stars are a few million years old, and there is still a substantial amount of ambient molecular gas. Again, these so-called T associations are commonly observed. On the other hand, we never see such groups with ages as high as ten million years. The reason must be that the stars themselves have driven off the molecular cloud and then dispersed into the field population. The obvious driving mechanism is ► [stellar winds](#). In this view, molecular outflows represent the dispersal of cloud gas, the key step in terminating star formation on both large and small scales.

Cross-References

- [Pre-main-sequence Star](#)
- [Protostars](#)
- [Stellar Winds](#)

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Birthline

Steven W. Stahler
Department of Astronomy, University of California, Berkeley, CA, USA

Keywords

Stellar evolution · Star formation

Definition

After they have acquired most of their mass, but before they begin to fuse hydrogen, stars slowly contract. In the HR diagram, these ► [pre-main-sequence stars](#) descend along paths whose location depends on the stellar mass. All paths start at the birthline, a curve lying above and roughly parallel to the main sequence. When the stars within young clusters are placed in the HR diagram, they lie between the birthline and the main sequence. The two curves intersect at a mass of about ten solar masses. Stars of greater mass ignite hydrogen while they are still ► [protostars](#). If a young cluster contains such objects, they lie on the main sequence.

Overview

Astronomers view the evolution of stars using the Hertzsprung-Russell (HR) diagram. Within this plot of stellar luminosity versus surface temperature, the point representing a star

moves about as the object evolves. Mature stars that are fusing hydrogen lie along the so-called main sequence. Pre-main-sequence stars are situated higher in the diagram and gradually descend to the main sequence. The actual path of descent, known as the pre-main-sequence track, depends on the stellar mass. All pre-main-sequence tracks begin on another curve known as the birthline.

This description of the birthline is essentially theoretical. Observationally, young ► [stellar clusters](#) are studied by placing their members in the HR diagram (also called the color-magnitude diagram in this context). The birthline is the upper envelope of the stellar distribution. That is, the member stars lie in the region below the birthline and above the main sequence. In the very youngest clusters, most stars are crowded close to the birthline. In older groups, stars of lower mass lie further below the envelope, while more massive objects are already on the main sequence.

To see why there is a birthline, one needs to consider stellar evolution prior to the pre-main-sequence phase. The very youngest stars, known as protostars, are optically invisible and still acquire their masses from the surrounding clouds. As a protostar's mass increases, so does its radius. Indeed, the radius of the protostar can be predicted with fair accuracy from knowledge of its mass alone. Once cloud infall ceases, the star appears as a visible object on the appropriate pre-main-sequence track. The protostar mass-radius relationship dictates the initial positions of stars on their tracks. The locus of initial positions for various stellar masses defines a curve in the HR diagram that is the birthline.

An interesting feature of the birthline is that it intersects the main sequence. Specifically, the two curves join at about ten solar masses. More massive objects have no pre-main-sequence phase, but ignite hydrogen while they are still protostars. Thus, the early evolution of massive stars is quite different from that of the more common objects akin to the Sun. The intersection of the birthline and main sequence can be seen clearly in the HR diagram of the Orion Nebula

Cluster, the nearest region currently forming massive stars.

Cross-References

- [Main Sequence, Star](#)
- [Pre-Main-Sequence Star](#)
- [Protostars](#)
- [Stellar Cluster](#)
- [T Association](#)

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Bitumen

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

Bitumen is the fraction of fossil organic matter in sedimentary rocks that is soluble in organic solvents (such as dichloromethane, hexanes, and methanol). It is a brown to black, highly viscous material that includes diverse organic macromolecules and chemical biomarkers. Bitumen is a component in petroleum.

Cross-References

- [Hydrocarbons](#)
- [Kerogen](#)
- [Molecular Fossils](#)

Black Holes

Mar Mezcuca

Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Magrans, Barcelona, Spain
Institut d'Estudis Espacials de Catalunya (IEEC), Carrer Gran Capità, Barcelona, Spain

Keywords

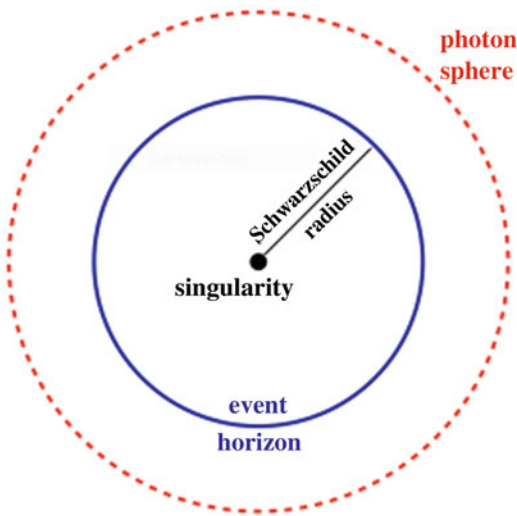
Black hole mass · Accretion · Active galactic nuclei · Galaxies

Acronyms

M_{BH}	Black hole mass
SMBH	Supermassive black hole
IMBH	Intermediate-mass black hole

Definition

Black holes are defined as a region in spacetime where gravity is so strong that particles and electromagnetic radiation cannot escape. At the center of a black hole, density and gravity become infinite, in what is called the singularity. The boundary region within nothing can escape is called the event horizon. The radius of this event horizon, which determines the size of a black hole, is called Schwarzschild radius and is directly proportional to the black hole mass (M_{BH}): $R_{\text{Sch}} = 2GM_{\text{BH}}/c^2$ where G is the gravitational constant and c the speed of light (see Fig. 1). Mass, spin, and charge are the three properties that characterize black holes. A nonrotating black hole with no charge is called Schwarzschild black hole, while a rotating one is called Kerr black hole (see section “History”). At a distance of 1.5 times the Schwarzschild radius of a nonrotating black hole, there is a spherical boundary where photons moving on tangential trajectories to that sphere are trapped around the black hole in circular orbits. For a Kerr black hole, this photon sphere has a radius that depends on the spin of the black hole and the orbit of the photon.



Black Holes, Fig. 1 Anatomy of a Schwarzschild black hole. The event horizon is spherical and its radius is called Schwarzschild radius (R_{Sch}). At $1.5R_{\text{Sch}}$, there is the photon sphere inside which photons move around the black hole in circular orbits

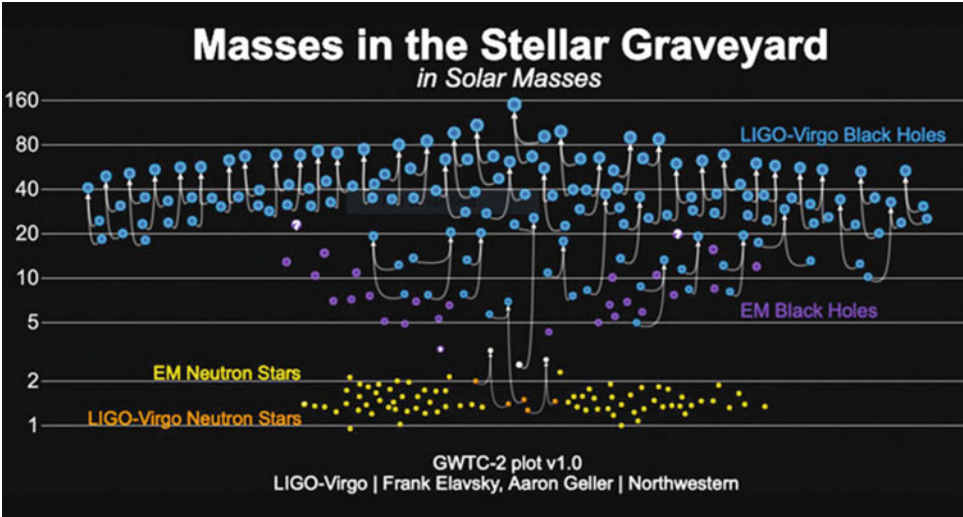
History

Black holes were proposed by Karl Schwarzschild in 1916 to solve the Einstein equations of general relativity. Schwarzschild's metric described a nonrotating black hole with no charge (Schwarzschild black hole). The solution for a rotating black hole was found in 1963 by Roy Kerr (Kerr black hole), and that of a rotating black hole electrically charged by Ezra Newman in 1965. Several observational techniques have since then provided evidence for the existence of black holes (e.g., the detection of signatures of black hole accretion, measurements of stellar and gas kinematics within the radius of influence of a black hole; see section “[Basic Methodology](#)”). However, it was not until 2016 that the detection of gravitational waves provided direct evidence that black holes exist and merge (Abbott et al. 2016).

Overview

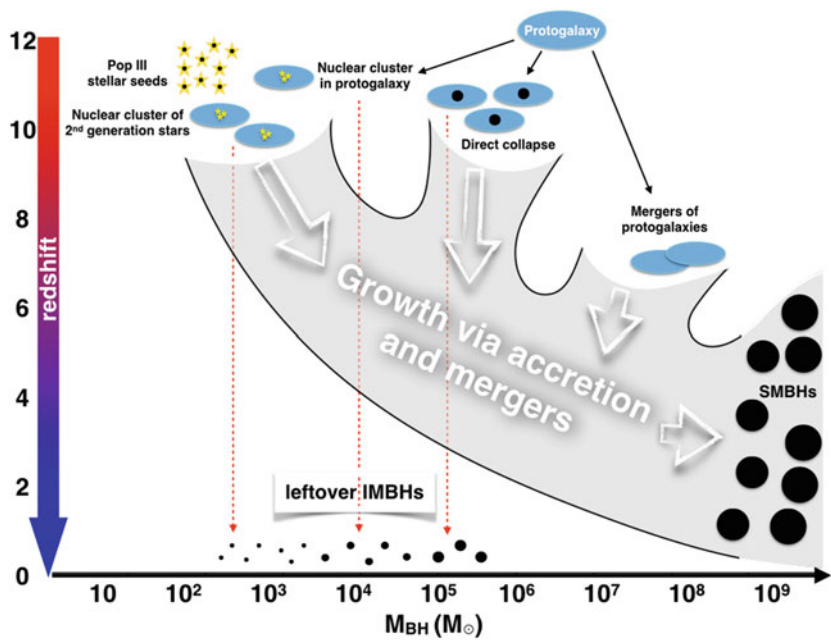
According to their mass, black holes are classified into three types:

- **Stellar-mass black holes.** They have a mass in the range $3 M_{\odot} < M_{\text{BH}} \leq 100 M_{\odot}$ and form when a massive star ($>15 M_{\odot}$) burns out its fuel supply and its internal pressure is no longer able to support gravitational collapse. Most stellar-mass black holes have been detected thanks to being part of an X-ray binary system in which the black hole accretes matter from a stellar companion via an accretion disk. The detection of X-ray and optical emission from X-ray binaries in the 1970s and 1980s (e.g., Cygnus X-1, LMC-X3; see review by, e.g., Remillard and McClintock 2006) provided the first observational evidence for the existence of stellar-mass black holes with a mass above $3 M_{\odot}$ (i.e., too large for a white dwarf or a neutron star). Since then, more than 20 stellar-mass black holes have been confirmed in X-ray binaries (e.g., Casares and Jonker 2014). The advent of gravitational wave interferometers such as LIGO and Virgo has provided the detection of tens of additional stellar-mass black holes (see Fig. 2).
- **Supermassive black holes (SMBHs).** They have a mass $M_{\text{BH}} \geq 10^6 M_{\odot}$ and reside typically at the center of massive galaxies (stellar mass $M_{*} \geq 10^{10} M_{\odot}$). SMBHs of up to $\sim 10^9 M_{\odot}$ in the local Universe are thought to result from the growth through cosmic time of stellar-mass black holes of a few tens of solar masses via accretion and mergers with other black holes. The detection of SMBHs of up to $\sim 10^{10} M_{\odot}$ when the Universe was less than 1 Gyr old (redshift $z \sim 7$; e.g., Wang et al. 2021) suggests they have to grow instead from higher-mass seed black holes of $100 M_{\odot} < M_{\text{BH}} < 10^6 M_{\odot}$ at $z > 10$ in order to reach $10^{10} M_{\odot}$ in such a short time (see Fig. 3). The best observational evidence for the existence of SMBHs comes from the measurement of stellar motions around the Galactic center, which revealed the presence of a SMBH of $4 \times 10^6 M_{\odot}$ (Ghez et al. 2008; Gillessen et al. 2009). More recently, the Event Horizon Telescope collaboration provided the first event-horizon-scale image of (the shadow of) a SMBH in the massive elliptical galaxy M87 (The EHT Collaboration



Black Holes, Fig. 2 Masses of all the compact binaries detected by LIGO/Virgo until October 2020. Stellar-mass black holes are shown in blue, neutron stars in orange. Those stellar-mass black holes and neutron stars detected

from electromagnetic observations (e.g., X-rays) are shown in purple and yellow, respectively. (Credits: LIGO/Virgo/Northwestern Univ./Frank Elavsky)



Black Holes, Fig. 3 Formation scenarios for IMBHs. Seed black holes in the early Universe could form from Population III stars, from mergers in dense stellar clusters formed out either from the second generation of stars or from inflows in protogalaxies, or from direct collapse of dense gas in protogalaxies, and grow via accretion and

merging to $10^9 M_{\odot}$ by redshift $z \sim 7$. SMBHs could also directly form by mergers of protogalaxies at $z \sim 6$. Those seed black holes that did not grow into SMBHs can be found in the local Universe as leftover IMBHs. (Credit: Mezcua (2017), International Journal of Modern Physics D, 26, 11, reproduced with permission)

et al. 2019). A SMBH that is actively accreting matter from its surrounding is called an Active Galactic Nucleus (AGN). An AGN can radiate over a trillion times the energy of the Sun, outshining the galaxy in which it resides.

- **Intermediate-mass black holes (IMBHs).** They have a mass $100 M_{\odot} < M_{\text{BH}} < 10^6 M_{\odot}$ and are thought to be the seeds from which SMBHs in the early Universe grew (see reviews by Mezcua 2017; Greene et al. 2020). Such seed IMBHs could form at $z > 10$ from the death of Population III stars of more than $260 M_{\odot}$, from direct collapse of pristine gas, or from runaway mergers in dense stellar clusters, among other possibilities (Rees 1978). They could then rapidly grow via accretion and mergers to become the SMBHs observed by $z \sim 7$ (see Fig. 3; Mezcua 2017 and references therein). Those seed black holes that did not grow should be found in the local Universe as leftover IMBHs, with a mass of $\sim 10^2$ – $10^3 M_{\odot}$ if they originated from Population III stars, of up to $10^4 M_{\odot}$ if they originated in nuclear stellar clusters, or of $\sim 10^4$ – $10^6 M_{\odot}$ if they formed via direct collapse of pregalactic gas. Hundreds of IMBH candidates have been found in the local Universe (e.g., Reines et al. 2013; Chilingarian et al. 2018; Mezcua and Domínguez 2020) and out to $z \sim 3.4$ (Mezcua et al. 2016, 2018b, 2019) as low-mass ($M_{\text{BH}} < 10^6 M_{\odot}$) AGN in dwarf galaxies. Because of their low mass (stellar mass $M_* \leq 3 \times 10^9 M_{\odot}$) and quiet merger history, dwarf galaxies are thought to resemble the first galaxies of the early Universe. Tens of additional candidates have been also found in globular clusters (e.g., Lützgendorf et al. 2013; see Table 1 in Mezcua 2017 and references therein) and in the outskirts of massive galaxies that have recently undergone a merger with a dwarf galaxy (e.g., Mezcua et al. 2015, 2018c; Barrows et al. 2019). The best observational evidence for the existence of IMBHs was provided by the LIGO/Virgo detection of a local IMBH of $142 M_{\odot}$ (Fig. 2; Abbott et al. 2020).

A possible fourth type of black holes are primordial black holes. These could have formed in

the presence of high-density fluctuations in the inflationary Universe or of abrupt changes in the plasma pressure, and could have masses ranging from sub-solar values to $10^8 M_{\odot}$ (e.g., Rubin et al. 2001; Carr and Kühnel 2020; Volonteri et al. 2021). Primordial black holes are currently being considered as a form of dark matter and for interpretation of gravitational wave events and, if sufficiently large, they can also be regarded as pregalactic seeds of SMBHs (e.g., Rubin et al. 2001; García-Bellido 2019; Carr and Kühnel 2020).

Basic Methodology

There are several ways to weight and detect black holes.

Dynamical Mass Measurements

In the case of stellar-mass black holes, most black hole masses come from dynamical measurements based on the detection of the radial velocity curve of the donor star in X-ray binaries (see review by, e.g., Casares and Jonker 2014). Other (indirect) methods, used to estimate the mass of a few IMBH candidates, include the detection of quasi-periodic oscillations (QPOs) and applying an inverse scaling relation found for stellar-mass black holes between QPO frequency and black hole mass (e.g., Pasham et al. 2014).

In globular clusters, the black hole mass of several IMBH candidates has been derived based on stellar kinematics and surface brightness profiles combined with dynamical modeling (e.g., Gebhardt et al. 2005; Lützgendorf et al. 2013). However, the absence of any signatures of accretion in the form of X-ray or radio emission precludes confirming the presence of IMBHs in these sources (e.g., Wrobel and Nyland 2020).

In the case of SMBHs, the best black hole mass measurements come from the monitoring of stellar proper motions around the black hole (e.g., Ghez et al. 2008; Gillessen et al. 2009) and from dynamical modeling of stellar and gas kinematics within the black hole sphere of influence (see review by, e.g., Kormendy and Ho 2013). Such dynamical mass measurements have been also

possible for a few nearby IMBHs (e.g., Davis et al. 2020). Beyond the local Universe (the Local Group in the case of IMBHs), where spatial resolution prevents performing such dynamical mass measurements, the detection of IMBHs and SMBHs has to rely on the finding of signatures of accretion in the form of AGN.

Active Galactic Nuclei (AGN)

AGN can be identified across the electromagnetic spectrum. In the optical and infrared regime, the presence of AGN ionization can be distinguished from ionization by galactic star formation using emission line diagnostic diagrams. AGN can also be identified by the detection of broad emission lines coming from gas clouds moving at velocities of ~ 3000 km/s around the central SMBH (the so-called “broad line region”). In the case of low-mass AGN in dwarf galaxies, these velocities can be of just hundreds of km/s (e.g., Reines et al. 2013). Such low velocities can be mimicked by some varieties of supernovae; however, unlike AGN, the broad line emission in supernovae would significantly decrease or disappear over a timespan of 5–15 years (e.g., Baldassare et al. 2016). In AGN with broad emission lines, the flux and width of the line can be used to estimate the black hole mass under the assumption that the gas in the broad line region is virialized.

In the mid-infrared regime, color-color diagrams can be also used to identify AGN (e.g., Stern et al. 2012). These diagrams are based on the colors that dust presents when heated by different mechanisms such as AGN or stars.

The detection of hard (2–10 keV band) X-ray emission from the corona of electrons sitting above the accretion disk around a black hole is a very strong tracer of black hole accretion. In massive galaxies, AGN can be identified as having an X-ray luminosity typically above 10^{42} erg/s. In dwarf galaxies, the AGN X-ray luminosity can be as low as 10^{38-39} erg/s, probing very low rates of accretion (e.g., Gallo et al. 2010). In this case, the contribution from X-ray binaries to the X-ray emission must be removed in order to confirm the presence of AGN (e.g., Mezcua et al. 2016, 2018b).

Some AGN eject a pair of collimated jets of relativistic plasma that radiate across the

electromagnetic spectrum via synchrotron emission. These jets are best observed at radio wavelengths, and their detection is a common tracer of AGN activity. Radio luminosities at 1.4 GHz above 10^{24} W/Hz are typically used to identify AGN, as these high radio luminosities cannot be explained even by extreme star formation. In the case of dwarf star-forming galaxies, the radio contribution from star formation processes must be removed in order to infer the presence of AGN (e.g., Mezcua et al. 2019).

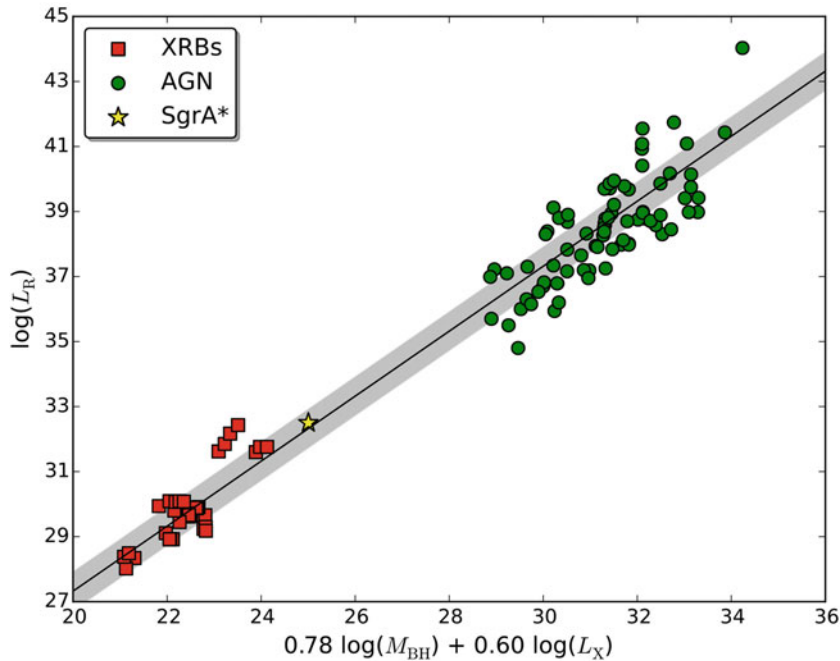
Gravitational Waves

Gravitational waves are ripples in the space-time that propagate at the speed of light. They are generated by massive accelerated objects such as two merging black holes. In a black hole binary, gravitational waves are emitted during the inspiral phase, the merger, and the final ring-down. This was the case of the first detection of gravitational waves by the LIGO and Virgo interferometers in 2015, when two black holes of 29 and 36 $M_{\odot}$ merged into a new black hole of 62 $M_{\odot}$ (Abbott et al. 2016). Since then, tens of gravitational wave observations resulting from the merger of two stellar-mass black holes have been reported (Fig. 1). One of such black hole binaries resulted in a final black hole of 142 $M_{\odot}$, thus in the IMBH regime (Abbott et al. 2020). The detection of gravitational waves from SMBH binaries will have to await the next generation of space-based interferometers (e.g., Amaro-Seoane 2018).

Key Research Findings

Universality of Black Hole Accretion

The process of black hole accretion and its connection with the ejection of large-scale outflows (i.e., jets) is predicted to be a universal mechanism covering the whole black holes mass scale. This implies that the same disc-jet connection governing stellar-mass black hole does also take place in SMBHs (e.g., Falcke et al. 2004). Observational evidence for this universality of black hole accretion comes from the finding of a correlation between X-ray luminosity (proxy of accretion flow), radio luminosity (proxy of jet



Black Holes, Fig. 4 Fundamental Plane of Black Hole Accretion correlating radio luminosity, X-ray luminosity, and black hole mass. The solid line shows the best-fit

regression from Merloni et al. (2003). Galactic black holes (XRBs) are shown as red squares, Sgr A* as a yellow star, and AGN as green dots

emission), and black hole mass extending from stellar-mass to SMBHs (the so-called Fundamental Plane of Black Hole Accretion; see Fig. 4; e.g., Merloni et al. 2003; Plotkin et al. 2012). The Fundamental Plane of Black Hole Accretion can be used to estimate black hole masses when nuclear radio and X-ray luminosities are available (e.g., Mezcua et al. 2015, 2018c; Gültekin et al. 2019).

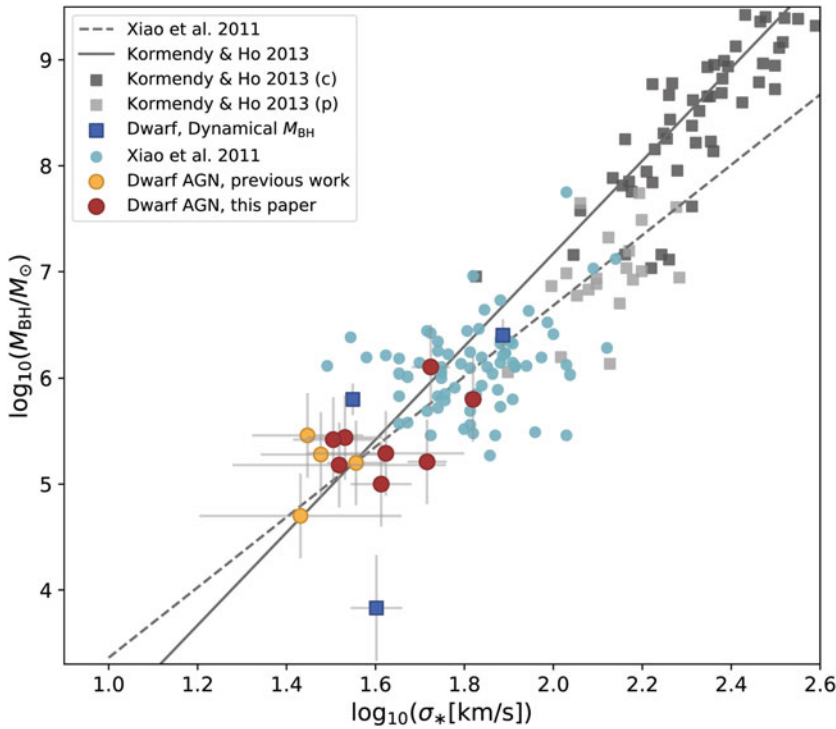
Black Hole-Galaxy Coevolution

Another key finding in black hole studies is that of a correlation between the mass of SMBHs and some host galaxy properties, such as bulge luminosity, stellar mass, or stellar velocity dispersion (see review by, e.g., Kormendy and Ho 2013), which implies that SMBHs and their host galaxies coevolve (see Fig. 5). While this synchronized black hole-galaxy growth was originally found for SMBHs of $>10^6 M_{\odot}$, recent studies have extended these correlations to the IMBH regime, where a flattening or large scatter seems to be observed (e.g., Martín-Navarro and Mezcua 2018; Baldassare et al. 2020; Greene et al.

2020). Feedback from the AGN onto the host galaxy is thought to be the main mechanism behind such black hole-galaxy evolution, via winds or jets that impact the formation of stars in the host galaxy and thus regulate its growth. Observational evidence for AGN feedback in massive galaxies comes from the finding that the radio jets of SMBHs fill the large-scale X-ray cavities of some galaxy clusters (e.g., McNamara et al. 2000). The effects of AGN feedback in dwarf galaxies are not so clear, but recent simulations (e.g., Sharma et al. 2020 and references therein) and observations (e.g., Mezcua et al. 2019; Liu et al. 2020) indicate it could be as significant as in massive galaxies.

Future Directions

The next generation of observational facilities will provide a major step forward in our understanding of black hole formation and evolution and the physics behind black hole accretion. Future radio observatories such as the Square Kilometer Array



Black Holes, Fig. 5 Black hole mass (M_{BH}) versus stellar velocity dispersion (σ_*). Gray squares are from the compilation of Kormendy and Ho (2013); dark gray squares show galaxies with classical bulges and light gray squares show galaxies with pseudo-bulges. Light blue circles show data for low-mass AGN from Xiao et al. (2011). Active dwarf galaxies with stellar velocity dispersion measurements measured in Baldassare et al. (2020) are shown as

red circles; active dwarf galaxies with previously existing data are shown in orange. Dwarf galaxies with dynamical black hole mass estimates are shown as dark blue squares. Also shown are the fits to the $M_{\text{BH}} - \sigma_*$ from Xiao et al. (2011; dashed line) and Kormendy & Ho (2013; solid line). (Credit: Figure and caption adapted from Baldassare et al. 2020, ApJ Letters, 898, L3, reproduced with permission)

(SKA) and X-ray satellites such as *Athena* or the mission-concept *Lynx* will provide a complete coverage of the phases that stellar-mass black hole transients undergo (i.e., the disk-jet coupling mechanism) and be able to detect SMBHs and their seed IMBHs out to $z = 10$ (e.g., Yu et al. 2015; Mezcua et al. 2018a; Whalen et al. 2020). In the new era of gravitational-wave astronomy, the Einstein Telescope will capture the gravitational-wave signal from millions of coalescing stellar binary black holes detectable out to $z \sim 15$ and up to masses of $10^3 M_\odot$ characteristic of (growing) black hole seeds, while LISA will detect the gravitational-wave signal from massive binary black hole coalescences ($\sim 10^4 M_\odot$ to $\sim 10^7 M_\odot$) across all cosmic ages (e.g., Amaro-Seoane 2018). A future of exciting discoveries awaits us.

Cross-References

- [Galaxy](#)
- [Globular Cluster](#)
- [Radio Astronomy](#)

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Black Smoker

Yves Fouquet

Institut Français de Recherche pour l'Exploitation de la mer (IFREMER), Issy-les-Moulineaux, France

Definition

A black smoker is a sulfide-rich hydrothermal vent or hot spring on the ocean floor.

Hydrothermal aqueous fluids with temperatures up to 400 °C are issued from the vent. These fluids contain high concentrations of dissolved metals, sulfur species, and silica. Cooling and dilution as the fluid mixes with seawater causes the precipitation of Fe-Cu-Zn-Pb sulfides, which give rise to the dark color of the fluid (hence the name black smoker). Accumulation of sulfides around the vent builds up chimneys that may reach 60 m in height and support an exotic ecosystem of anaerobic fauna and ► [chemolithoautotroph](#) communities. Long-lived black smoker complexes may accumulate large volumes of sulfide which, when accreted to the continent, can be mined as ore deposits. Black smokers occur along modern ► [mid-ocean ridges](#), in back-arc basins and on the flanks of island arcs; their fossilized equivalents are found in Phanerozoic and Precambrian greenstone belts. The hydrothermal fluids form as seawater seeps down into the oceanic crust where it is heated and interacts with mainly basaltic rocks. The heated fluid then ascends through fractures and exits at the sea floor.

Cross-References

- [Chemolithoautotroph](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Mid-Ocean Ridge](#)

Black Smoker, Organic Chemistry

Koichiro Matsuno

Nagaoka University of Technology, Nagaoka, Japan

Keywords

Chimney · Hydrothermal vents · Pyrite · Reducing agents · Sulfide

Synonyms

[Submarine hot spring](#)

Definition

A specific organic chemistry proceeds in the vicinity of a black smoker, or a hydrothermal vent, from which a cloud of black particles is emitted on the floor of the ocean. The main ingredients of the black particles are metal sulfides. Pyrite deposited around the smoker can serve as an efficient reducing agent for synthesizing reduced carbon compounds from primary carbon sources, such as carbon monoxide.

Overview

A black smoker is a type of hydrothermal vent found on the seafloor, appearing in the form of a chimney-like structure. Hydrothermal vents are located around fissures at mid-ocean ridges where tectonic plates are moving apart, from which heated water issues. Besides Earth, planetary bodies that might possibly have or had such hydrothermal systems include Europa, a satellite of Jupiter, and ancient Mars.

The cloud of black materials emitted out of the chimney includes a significant amount of black particles made of metal sulfides. When the hot water from the chimney comes in contact with the surrounding cold water, the black materials precipitate on top of the chimney, and it can gradually grow in height until its inevitable collapse. The piling up of the black chimney-like structures is considered to be a major source of sulfide ore deposits on Earth.

► **Pyrite** is a typical metal sulfide deposited by black smokers. It is a crystalline mineral composed of iron and sulfur. Pyrite possesses a positive surface charge at ambient seawater pH and accordingly can adsorb anions or organic compounds having anionic carboxylate or phosphate groups. In particular, when hydrogen sulfide reacts with iron in solution to form iron sulfide under conditions expected in the vicinity of the black smokers, the reaction produces electrons that can reduce various chemicals if relevant reactants are available. Iron sulfide formed in the hydrothermal environment can serve as a reducing agent that can drive a series of various

synthetic reactions. An experimental demonstration of the reducing capability associated with the formation of pyrite from hydrogen sulfide and iron is the synthesis of acetate from carbon monoxide (Huber and Wächtershäuser 1997).

It might therefore be expected that ► **Fischer-Tropsch**-type reactions using acetic acid or formic acid as the primary carbon sources may synthesize saturated fatty acids in the vicinity of hydrothermal vents, perhaps using cobalt-based catalysts where deleterious influences from sulfur catalyst poisoning could be avoided. Organic chemistry proceeding in and around black smokers could be quite rich, although some of the synthetic reactions might mutually be inhibitive. To date, the only unambiguously abiogenic organic compounds detected in these systems on Earth are simple hydrocarbons such as methane, ethane, and propane.

Cross-References

- **Black Smoker**
- **Fischer-Tropsch-Type Reaction**
- **Hydrocarbons**
- **Hydrothermal Environments**
- **Hydrothermal Reaction**
- **Hydrothermal Vent Origin of Life Models**
- **Pyrite**

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Blackbody

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Electromagnetic radiation · Temperature · Emission · Spectrum

Synonyms

Thermal emission

Definition

A blackbody is a hypothetical object that is a perfect radiator, absorbing all radiation that impinges upon it and emitting over the whole electromagnetic spectrum, however preferentially around a certain wavelength. The overall power and the spectral energy distribution depend only upon the object's temperature.

Overview

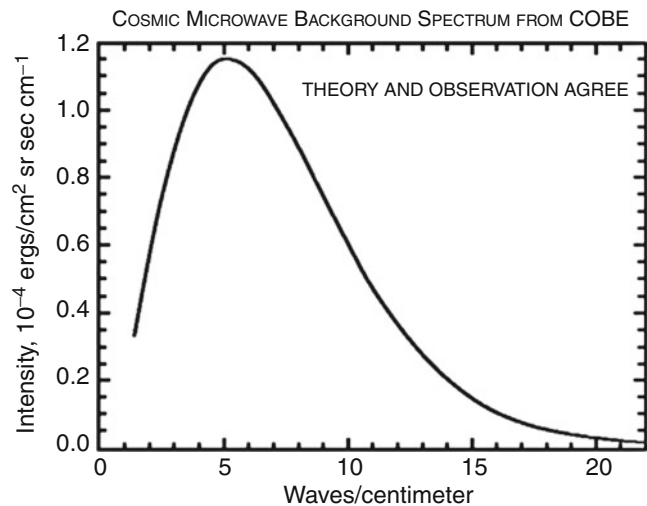
At the laboratory, a good approximation of a blackbody is a small-hole entrance to a cavity with absorbing walls within a block maintained at a fixed temperature. The spectral distribution of the blackbody emission is described by Planck's law and depends only on the temperature of the object: it peaks at a wavelength given by Wien's law, approximately $\lambda(\mu\text{m}) = 3,000/T(\text{K})$. On the short-wavelength side, the intensity decreases very fast, while it varies in a smoother way at wavelengths beyond the maximum (Fig. 1). The total power radiated by a blackbody is proportional to the fourth power of the temperature

(Stephan's law). As a first approximation, stars' and planets' emission can be described by blackbody radiation. The most perfect astrophysical blackbody is without any contest the Universe itself, which emits radiation peaking in the millimetric range, the cosmic microwave background (CMB); it fits Planck's law (at $T = 2.73 \text{ K}$) to within 1 part in 1,000, as revealed by the satellite COBE. The blackbody emission is indeed universal and is observed in a large variety of celestial objects at very different wavelengths. To give several examples, the emission of a star as the Sun, with $T = 6,000 \text{ K}$, peaks at $\lambda(\mu\text{m}) = 0.5 \mu\text{m}$ (visible); a planet as the Earth, with $T = 300 \text{ K}$, emits mainly at $\lambda(\mu\text{m}) = 10 \mu\text{m}$ (infrared); and the hot gas in a cluster of galaxies, with $T = 30 \times 10^6 \text{ K}$, peaks at $\lambda(\mu\text{m}) = 10^{-4} \mu\text{m}$, i.e., in the X-ray domain. Obviously celestial objects are not strictly black in general; this is why an approximation called the gray-body radiation is often used in models.

Cross-References

- [Bremsstrahlung Radiation](#)
- [Effective Temperature](#)
- [Electromagnetic Radiation](#)
- [Electromagnetic Spectrum](#)
- [Grey Body](#)
- [Radiative Processes](#)

Blackbody, Fig. 1 The spectral distribution of the blackbody emission of the Universe as seen by the satellite COBE. One notes the strong asymmetry between the short- and the long-wavelength sides with an abrupt exponential decrease in the first case and a smoother power-law decrease in the second case



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Blue-Green Algae

► [Cyanobacteria, Diversity and Evolution of](#)

Blue-Green Bacteria

► [Cyanobacteria](#)

BNSC

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[British National Space Council](#)

Definition

The British National Space Council (BNSC) was established in 1985 replacing the Space Research Management Unit that was running the UK space activities since 1963. The BNSC aimed to help Britain to get an optimal return of national and international activities in space, both economically and scientifically. BNSC was a voluntary partnership between ten government departments and research councils. Their combined expenditure on civil space amounts to around £180 million per year.

The ► [UK Space Agency](#) took over in March 2010 to become a full agency replacing the BNSC by April 1, 2011.

Cross-References

► [UK Space Agency](#)

Bolometer

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Pyrometer](#); [Radiometer](#)

Definition

A bolometer is a detector that measures electromagnetic power incident on its absorbing surface by sensing a temperature change through some temperature-dependent physical mechanism in the detector, generally its electrical resistance. In a typical bolometer, the radiative power is thermalized either by a crystal lattice or by the electrons in the absorber. The small resulting temperature rise is sensed by a thermometer – a temperature-dependent semiconductor in the case of a semiconducting bolometer or a superconducting metal film in the case of a transition-edge superconducting detector. The lower the temperature, the better the performances of a bolometer: 100 mK is current in the most sensitive instruments.

Because they absorb any radiation, bolometers are able to measure the power received from celestial objects over a broad range of wavelength; they are however used mainly in the infra-red and millimeter bands.

Cross-References

► [Bolometric Magnitude](#)

Bolometric Magnitude

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The bolometric magnitude is a way to quantify the total power emitted by a celestial object in the form of electromagnetic radiation. The bolometric magnitude is the ► [magnitude](#) of a celestial object based on its flux integrated over the whole electromagnetic spectrum. By convention, the bolometric magnitude of the star Vega is zero. The bolometric correction, BC, is the difference between the visual and the bolometric magnitudes.

Cross-References

- [Magnitude](#)
- [Magnitude, Absolute](#)

Borate

Kateryna Klochko
Carnegie Institution of Washington, Washington,
DC, USA

Definition

Borate is a common oxoanion (BO_3^{3-}) found in boron-containing minerals (e.g., boracite, borax, kernite, colemanite, etc.), some borosilicates (e.g., tourmaline), and in association with natural carbonates. In natural aqueous environments, borates exist in equilibrium with boric acid $\text{B}(\text{OH})_3^\circ$ and borate anion $\text{B}(\text{OH})_4^-$. The pH-dependent equilibrium between these species in seawater ($\text{pK}_a = 8.597$, (Dickson 1990)) is accompanied by boron isotope fractionation of 27.2‰

(Klochko et al. 2006). The two naturally occurring and stable isotopes are ^{11}B (80.1%) and ^{10}B (19.9%). The mass difference results in a wide range of boron isotopic compositions in terrestrial environments, and boron isotopic compositions in marine carbonates have been used as a paleo-pH proxy of the oceans (Hemming and Hanson 1992). Borates have also been found to stabilize ► [ribose](#) (Ricardo et al. 2004), which may have been important for the origin of life on early Earth, although the prebiotic availability of borate minerals has been questioned (Hazen et al. 2008).

Cross-References

- [Formose Reaction](#)
- [Ribose](#)

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Boron Isotopes

Marc Chaussidon
Institut de Physique du Globe de Paris (IPGP),
Paris, France

Keywords

Boron · CAIs · Chondrites · Isotopes ·
Nucleosynthesis · pH · Seawater

Definition

Boron has two stable isotopes (^{10}B and ^{11}B), ^{11}B being the most abundant since the average terrestrial $^{11}\text{B}/^{10}\text{B}$ isotope ratio is of ≈ 4.04 . Strong variations of this ratio were present in the presolar molecular cloud and in the accretion disk, part of them due to the radioactive decay of ^{10}Be to ^{10}B . Low-temperature isotopic fractionations are responsible of large (up to $\approx 100\%$, where ‰ is parts per mil) variations of the $^{11}\text{B}/^{10}\text{B}$ ratio in seawater and terrestrial rocks. Some of these variations may be used to reconstruct paleo-seawater pH and paleo-atmospheric P_{CO_2} .

Overview

Boron is one member of the lithium-beryllium-boron (Li-Be-B elements) clan, three elements which share some unique properties due to a common nucleosynthetic history. The cosmic abundance (or solar abundance) of Li-Be-B elements (Lodders 2003) is a factor of $\approx 10^7 - 10^{10}$ lower than elements of neighboring atomic mass such as He, C, and O. This is due to the fact that light elements (D and Li-Be-B clan) cannot be synthesized by nuclear reactions in stellar interiors at temperatures higher than $\approx 10^6$ K, being rather destroyed at these temperatures (Burbidge et al. 1957). Contrary to ^7Li , for which a fraction is produced during the Big-Bang nucleosynthesis, the two stable isotopes of B (^{10}B and ^{11}B) are produced in the interstellar medium by endothermic spallation reactions. These reactions occur at high energies, typically higher than a few MeV (Reeves et al. 1970). High-energy collisions between accelerated protons (and alpha particles) and O and C nuclei at rest (mostly ^{16}O and ^{12}C) are responsible of the production of ^{10}B and ^{11}B with an isotope ratio $^{11}\text{B}/^{10}\text{B} \approx 2.5$, as modeled from available cross sections (Meneguzzi et al. 1971) and as measured in present-day galactic cosmic rays (GCR) ($^{11}\text{B}/^{10}\text{B}$ from ≈ 1.5 to ≈ 3.2 depending on the energy, Krombel and Wiedenbeck 1988). The poor efficiency of these reactions is responsible of the low cosmic abundance of B.

This nucleosynthetic origin makes the isotopic composition of B in the Solar system quite intriguing. In the Earth and meteorites, the $^{11}\text{B}/^{10}\text{B}$ ratio (≈ 4.04 ; Palmer and Swihart 1996) is enriched in ^{11}B relative to GCR. Boron in diffuse interstellar clouds is also ^{11}B -rich ($^{11}\text{B}/^{10}\text{B} = 3.4 \pm 0.7$, Lambert et al. 1998) relative to GCR. This ^{11}B enrichment has been proposed to result from the addition of B made by low-energy spallation which would be enriched in ^{11}B according to predictions made from available cross sections (Reeves 1994) and/or to the addition of B made by neutrino-induced spallation of C in type II supernovae (Lambert et al. 1998). These processes are likely to operate at galactic time scales but irradiation processes around the young forming Sun also produced a fraction of the Solar System boron. This is demonstrated (McKeegan et al. 2000) by the presence in Ca-Al-rich refractory inclusions ($\blacktriangleright$ CAIs) from chondritic meteorites of ^{10}B excesses due to the radioactive decay of short-lived ^{10}Be (^{10}Be β decays to ^{10}B with a half-life of 1.39 Ma). The magnitude of the ^{10}B excesses implies that the $^{10}\text{Be}/^9\text{Be}$ ratio at the time of formation of CAIs was up to $\approx 8.8 \times 10^{-4}$ (Chaussidon et al. 2006) but large variations are expected in this ratio depending on the conditions of the irradiation processes in the early Solar System (Chaussidon and Gounelle 2006). One attractive model is the formation of ^{10}Be and of B isotopes (^{10}B and ^{11}B) by reactions between flares emitted by the young active Sun when a classical T-Tauri star and grains and/or gas at the inner edge of the accretion disk.

While B isotopic variations inherited from nucleosynthesis might be present in the accretion disk (Chaussidon and Robert 1995, 1998), they are most probably averaged at planetary scale. However, B isotopic variations around this ratio of ≈ 4.04 are widespread in terrestrial rocks. They are due to low-temperature stable isotopic fractionations and are generally reported as deviations in permil from the $^{11}\text{B}/^{10}\text{B}$ ratio of the international standard (NBS boric acid SRM 951 with $^{11}\text{B}/^{10}\text{B} = 4.04367$, Catanzaro et al. 1970) using the classical delta notation ($\delta^{11}\text{B}_{\text{sample}} = ((^{11}\text{B}/^{10}\text{B})_{\text{sample}} / (^{11}\text{B}/^{10}\text{B})_{\text{SRM951}} - 1) \times 1000$). Boron in the silicate Earth is grossly distributed

as follows: $\approx 10\%$ in seawater, $\approx 35\%$ in the crust (continental and oceanic), and $\approx 55\%$ in the mantle (upper plus lower mantle). Very little is known for boron isotope variations in organic matter (Williams et al. 2001) because of analytical difficulties, even though boron is a key element for life and has a complex biogeochemical cycle (Park and Schlesinger 2002). Boron in the primitive mantle has a $\delta^{11}\text{B} \approx -10\%$ as indicated by oceanic basalt glasses (Chaussidon and Marty 1995) and this is most probably the bulk $\delta^{11}\text{B}$ of the Earth. There is no significant isotopic fractionation associated with the extraction of boron from the mantle to the crust, because boron isotopic fractionations at mantle temperatures are minimum. This is confirmed by analyses of tourmalines from granitic rocks of various ages which allow to define an average $\delta^{11}\text{B}$ for the continental crust (at a mean age of 2 Ga) between $\approx -8\%$ and $\approx -13\%$ (Chaussidon and Albarède 1992). However, in more details, mass balance implies that the $\delta^{11}\text{B}$ of the crust has evolved over geologic times in response to crustal growth and to the change of the relative fractions of B hosted in the main surface reservoirs. In fact, a major isotopic fractionation occurs for boron during adsorption processes on clay minerals (Schwartz et al. 1969; Palmer et al. 1987) and various other phases such as, for instance, humic acids (Lemarchand et al. 2005). This isotopic fractionation is due to the facts that (1) boron in solution occurs both as boric acid ($\text{B}(\text{OH})_3$, named B_3 in the following) and borate anion ($\text{B}(\text{OH})_4^-$, named B_4 in the following), the relative proportions of the two species depending on the acidity constant (pK) of boric acid, which itself depends on temperature and salinity, and (2) there is a strong equilibrium isotopic fractionation between boric acid and borate anion ($\alpha_{\text{B}_3-\text{B}_4} = 0.97352$ at 25 °C, Pagani et al. 2005; Klochko et al. 2006; Rollion-Bard and Erez 2010). Boron adsorbed at the surface of growing minerals (clays, carbonates) is dominantly B_4 , which is thus strongly isotopically fractionated from the solution. During crystal growth, this adsorbed boron is incorporated into the structure of the minerals (Spivack et al. 1987). This property allows the boron isotopic fractionation to be

calculated between a mineral and the pH of the solution and has been widely used and investigated to try to reconstruct paleovariations of seawater pH and atmospheric P_{CO_2} (e.g., Pearson and Palmer 2000, refs. therein). These reconstructions are complicated by the fact that the $\delta^{11}\text{B}$ of seawater might have changed over geological times (Lemarchand et al. 2000) and that a significant fraction of B_3 can also be adsorbed. However, boron isotopes are one of the best tools used to infer the pH of a solution from which a mineral grew. This has been useful to unravel the origin of the so-called vital effect on the oxygen isotopic fractionation between biogenic carbonates and seawater. Micrometer scale variations of $\delta^{11}\text{B}$ values in coral skeletons have shown that strong pH variations occurred during the formation of calcite and that these changes of pH modify the kinetic of oxygen isotopic exchanges between dissolved carbonate species (H_2CO_3 , HCO_3^- and CO_3^{2-}) and water via the two reactions of hydration and hydroxylation (Rollion-Bard et al. 2003). Boron isotopes in sedimentary rocks are thus key for the reconstruction of past paleo-environmental changes on Earth.

Cross-References

- CAIs
- Chondrite
- Nucleosynthesis, Stellar

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Brahe (55 Cancri c)

► 55 Cancri

Branching Fraction

► Branching Ratio

Branching Ratio

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Synonyms

[Branching fraction](#)

Definition

In chemistry and physics, the branching ratio is the ratio of the rate constant for a particular product of a reaction to the rate constant for the total set

of possible products. For example, in nuclear physics, the branching ratio for a decay process is the ratio of the number of particles which decay via a specific decay mode with respect to the total number of particles which decay via all decay modes. It is also equal to the ratio of the partial decay constant to the overall decay constant.

Brazilian Space Agency

► [AEB, Brazil](#)

Breccia

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Sedimentary rock · Meteorite impact · Planetary surface · KREEP · Anorthosite · Regolith · Brecciated meteorites

Synonyms

[Rubble rock](#)

Definition

Breccia is an Italian word that means “rubble.” Indeed, breccia is a detrital rock composed of angular fragments of minerals or rocks. These fragments can be produced by sedimentary, magmatic, or tectonic processes. Breccia containing angular clasts and fine-grained matrix produced by meteoritic impacts is a common rock covering planetary surfaces such as the Moon’s highlands.

Overview

A *sedimentary breccia* is a coarse-grained (particle size >2 mm) detrital rock composed of

angular rock or mineral fragments held together by a cement or dispersed in a fine-grained solidified matrix. It originates as a result of localized sedimentary processes such as talus accumulation (*sedimentary breccia*), disturbance during sedimentation (*intraclastic breccia*), or collapse of rocky surfaces such as the roof of a cave (*collapse breccia*). The reason that the rock debris is angular is indeed an indication that the rock was little exposed to weathering and that transport by meteoric agents (winds, water, ice) was minimal. *Glacial breccia* is the product of mechanical fragmentation of the rock substratum by a moving ice sheet or glacier. These products are often found in moraines which are accumulation of unconsolidated debris previously carried along by a glacier or an ice sheet.

Volcanic breccia results from explosive eruptions (*pyroclastic or tuff breccia*), hydrovolcanic (highly pressurized water) fragmentation in diatremes (funnel-shaped pipes), or mechanical fragmentation in intrusive settings.

Local tectonic processes such as brittle deformation along a fault can produce a *fault (or tectonic) breccia*. Sometimes this breccia can contain vitreous debris derived by frictional melting of the rocks along the fault plane during large earthquakes and are called *pseudotachylitic breccia*.

Heavily craterized planetary surfaces contain also breccia produced by meteorite impacts, such as on the Moon. On Earth, plate tectonics have shaped the planetary surface in the last 3 billion years wiping the remains of meteoritic breccias except in a few well-preserved large impact areas, such as the Vredefort (South Africa), or Sudbury (Canada) structures, or several smaller size craters. These breccia contain a complex mixture of target-rock lithologies. Impact breccias characterized by partial melting of the targeted rock are thus often called *pseudotachylitic breccia* or PTB (Reimold et al. 2017), for their similarities with frictional tectonic breccia. The most likely process for the genesis of PTB is decompression melting upon formation and collapse of the central uplift, during the modification stage of impact cratering.

On the Moon, there are two families of breccias: *lunar regolith breccias* and *fragmantal*

breccias. Regolith is the name of the layer of unconsolidated material that covers solid bedrock at the surface of a planet. On Earth is synonymous of “soil.” On the Moon, the *regolith* and *fragmented breccias* are both generated by the impact of a bolide on the planetary surface. However the first consists of fine-grained material, partially melted, from the upper few meters; the second consists of material that was deeper settled, likely fragmented rock that shattered on place by the impact-generated shock waves. The *lunar regolith breccias* consist of two distinct lithologies: *glass spherules* and *agglutinates*. Glass spherules can be produced either by rock melted during the impact and ejected in form of small globs that are rapidly quenched or by erupting volcanoes. Agglutinates are tens of micrometers to a few millimeters glassy breccias formed when a micrometeorite strikes the lunar regolith. Depending on the dominant mineralogy of the targeted rocks by the meteorite impact, lunar breccias are also named as *anorthositic breccias*, *feldspathic breccias*, or *highlands breccias*.

Finally, pieces of those breccias can be ejected from the planet during impacts and then brecciated meteorites can be found on Earth, as lunar achondrite NWA 2995 which is a fragmental breccia found in 2005 in Algeria. Martian meteorites can also be composed of breccias, and following the Meteoritical Society recommended classifications, a *Martian (basaltic) breccia* means “a Martian meteorite that is a breccia dominantly composed of basaltic clasts; this Martian meteorite is not assigned to the shergottite, nakhlite, or chassignite types.”

Cross-References

- [Crater, Impact](#)
- [Impact Basin](#)
- [Impact Melt Rock](#)
- [Impactite](#)
- [Monomictic Breccia](#)
- [Polymictic Breccia](#)
- [Sudbury Impact Structure](#)
- [Suevite](#)

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Bremsstrahlung Radiation

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Free-free emission](#)

Definition

Bremsstrahlung is a German word used in physics to describe the electromagnetic radiation emitted by a plasma in which high-speed charged particles (electrons, protons) are accelerated by other charged particles (ions). The bremsstrahlung radiation emitted by a plasma shares some analogy with ► [blackbody](#) radiation and is, as well, considered as *thermal emission*, as opposed to non-thermal processes, like synchrotron emission. The notable difference with blackbody emission is that bremsstrahlung features a plateau of quasi-constant intensity in a broad region of wavelengths, while the blackbody emission exhibits a pronounced peak.

Cross-References

- [Blackbody](#)
- [Radiative Processes](#)
- [Radio Astronomy](#)

Brethren of Purity

► [Ikhwan al-Safa](#)

British National Space Council

► [BNSC](#)

Broadband Line Survey

► [Molecular Line Survey](#)

Brown Dwarf

Gibor Basri¹ and Adam J. Burgasser²

¹Astronomy Department, University of California, Berkeley, CA, USA

²Center for Astrophysics and Space Sciences, Department of Physics, UC San Diego, La Jolla, CA, USA

Keywords

Very cool stars · Very low-mass stars

Synonyms

[Substellar objects](#)

Definition

A brown dwarf is a gravitationally bound astronomical object intermediate in mass between stars and giant planets, sometimes called a substellar object. Brown dwarfs are different from stars because they never achieve stable luminosities by nuclear fusion and are different from planets because they fuse light elements such as deuterium and lithium early in their evolution. Brown dwarfs are structurally supported by electron degeneracy pressure, and the lack of sustained fusion causes these objects to cool and dim over

time. A young brown dwarf closely resembles a very low-mass star in physical and spectral appearance, but as they cool, brown dwarfs develop atmospheres that are more like those of warm giant planets.

Overview

Brown dwarfs are classified by astronomers as substellar objects, meaning they have masses below that of hydrogen-fusing stars, about 75 Jupiter masses or 0.072 solar masses for a solar elemental composition. This is the mass above which the nuclear luminosity from the fusion of ordinary hydrogen in the core balances the thermal luminosity at the surface, resulting in an object that is in thermal equilibrium. Brown dwarfs are distinguished from planets because they have masses above the threshold for the fusion of deuterium (“heavy hydrogen,” a rare isotope produced in the Big Bang), about 14 Jupiter masses. Brown dwarfs are believed to form in a manner analogous to stars, contracting out of giant molecular clouds under the influence of self-gravity. In the hydrostatic stage of contraction, the cores of protostars and brown dwarfs increase in temperature, eventually initiating deuterium fusion. After deuterium is depleted in a few million years, true stars will continue to contract until their central temperatures are high enough to fuse ordinary hydrogen. For sun-like stars, the thermal pressure from this reaction provides the pressure support to stop a star’s collapse, and the nuclear luminosity eventually balances the surface luminosity, allowing a star to join the “main sequence.” While massive brown dwarfs can fuse light elements, such as deuterium, lithium, beryllium, and boron, and ordinary hydrogen early in their evolution, the luminosity from these reactions is insufficient to balance the thermal radiation at the surface over a long time period, resulting in an object that loses thermal energy by surface radiation.

Brown dwarfs never reach the temperatures necessary for sustained hydrogen fusion because their contraction is halted by free electron degeneracy pressure. This form of pressure does not

depend on temperature and is a consequence of the Paul exclusion principle that prevents electrons from occupying the same low-energy quantum states at very high densities. Degeneracy pressure scales with density, resulting in the counterintuitive property that adding more mass to a brown dwarf requires a higher-density core to support it, and hence produces a smaller object. Thus, a fully contracted brown dwarf is slightly smaller than Jupiter, with the most massive brown dwarfs being the smallest and densest hydrogen-rich objects known. Brown dwarfs achieve this state before reaching the temperatures necessary for sustained hydrogen fusion, and the imbalance between core fusion luminosity and surface thermal luminosity results in an endless slide toward cooler and fainter states (Chabrier and Baraffe 2000; Burrows et al. 2001). It is worth noting that the non-fusing remnant cores of stars like the Sun which have depleted their hydrogen supply are also supported by free electron degeneracy pressure. These remnants, known as “white dwarfs,” are both considerably hotter (hence “white”) and much more massive than brown dwarfs and can be as small as the Earth in radius, ten times smaller than a brown dwarf.

History

Brown dwarfs were first hypothesized in the early 1960s by Kumar (1962) in the United States and Hayashi and Nakano (1963) in Japan. Kumar originally called these objects “black dwarfs”; Jill Tarter proposed the name “brown dwarf” in 1975 to account for their evolving colors as they cool. Brown dwarfs are not actually brown. They would appear to the eye to range from deep red to magenta depending on their temperature, as the bulk of their radiation emerges at infrared wavelengths with only a small fraction emerging at visible wavelengths. Searches for brown dwarfs were conducted from the 1970s onward, and while some very cool stars and brown dwarf candidates were identified, no bona fide brown dwarfs were definitively known before 1994. A brown dwarf can be identified by having an effective temperature below the minimum main

sequence stellar temperature, about 1,800 K. Such objects, which may be identified as companions to other stars or found as free-floating objects, are extremely faint and red and eluded detection until the development of sensitive infrared cameras. Alternately, warmer and brighter young brown dwarfs can be distinguished from stars of the same temperature by the detection of lithium absorption in their spectrum (Magazzu et al. 1993). Lithium is destroyed in fusion reactions in the core that occur at a lower temperature than hydrogen fusion. Because the interiors of very low-mass stars and brown dwarfs are fully convective, lithium is mixed into the core so that fusion can deplete all of a star’s lithium content on time scales of 10–100 million years (this makes lithium depletion a useful mechanism for age-dating young clusters; see Stauffer et al. 1998). On the other hand, brown dwarfs with masses below 60 Jupiter masses never get hot enough to destroy lithium. In 1995, both methods produced verified discoveries (Basri 2000). The lithium test was used to confirm the brown dwarf status of two young objects in the Pleiades cluster, PPl 15 and Teide 1 (Rebolo et al. 1995, 1996; the first object was later determined to be the first brown dwarf binary). In the same time frame, astronomers at Palomar Observatory identified a faint companion to a very low-mass red dwarf star, Gliese 229, whose infrared spectrum indicated the presence of methane in its atmosphere, indicating an atmospheric temperature less than about 1,300 K (Nakajima et al. 1995; Oppenheimer et al. 1995). These three objects are widely recognized as the first brown dwarf discoveries and have been followed by the detection of thousands of brown dwarfs confirmed by their temperature, presence of lithium absorption, and in some cases direct mass measurements. The majority of brown dwarfs now known were uncovered by wide-field infrared imaging surveys such as DENIS, 2MASS, SDSS, and *WISE*.

Key Research Findings

The surface temperature of a brown dwarf depends on both its mass and age. All brown

dwarfs start off as large and relatively hot objects heated by their gravitational contraction, with the more massive brown dwarfs starting off hotter as they transform more gravitational potential energy to thermal energy. Brown dwarfs subsequently cool with time. As such, a younger, less massive brown dwarf can have the same temperature as an older, more massive one. This characteristic makes brown dwarfs fundamentally different from main sequence stars, for which temperature is directly related to mass and only weakly dependent on age. The most massive and youngest brown dwarfs have temperatures as high as 3,000 K, overlapping with the temperatures of red dwarf stars. All brown dwarfs eventually cool below the minimum stellar temperature of about 1,800 K, with more massive brown dwarfs taking more time to reach this threshold. A 25-Jupiter mass brown dwarf takes about 100 million years to reach this limit, while a 60-Jupiter mass brown dwarf takes about 1 billion years. The oldest and least massive brown dwarfs can cool to temperatures below 300 K. Since age and size are often hard to measure directly, the mass of a brown dwarf will be uncertain unless it is located within a cluster or bound to a more massive star of known age (where the mass is inferred from evolutionary models) or is part of a binary with a measured orbit (where the mass can be determined directly). Eclipsing binary brown dwarf systems, for which both size and mass can be independently measured, are exceptionally valuable systems for testing models for brown dwarfs. Several such systems are now known, most of which consist of a brown dwarf closely orbiting a main sequence star (Carmichael et al. 2020).

The youngest and warmest brown dwarfs have atmospheres and spectra that are largely identical to those of the least massive stars, known as M dwarfs. These spectra show strong absorption bands of metal oxides such as H_2O , CO, TiO, and VO. As brown dwarfs cool below about 2,200 K, mineral condensate grains form in their atmospheres, which are often characterized as “dusty” (Allard et al. 2001; Lodders and Fegley 2006). The dust is made of the most refractory compounds: calcium, aluminum, and titanium oxides like corundum (Al_2O_3) and perovskite (CaTiO_3).

The presence of dust smoothens and reddens the infrared spectra of brown dwarfs, while the fading TiO and VO absorption bands at optical wavelengths are replaced by metal hydrides (FeH, CrH, CaH) and heavily pressure-broadened features from the electronic transitions of neutral alkali elements, especially sodium and potassium (weaker lines from rubidium and cesium are also seen in these spectra). These spectral differences led to the delineation of a new stellar spectral class, the L dwarfs (Kirkpatrick et al. 1999). At even cooler temperatures, below about 1,300 K, carbon transitions from CO to CH_4 , resulting in broad methane features in the infrared which signify another new stellar spectral class, the T dwarfs (Burgasser et al. 2006). The transition from L dwarf to T dwarf is also reflected in a rapid depletion of condensates from the atmosphere, a process that is still not fully understood. At lower temperatures, nitrogen transitions from N_2 to NH_3 , which can be discerned in mid-infrared spectra, while new condensates composed of sulfides and halide salts emerge. The coldest and most recently defined spectral class, the Y dwarfs, encompasses these objects and extends in temperature from about 700 K to below 300 K, the temperature of the coldest brown dwarfs currently known (Cushing et al. 2011).

The condensate species that form in the L dwarfs and in the late T and Y dwarfs are believed to be organized into cloud structures, based on the balance of vertical upwelling, downward settling, and atmospheric dynamics. The structures of these clouds are inferred from the rotational modulation of their brightnesses and spectra (Biller 2017). Periodic brightness variations trace azimuthal cloud structure, while long-term changes may reflect jet and band structure analogous to the gas giant planets. Cloud vertical structure can be traced by brightness and phase variations at different wavelengths. The vast majority of brown dwarfs appear to be variable, with the strongest amplitudes found at the transition between the L dwarf and T dwarf classes. In addition to these time-dependent phenomena, variations in the spectral energy distributions of brown dwarfs of similar temperatures have been ascribed to differences in global cloud properties,

and the most successful atmosphere models of brown dwarfs incorporate variations in the cloud structure, composition, and fractional surface coverage (Saumon and Marley 2008). Some of this variance can be attributed to other properties, such as surface gravity (young L-type brown dwarfs appear to be “cloudier”), elemental composition (brown dwarfs with fewer heavy elements are less cloudy), or viewing angle. The additional opacity from condensate grain scattering can also influence the physical structure of a brown dwarf, with the increased opacity modulating radii by of order 10%. The actual formation processes of condensates, their size distribution and composition, and optical properties remain active areas of investigation; even the formation of clouds on the Earth is tricky.

It appears that brown dwarfs form in much the same way as stars, constituting the lowest-mass end of the star formation process (Luhman et al. 2007). This is evident from the continuous nature of the initial mass function across the hydrogen-fusing mass limit and the fact that newly formed brown dwarfs possess the same kinds of circumstellar disks and jets as newly formed stars. Brown dwarfs have lower accretion rates and smaller and longer-lived disks than stars but nevertheless undergo similar stages of pre-main sequence evolution. The existence of brown dwarf disks suggests that they may also harbor planetary systems. The lowest-mass star with a confirmed planetary system, TRAPPIST-1, has a mass just above the hydrogen-fusing limit (Gillon et al. 2017). Brown dwarfs are found as isolated objects and as companions to stars and even to each other. The binary fraction of brown dwarfs (10–25%) is lower than that of very low-mass stars (20–35%), in line with the known decrease of the binary fraction with stellar mass along the main sequence (Duchêne and Kraus 2013). Brown dwarf binaries are also more closely separated and found in more equal-mass compositions than stars. Because brown dwarf masses are below the typical Jean’s mass limit of giant molecular clouds, alternative formation scenarios have been proposed for these objects. These include formation in especially turbulent environments, early ejection from clusters of protostellar clumps, photoevaporation in

the proximity of a massive star, and fragmentation of massive protostellar disks (Whitworth 2018). While the collection of observational evidence to distinguish these various formation paths is ongoing, the demographics of young and evolved brown dwarfs is consistent with a population of isolated objects forming like stars down to the high planetary mass domain. These results apply for young clusters and the population of stars and brown dwarfs closest to the Sun. Little is as yet known about the frequency of brown dwarfs in other galactic populations (the halo and bulge), globular clusters, or extragalactic populations.

One respect in which brown dwarfs are more like giant planets than stars is that they tend to be very rapid rotators, with periods as short as a few hours rather than days to months for most low-mass stars. This behavior reflects a change in angular momentum loss mechanisms, which for stars like the Sun is driven by magnetized winds and leads to a steady decline in rotation rates (and magnetic activity) with time. Brown dwarfs are magnetically active, as evidenced from persistent nonthermal emission, in particular radio emission, and Zeeman splitting of metal line and band features even among the coldest brown dwarfs. It is likely that as a brown dwarf surface cools, its magnetic field becomes decoupled from its increasingly neutral photospheric plasma, making it difficult to sustain the coronal heating that drives winds (Reiners and Basri 2008). The properties of magnetic fields on brown dwarfs may also differ from those of low-mass stars, being produced in a fully convective interior subject to rapid rotation. The magnetic radio emission is also distinct, being far brighter than expected from scaling laws linking X-ray heating and radio emission in stars and exhibiting unique phenomena such as highly polarized pulsations and both short- and long-term variability. Nonthermal emission from brown dwarfs may be more similar to the auroral emission processes on the Solar planets, another shared trait.

Infrared sky surveys and other techniques have uncovered thousands of brown dwarfs in nearly every environment in the Milky Way Galaxy. The demographics of brown dwarfs in young clusters and the local field populations suggest that the

ratio of brown dwarfs to stars is roughly 1:6, which implies there are tens of billions of brown dwarfs in our Galaxy. Before their discovery, brown dwarfs were conjectured to be a significant component of “dark matter” since they are too faint to be seen except when very close by, but both microlensing experiments and the now-established luminosity function of brown dwarfs have firmly ruled this out. Nevertheless, brown dwarfs are an important probe of the Milky Way system. Because brown dwarfs do not fuse hydrogen, they never “die,” which means that every brown dwarf ever formed still exists and has preserved its birth composition of elements, with the exception of deuterium and (in the most massive brown dwarfs) lithium, beryllium, and boron. Since they cool with time, brown dwarfs also provide age information useful for tracking the Milky Way’s star formation history. Finally, as brown dwarfs cool, their atmospheres increasingly take on the characteristics of “hot” giant planets, valuable for exoplanet studies.

Cross-References

- [Binary Stars, Young](#)
- [Dwarf Star](#)
- [Jeans Criterion](#)
- [Low Mass Star](#)
- [Planet](#)
- [Protostars](#)
- [Spectral Type](#)

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Brownlee Particle

► [Interplanetary Dust Particle](#)

Bruno, Giordano

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Giordano Bruno (1548–1600) was an Italian heterodox philosopher and theologian. Because of his ideas and writings, Giordano Bruno left Naples, his home town, in 1576. In 1583, he abandoned his life as a Dominican friar and left Italy, living thereafter in France, England, and Germany.

As a supporter of Copernicus's heliocentric theory, of which he became a staunch supporter, Giordano Bruno collected countless enemies because of his unorthodox ideas. In his book *De l'Infinito, Universo e Mondi* (1584), he argued that the universe was infinite, that it contained an infinite number of worlds, and that these are all inhabited by intelligent beings. He came to Venice in 1591, where he got arrested and tried by the Inquisition in 1592. After he recanted, Bruno was sent to Rome the same year, for another trial. After eight years of successive interrogations, he was declared a heretic. In 1600, Bruno was burned at the inquisitorial stake because of his opinions concerning the Trinity, virginity of Mary, transubstantiation, and other beliefs contrary the Catholic faith.

BSL

► [Biological Safety Level](#)

Buckminsterfullerene

► [Fullerene](#)

Buckyball

► [Fullerene](#)

Buffer

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Buffer is a solution of a conjugated pair of acid and base that at a pH around its pK_a can tolerate moderate additions of acid or base without a remarkable pH change.

Buffon's Conception of Origins of Life

Stéphane Tirard
Centre François Viète d'Histoire des Sciences
et des Techniques EA 1161, Faculté des
Sciences et des Techniques de Nantes, Nantes,
France

Keywords

History of earth · Spontaneous generation

History

Georges-Louis Leclerc, Comte de Buffon (1707–1788) was one of the most important French naturalists of the eighteenth century. In 1739, he became *Intendant du Jardin et du Cabinet d' Histoire Naturelle du Roi*. For four decades (1749–1789), he published his *Histoire Naturelle* (22 volumes, with the supplements).

From the beginning of this voluminous work, he presented several important concepts and used them in his description of living beings. According to him, every animal and vegetable organism was made of “organic molecules,” which were the smallest living entities. In each body, the organic molecules took the mark of the “internal mold” specific for each species. During reproduction, the male and the female would give some organic molecules with the mark of the parental internal molds, and the young organism would then depend on it.

It is very important to note that Buffon was not a transformist. Indeed, he conceived some modifications in the limit of each species, which could be reversible; however, he never accepted any link between species by means of modifications.

As far as the history of Earth is concerned, Buffon's conception evolved during his career. In the first volume of his *Histoire Naturelle*, he developed a cyclic conception of the history of Earth. Thirty years later, he claimed a sagittal theory and gave a description of “the Epochs of the Nature” in a supplementary volume (V) of his *Histoire Naturelle*. He described seven epochs. At the beginning, the Earth was an incandescent sphere of matter. The temperature progressively decreased and the Earth became solid. Therefore, his history of Earth was irreversible and depended on the decrease in temperature.

Buffon asserted that species were formed by spontaneous generation and had been constituted by the organic molecules that were very abundant in the soil during the first epochs of nature. For him, spontaneous generations were still active in nature, but only for the little species.

Cross-References

► [Spontaneous Generation, History of](#)

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Building Blocks of Primitive Life

► [Endogenous Synthesis](#)

Bulk Silicate Earth

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, Qc, Canada

Keywords

Chondrite · Primitive mantle · Differentiation · Lithophile · Peridotite

Synonyms

[Primitive mantle](#)

Acronyms

BSE

Definition

Bulk Silicate Earth refers to the original chemical composition of the silicate part of the Earth, after the separation of the metallic core but prior to the differentiation of the crust. For this reason, the

Bulk Silicate Earth composition is synonymous with the composition of the Earth's "primitive mantle."

Overview

The present-day "silicate" part of the Earth, that is, the mantle and the crust (both oceanic and continental), makes up 67.5% of the whole Earth's mass, while the metallic core makes up the remaining 32.5%. The silicate portion of the Earth is presently composed of several sub-reservoirs, namely the continental and oceanic crusts, the depleted mantle (i.e., depleted in meltable elements which were extracted by partial melting from the mantle to form the crust), and the primitive mantle, which is inversely enriched in meltable elements having not, *à priori*, participated to the formation of the crust. It would be reasonable to assume that the original BSE chemical element composition is the mass balance between these different silicate reservoirs. However, it is not a simple calculation because these reservoirs have heterogeneous chemical compositions (particularly the continental crust), the amount of crust recycled back in the mantle through eons by plate tectonics is unknown, as well as the exact size of the mantle sub-reservoirs.

There are fundamentally two approaches to establish the BSE initial composition of the Earth, both with their limitations (e.g., Lyubetskaya and Korenaga 2007). The first is called the petrological model and it is based on the chemical composition of the least differentiated peridotites (e.g., Jagoutz et al. 1979; Sun 1982). Peridotite is an Mg-rich rock made of olivine, pyroxene, and an aluminous mineral phase such as plagioclase, garnet, or spinel. The mantle would have basically a peridotitic composition. However, a large spectrum of peridotite compositions exists with "lherzolites" being the richest in elements, which are easily melted (Ca, K, Na, Al), and "harzburgites," which are depleted in those "meltable" elements. The degree of depletion in meltable elements indicates the progressive partial melting of peridotite to form basalts during oceanic crust extraction. Thus, the

average major-elements composition of the least depleted (i.e., the most primitive) peridotites would give an estimate of the BSE (Jagoutz et al. 1979). However, because of the large scattering in the major-element composition of worldwide peridotites and the fact that a significant amount of the present-day mantle has undergone partial melting to extract the Earth's crust, the resulting BSE composition remains somehow approximate. This is particularly true for high incompatible trace elements (such as U, Th, Cs, Ba), which are preferentially partitioned in the Earth's crust.

An alternative means of estimating the BSE is to look at the chemical composition of the most undifferentiated/primitive meteorites: the chondrites, which do not show any evidence of having been melted since the formation of their parent bodies at the beginning of the Solar system. Among them, the CI carbonaceous chondrites have been proposed to be the best candidates to represent the geochemical composition of BSE, although some isotope tracers suggest that none of the existing chondrite types actually reproduce BSE (Burkhardt et al. 2016). Chondrites are composed of an assemblage of olivine and pyroxenes (silicate minerals) and Fe-Ni metal grains. Excluding the Fe-Ni grains, their composition is very close to that of mantle peridotite. However, during cooling of the solar nebula, moderate and high volatile elements tend to condensate over a large range of temperatures, resulting in elemental fractionation. Only refractory elements (such as Al, Ca, Ti) condensate in a narrow range of temperatures and thus their original "solar" elemental ratios are mostly preserved. Si and Mg, which are important constituents of the BSE, are in between the refractory and the moderate volatile elements, and thus partially fractionated. Thus, the undifferentiated meteorites only allow determining precisely the ratios of refractory lithophile elements in the Earth's primitive mantle (Jagoutz et al. 1979).

Cross-References

- [Archean Mantle](#)
- [Carbonaceous Chondrite](#)

- [Chondrite](#)
- [Differentiation, Planetary](#)
- [Lithophile Elements](#)
- [Mantle](#)
- [Peridotite](#)

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whose atmospheres contain more carbon than oxygen, the excess carbon presumably produced by helium fusion in the latter stages of the star's life). It is an intermediary in the rich carbon chemistry of these stars and of cold, dark interstellar clouds; both contain polyacetylenes, ► [cyanopolyyne](#), and related carbon-chain species. Both deuterated and ¹³C variants of C₄H have been detected in astronomical sources (Cernicharo et al. [2000](#)).

History

The astronomical identification of C₄H in the envelope of the carbon star IRC + 10216 (Guélin et al. [1978](#)) prior to laboratory measurements of the rotational spectrum provides another example of the ability of high-frequency radio astronomy to contribute to fundamental molecular physics (cf. the discussion for ► [C₃N](#)). Subsequently, this radical was also detected in interstellar molecular clouds (Irvine et al. [1981](#)).

Butadiyne

- [Diacetylene \(C₄H₂\)](#)

Butadiynyl Radical (C₄H)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[C₄H](#)

Definition

The univalent five-atom ► [radical](#) C₄H is found both in interstellar ► [molecular clouds](#) and in the envelopes of evolved carbon stars (evolved stars

Cross-References

- [Cyanoethynyl Radical \(C₃N\)](#)
- [Cyanopolyyne](#)
- [Deuterium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radical](#)
- [Stellar Evolution](#)

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Bücherer-Bergs Synthesis

Robert Pascal
Institut des Biomolécules Max Mousseron
CC1706, Université de Montpellier II,
Montpellier, Francep

Synonyms

Hydantoin formation

Definition

The Bücherer-Bergs synthesis (Ware 1950) of ► [hydantoins](#) is carried out by reacting cyanohydrins (the addition products of cyanide anion to aldehydes or ketones) with ammonium carbonate (or CO_2 and NH_3). Its mechanism, closely related to the ► [Strecker synthesis](#), involves α -aminonitriles as intermediates that

are processed via a carbon dioxide-promoted reaction (Fig. 1) (Pascal et al. 2005).

The Hydantoins can be ring-opened hydrolytically to form N-carbamoylamino acids. It is considered relevant to amino acid formation on the early Earth because it is likely to have prevailed over Strecker synthesis in a CO_2 -rich atmosphere. Peptides are potentially produced through conversion of N-carbamoylamino acids to amino acid N-carboxyanhydrides (Pascal et al. 2005) (Fig. 1).

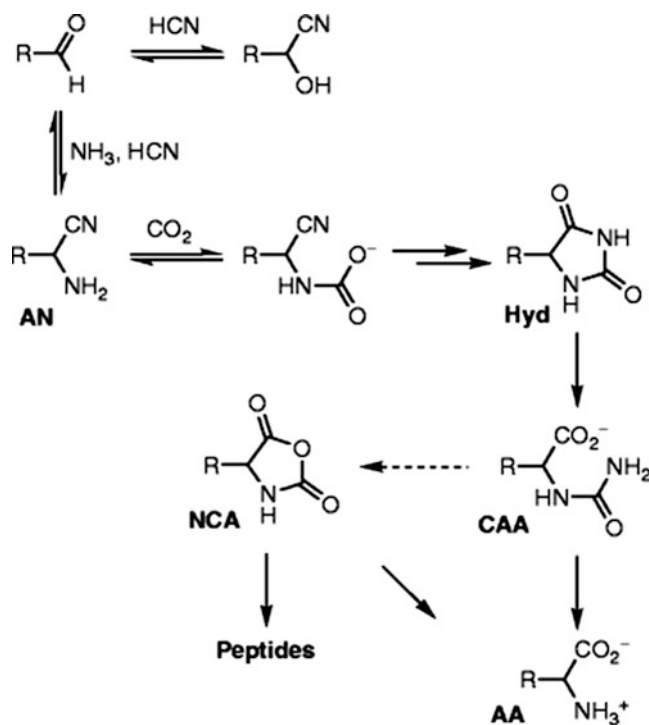
Cross-References

- [Amino Acid N-Carboxy Anhydride](#)
- [N-Carbamoyl Amino Acid](#)
- [Strecker Synthesis](#)

References and Further Reading

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Bücherer-Bergs Synthesis, Fig. 1



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Butanedioic Acid

► [Succinic Acid](#)

Butlerow Reaction

► [Formose Reaction](#)

Butyrine

► [Aminobutyric Acid](#)

C

C₂H

- [Ethyne Radical \(C₂H\)](#)

C₂H₄O

- [Ethylene Oxide \(C₂H₄O\)](#)

C₂H₅OCHO

- [Ethyl Formate](#)

C₃H₂, c-C₃H₂

- [Cyclopropenylidene \(C₃H₂\)](#)

C₃H₇CN

- [Propyl Cyanide \(C₃H₇CN\)](#)

C₃N

- [Cyanoethynyl Radical \(C₃N\)](#)

C-Asteroid

Alan W. Harris
DLR, Institute of Planetary Research, Berlin,
Germany

Definition

► [Asteroid](#) taxonomic systems are based on spectral features observed in reflected sunlight, with letters of the alphabet used to denote different taxonomic types. A C-type asteroid is one with a relatively flat and featureless reflection spectrum in visible light, similar to that of ► [carbonaceous chondrite meteorites](#) and with a low ► [albedo](#) (typically 0.03–0.1), characteristics indicative of a carbonaceous (carbon-rich) mineralogy. C-type asteroids are common in the outer main belt but are also present in the near-Earth asteroid population. Many C-type asteroids have weak absorption features in the near-infrared region of the spectrum, apparently due to the presence of water-bearing ► [minerals](#).

Cross-References

- [Albedo](#)
- [Asteroid](#)
- [Asteroid Belt, Main](#)

- [Carbonaceous Chondrite](#)
- [Meteorites](#)
- [Mineral](#)
- [Near-Earth Objects](#)

C₃N[−] Anion

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Synonyms

[Cyanoacetylide anion](#)

Chemical Formula

C₃N[−]

Definition

The negative ion C₃N[−] is a closed-shell species isoelectronic with cyanoacetylene (HC₃N). The characterization of its rotational spectrum in the laboratory allowed to detect it in the carbon-rich circumstellar envelope IRC + 10216 (Thaddeus et al. 2008) and, later on, in the cold dark cloud TMC-1 (Cernicharo et al. 2020). In circumstellar and interstellar clouds, it is thought to be formed by radiative electron attachment to the radical C₃N (Millar et al. 2017). The anion C₃N[−] was also tentatively identified in the upper atmosphere of Titan, where it is thought to be produced by photochemistry (Vuitton et al. 2009; Dobrijevic et al. 2016).

Cross-References

- [Anion](#)
- [Cyanoacetylene](#)
- [Cyanoethynyl Radical \(C₃N\)](#)
- [Radiative Attachment](#)

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C₄H

- [Butadiynyl Radical \(C₄H\)](#)

C₄H₂

- [Diacetylene \(C₄H₂\)](#)

C₅N[−] Anion

Agúndez Marcelino
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Chemical Formula

C₅N[−]

Definition

The negative ion C₅N[−] is a closed-shell species isoelectronic with cyanodiacetylene (HC₅N). It was assigned, based on high-level ab initio calculations, to a series of harmonically related lines in the carbon-rich circumstellar envelope

IRC+10216 (Cernicharo et al. 2008) and in the cold dark cloud TMC-1 (Cernicharo et al. 2020). In circumstellar and interstellar clouds, it is thought to be formed by radiative electron attachment to the radical C_5N (Millar et al. 2017). The anion C_5N^- has been also tentatively identified in the upper atmosphere of Titan, where it is thought to be produced by photochemistry (Vuitton et al. 2009).

Cross-References

- [Anion](#)
- [Cyanobutadiynyl Radical \(\$C_5N\$ \)](#)
- [Radiative Attachment](#)

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C_6H_6

- [Benzene \(\$C_6H_6\$ \)](#)

CA

- [Cyanoacetylene](#)

CAA

- [N-Carbamoyl Amino Acid](#)

CAB, Spain

Michel Viso

Innovaxiom, Paris, CX, France

Definition

The Spanish Centro de Astrobiología (CAB) was created as a Joint Center between CSIC (Consejo Superior de Investigaciones Científicas) and the Spanish space agency INTA (Instituto Nacional de Técnica Aeroespacial) with the support of the Comunidad Autónoma de Madrid (CAM). The main goal of the CAB is to provide a truly trans-disciplinary research environment for the development of the new science of Astrobiology. The CAB operates with the specific new contribution of a common methodology based on complexity theory and the application of the scientific method to understanding the origin of life by exploring the habitability conditions on Earth and beyond, within the Solar System, or in extra-solar planets. CAB scientific activities started in late 1999 at temporary buildings, while awaiting a new building to be constructed and equipped. The new CAB premises were inaugurated in January 2003.

CAB is located within the campus of INTA and, in addition, has one astronomical facility with a robotic telescope at the Observatorio Astronómico Hispano-Alemán de Calar Alto (CAHA). CAB's scientists and engineers are deeply involved in space missions such as MSL, ► [ExoMars](#), INTEGRAL, Bepi Colombo, PLATO, HERSCHEL, and SPICA.

History

The origin of the CAB goes back to a proposal presented to NASA in 1998 by a group of Spanish and American scientists, led in Spain by Juan Pérez-Mercader, to join the newly created NASA Astrobiology Institute (NAI). The group was integrated within the ► [NAI](#) as a full Associate Member in 2000. Following an

exchange of letters at Government level, CAB became the first Associate Member of NAI outside the US. The other NAI Associate Member since 2003 is the Australian Centre of Astrobiology.

Cross-References

- [Evolution, Biological](#)
- [ExoMars](#)
- [Extremophiles](#)
- [Genetics](#)
- [Geomicrobiology](#)
- [Herschel, William](#)
- [Mars Science Laboratory](#)
- [NAI](#)
- [PLATO 2.0 Satellite](#)
- [Terrestrial Analog](#)

Cahn Ingold Prelog Rules

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[CIP rules](#)

Definition

In chemistry, these are a set of rules for determining the stereochemistry of a molecule. For molecules with double bonds, stereoisomerism can be E (entgegen, German for opposed) or Z (zusammen, German for together), also referred to in English as *trans* and *cis*, respectively. For

stereocenters, molecules are denoted as S or R (for *sinister* or *rectus*) indicating whether the sequence of groups follows a left or right direction of viewing, with priority of substituents assigned on the basis of molecular weight.

Cross-References

- [Stereoisomers](#)

CAIs

Matthieu Gounelle
Laboratoire de Minéralogie et Cosmochimie du
Muséum (LMCM) MNHN USM 0205 – CNRS
UMR 7202, Muséum National d'Histoire
Naturelle, Paris, France

Keywords

Chondrites · Chronology · Inclusions

Synonyms

[Calcium-aluminum-rich inclusions](#)

Definition

CAIs (calcium-aluminum-rich inclusions) are white inclusions found in carbonaceous chondrites. They are made of calcium- and aluminum-rich oxides and silicates. They are among the oldest solids of the solar system. They provide clues on the immediate environment of the nascent solar system and on its earliest phases.

Overview

CAIs were discovered in the Vigarano ► [chondrite](#) by M. Christophe Michel-Levy in 1968.

They are an assemblage of calcium and aluminum oxides and silicates, i.e., spinel, hibonite, grossite, melilite, anorthite, and calcium- and aluminum-rich pyroxenes. CAIs are enriched in refractory elements by a factor of 10–100 relative to bulk chondrites. They have variable textures: irregular, fluffy, round, and compact. Some CAIs show evidence of melting, probably during chondrule formation. Others exhibit evidence of reprocessing in the chondrite parent bodies. CAIs are enriched in oxygen-16 relative to chondrites. Some of them are enriched in the heavy isotopes of magnesium and silicon. They often are isotopically anomalous relative to the bulk solar system. These anomalies, at the level of a few hundred ppm, were found mostly in neutron-rich isotopes, such as ^{48}Ca or ^{50}Ti . They contain a high abundance of short-lived radionuclides (see entry ► [Cosmochemistry](#)). Their Pb-Pb absolute ages (about 4,567 Ma) are older than those of chondrules or differentiated meteorites.

CAIs are very abundant in carbon-rich carbonaceous chondrites, while they are virtually absent from other chondrites. Studies of CAIs during the last 30 years are heavily biased toward CAIs found in the CV3 chondrites epitomized by the Allende meteorite which fell in Mexico in 1969. The reason for that bias is that CAIs in CV3 chondrites are large (up to a cm) and abundant (~10% volume). It is, however, important to note that CAIs in CV3 chondrites are quite peculiar when compared to CAIs in other chondrite groups and may record specific events in the solar protoplanetary disk. More studies should and will be dedicated to CAIs in other chondrite groups. A few CAIs were found among the dust brought back by the Stardust spacecraft from comet Wild 2.

Most CAIs probably formed by condensation. Some of them endured severe evaporation. Because of their old age, the extent of the isotopic anomalies they bear, and their richness in short-lived radionuclides, they are believed to be the first solids to have formed in the solar

protoplanetary disk. As such, they record the earliest phases of solar system formation. Short-lived radionuclides as well as isotopic anomalies record nucleosynthesis processes in generations of stars prior to the solar system. Some short-lived radionuclides also record irradiation processes in the early solar system. Because they formed at high temperature, in a gas-poor region, they are believed to have formed close (0.1 AU) to the protosun. They were transported to chondrite formation distances either by winds powered by the magnetic interaction between the Sun and the disk or by turbulence.

Cross-References

- [Cosmochemistry](#)
- [Cratering Chronology](#)
- [Meteorite, Allende](#)
- [Meteorites](#)
- [Parent Body](#)
- [Protoplanetary Disk](#)

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Calcareous Sediment

- [Carbonate on Mars](#)

Calcium-Aluminum-Rich Inclusions

► [CAIs](#)

Caldophile

► [Thermophile](#)

Callisto

Therese Encrenaz
Observatoire de Paris, PSL, CNRS, Sorbonne University, University Paris-Diderot, Meudon, France

Definition

Callisto is a satellite of Jupiter discovered by ► [Galileo Galilei](#) in January 1610; it is the outermost of the Galilean satellites. With a radius of 2,410 km, Callisto is, after Ganymede and Titan, the third biggest satellite in the solar system. Its distance to ► [Jupiter](#) is 1,882,700 km or 26 Jovian radii. Its density is 1.8 g/cm³, typical of icy objects. Callisto has been investigated by the Voyager 1 and 2 spacecraft in 1979, then by the Galileo orbiter between 1995 and 2003. The surface of Callisto is heavily cratered and consists of a mixture of ice and dust. A great basin, Valhalla, over 500 km in diameter, is the signature of a large major impact. As in the case of Ganymede, a liquid ocean could exist below the icy crust. Callisto is expected to be explored by the European JUICE mission, planned for arrival in the Jovian system in 2031.

Cross-References

► [Galileo Galilei](#)
► [Jupiter](#)

Calvin's Conception of Origins of Life

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

History

Melvin Calvin (1911–1997) was an American biochemist, who discovered, with Andrew Alm Benson (1917–), the cycle of reactions in the obscure phase of photosynthesis during the 1940s (Calvin-Benson cycle). Calvin obtained the Nobel Prize in 1961 for this discovery.

In 1951, Calvin published one of the first works in prebiotic chemistry. He reduced carbon dioxide in aqueous solution, by ionizing radiation, to formic acid.

In 1953, Harold Clayton Urey (1893–1981) rejected this result because of the presence of CO₂. Urey was in favor of a reductive primitive atmosphere without CO₂. However, Calvin maintained his interest for origins of life during the rest of his career and published his main book on this topic in 1969 (*Molecular Evolution towards the Origin of Living Systems on Earth and Elsewhere*).

Cross-References

► [Calvin-Benson Cycle](#)
► [Miller, Stanley](#)
► [Urey's Conception of Origins of Life](#)

Calvin-Benson Cycle

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Keywords

Biosynthesis · Autotrophy · Carboxylation · Carbon dioxide

Synonyms

Dark reactions; Reductive pentose phosphate cycle

Definition

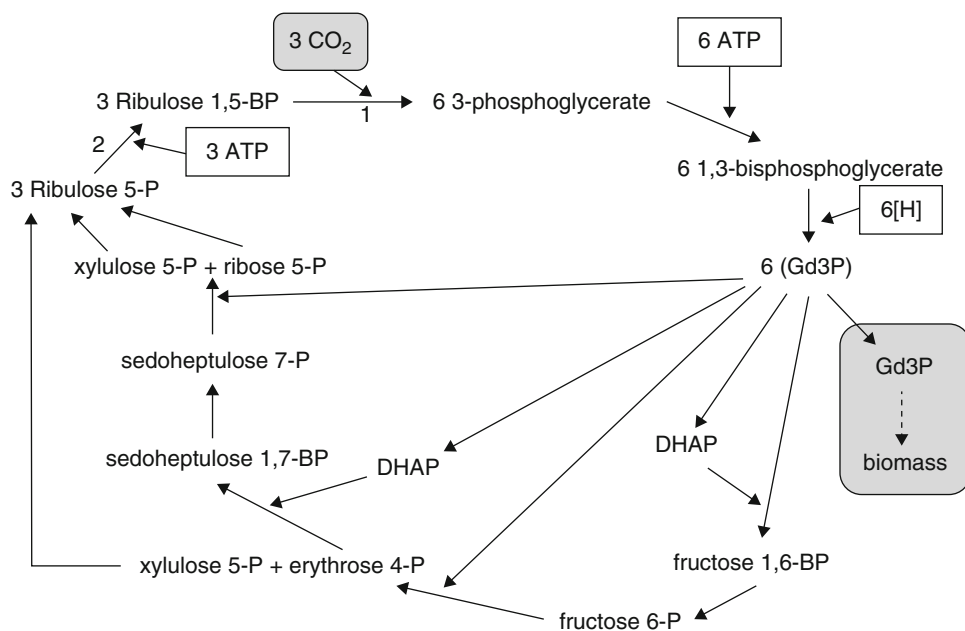
A carbon dioxide fixation pathway where a molecule of CO_2 condenses with a 5-C compound (ribulose 1,5-bisphosphate) to yield two molecules of a 3-C compound (3-phosphoglycerate). These 3-C molecules serve both as precursors for biosynthesis and, through a cyclic series of enzymatic reactions, to regenerate the 5-C molecule necessary for the first carboxylating step (Fig. 1). The pathway is present in several bacterial lineages (e.g., cyanobacteria), and its acquisition by eukaryotic cells (chloroplast in algae and plants) was through the endosymbiotic association with ancient cyanobacteria.

History

Melvin Calvin (1911–1997) and coworkers established this autotrophic path of carbon in phototrophic organisms using ^{14}C -labeled carbon dioxide and *Chlorella* (a green algae) cultures (Benson and Calvin 1950). Calvin was awarded with the Nobel Prize in Chemistry in 1961 “for his research on the carbon dioxide assimilation in plants.”

Overview

The Calvin-Benson cycle allows the synthesis of one triose from three molecules of carbon dioxide (Fig. 1): 12 electrons (provided by redox coenzymes like NADH or NADPH) and 9 ATP equivalents are required for bringing CO_2 to the oxidation level of the triose glyceraldehyde 3-phosphate. These fueling requirements are supplied by either a phototrophic or a



Calvin-Benson Cycle, Fig. 1 The Calvin-Benson cycle. The stoichiometry of the cycle allows the net synthesis of one molecule of triose from three molecules of carbon dioxide (gray boxes). Other five trioses (5 C_3) are converted into three pentoses (3 C_5) necessary to initiate the cycle again. The energetic cost for the synthesis of one triose is nine ATP molecules and six reducing equivalents (NADH or NADPH). These energetic requirements could

be satisfied by a photosynthetic apparatus or a chemolithotrophic metabolism. Except for two key enzymatic steps (1 and 2), all the transformations are a combination of enzymes participating in the Embden-Meyerhof-Parnas pathway and the non-oxidative pentosephosphate pathway. Key enzymatic steps: (1) Rubisco; (2) phosphoribulokinase. Abbreviations: Gd3P glyceraldehyde 3-phosphate, DHAP dihydroxyacetonephosphate

chemolithotrophic metabolism. The cycle can be divided into two stages: a reductive carboxylation of the pentose ribulose 1,5-bisphosphate (RuBP) up to glyceraldehyde 3-phosphate and a series of rearrangements of carbon skeletons from trioses to regenerate RuBP throughout 4-, 6-, and 7-C sugar intermediates (Fig. 1). The first step is catalyzed by the key carboxylating enzyme ► [Rubisco](#). As other carboxylases, Rubisco also shows a preference for lighter stable isotopes, and thus CO₂ fixation results in the depletion of ¹³C (δ¹³C) in the biosynthesized organic matter ranging from −20 ‰ to −30 ‰. The second stage of the cycle occurs by the combination of several enzymatic activities from the ► [Embden-Meyerhof-Parnas pathway](#) and the nonoxidative branch of the pentose phosphate pathway.

The Calvin-Benson cycle was originally described in green plant (i.e., chloroplast) photosynthesis (Benson and Calvin 1950). It is also active in endosymbiotic chemolithotrophic proteobacteria of invertebrates living in close proximity to hydrothermal vents. In free-living prokaryotes, this pathway has been demonstrated in cyanobacteria (the group to which the ancestors of plastids belonged), some aerobic or facultative anaerobic proteobacteria, CO-oxidizing mycobacteria, diverse iron-sulfur-oxidizing firmicutes, and in some green sulfur bacteria. Although Rubisco has been isolated from some Archaea, there is no evidence for the operation of the full cycle in autotrophic species from this domain (Berg et al. 2010).

Cross-References

- [Autotrophy](#)
- [Embden-Meyerhof-Parnas Pathway](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Rubisco](#)

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Campbellrand-Malmani Platform, South Africa

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

The Campbellrand-Malmani carbonate platform was deposited on the ► [Kaapvaal craton, South Africa](#), between 2,588 and 2,520 Ma (Neoproterozoic). This 1.9-km-thick carbonate platform is preserved over at least 190,000 km² and probably originally covered the entire extent of the Kaapvaal craton (~600,000 km²). The Campbellrand-Malmani is the first extensive carbonate deposit of the Neoproterozoic, prior to the buildup of oxygen in the ocean and atmosphere about 2.35 Ga ago. The abundance of aragonite pseudomorphs in this unit suggests a neutral to slightly alkaline ocean, which in turn may indicate a low atmospheric CO₂ concentration.

Cross-References

- [Calcareous Sediment](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Great Oxidation Event](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygenation of the Earth's Atmosphere](#)

CAN, Canada

Greg Slater¹, Penny L. Morrill² and Richard Léveillé³

¹McMaster University, Hamilton, ON, Canada

²Memorial University of Newfoundland,
St. John's, NL, Canada

³McGill University, Montreal, QC, Canada

Synonyms

[Canadian Astrobiology Network](#)

Definition

The Canadian Astrobiology Network is composed of members from across Canada. It was formed to promote scientific interaction and collaboration among researchers, to facilitate graduate training and interaction opportunities, and to promote awareness about research in astrobiology. Membership is open to all professionals and students interested in astrobiology or related fields. The Canadian Astrobiology Network is an Affiliated Partner of the NASA Astrobiology Institute (NAI).

Cross-References

► [NAI](#)

Canadian Astrobiology Network

► [CAN, Canada](#)

Canadian Precambrian Shield

Phil Thurston

Laurentian University, Sudbury, ON, Canada

Keywords

Accreted terrane · Accretion · Craton · Geological province · Magmatic arc · Supercontinent cycle

Synonyms

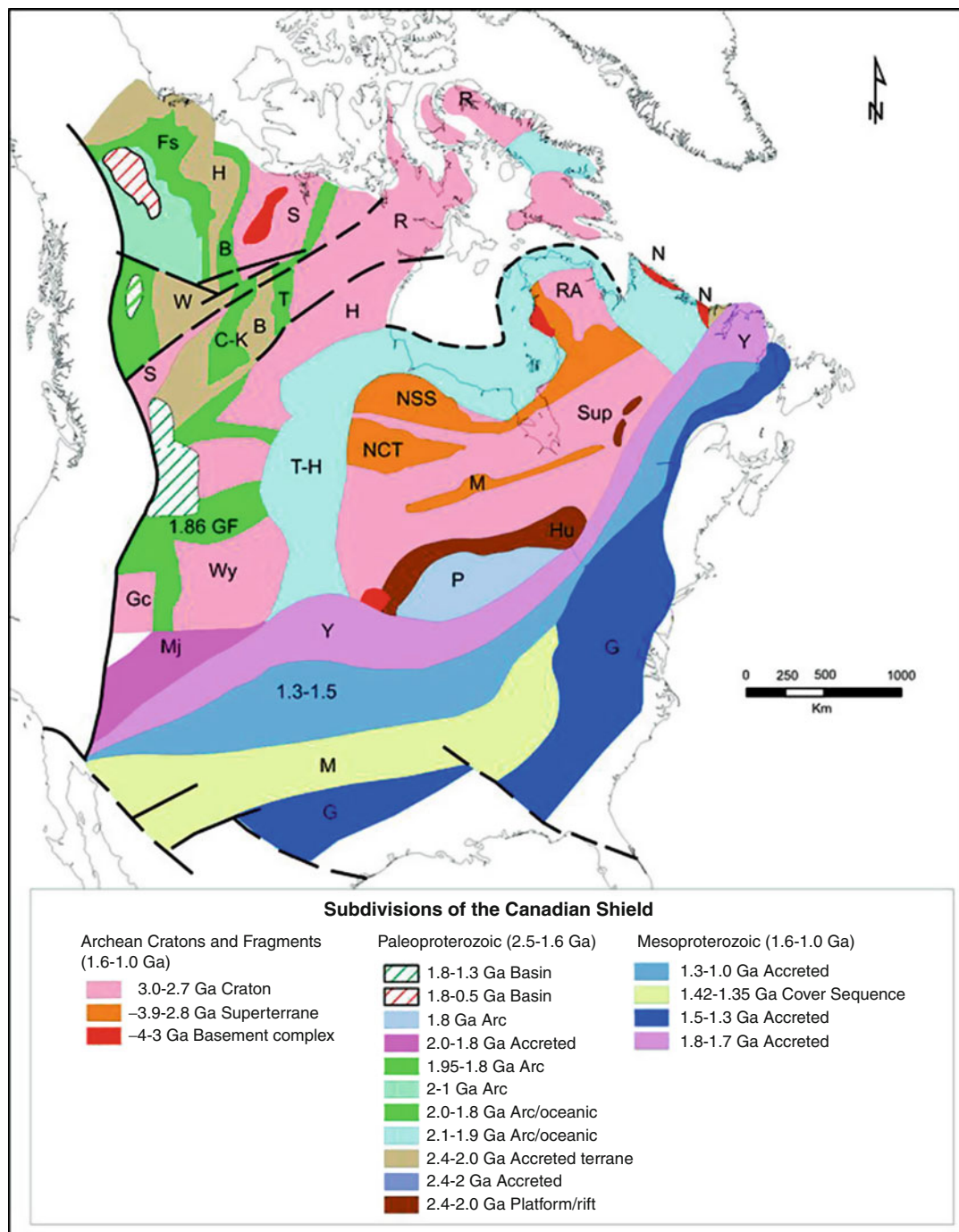
[Canadian shield](#); [North American shield](#)

Definition

The Canadian ► [Shield](#) is the region of North America underlain by Precambrian rocks (>542 Ma), extending from the Arctic Ocean to the Great Lakes and further south and west in the subsurface (Fig. 1).

Overview

The Canadian Precambrian Shield is subdivided into geological provinces (regions of similar age). The major Archean (>2.5 Ga) provinces are the Slave (S), Superior (Sup), Rae (R), and Hearne (H). All of them have a similar architecture: linear sub-provinces or belts of fine-grained sediment and subaqueously erupted volcanic rocks which are surrounded and cut by granites (Hoffman 1989). In detail, the Superior province consists of an old (~3 Ga) core (NCT) surrounded by linear belts of volcanic rocks that alternate with granites and belts of sedimentary rocks which become younger (2.9 to ~2.7 Ga) north and south of the core (Percival 2007). This architecture suggests the Archean provinces (pink on Fig. 1) grew as successively younger belts of volcanic and volcano-sedimentary rocks added to the continental margin by plate-tectonic processes. This was followed by the intrusion of much granitic rock during the interval 2.7–2.6 Ga, transforming the Archean provinces into a comparatively light, buoyant ► [craton](#). The crustal thickness of the cratons is typically ~40 km. The cratonization processes involved the development of large-scale faults that brought gold-bearing fluids from deep in the Earth to the near-surface environment. Several cratons of this age (2.7 Ga) joined to form the ► [supercontinent](#) “Kenorland” (Aspler and Chiarenzelli 1998). The edges of Kenorland include some much older (~3.8 Ga) fragments (red units on Fig. 1) that were accreted onto the margin of the supercontinent. Kenorland broke apart by the development



Canadian Precambrian Shield, Fig. 1 Subdivisions of the Canadian Shield of North America based on the age of the rock unit. Archean cratons and subdivisions within: *Sup* Superior craton, *NSS* Northern Superior superterrane and Hudson Bay terrane, *RA* Riviere Arnaud terrane, *NCT* North Caribou terrane, *M* Marmion terrane, *N* Nain craton,

S Slave craton, *R* Rae craton, *H* Hearn craton, *Wy* Wyoming craton, *GC* Grouse Creek block. Paleoproterozoic (2.5–1.6 Ga) tectonic domains after Ross (2002) and Aspler et al. (2003); *Hu* Huronian, *T* Taltson, *B* (brown) Buffalo Head, *B* (green) Great Bear, *H* Hottah, *Fs* Fort Simpson, *W* Wabamun, Chinchaga and Ksituan terranes

of 2.48–2.10 Ga old rifts containing dikes and volcanic rocks followed by the deposition of uranium-bearing, dominantly sandy continental margin sedimentary units [e.g., Hu in brown on Fig. 1, on the south edge of the Superior craton]. The various Archean cratons then drifted apart and became separated by ocean basins and island arcs. The oceans later closed, and the various accreted terranes and 2.0–1.8 Ga volcanic arcs accreted onto the margins of the Archean cratons to form the “Columbia” supercontinent (Zhao et al. 2004). During the interval 1.8–1.2 Ga, Columbia grew by the accretion of multiple belts, again consisting mostly of volcanic and granitic rocks along its southern and eastern margins, e.g., the Yavapai-Central Plains belt [Y on Fig. 1, (1.8–1.7 Ga)], the Mazatzal (M) (1.7–1.5 Ga) belt in the USA, the Labradorian belt of Quebec and Labrador, and the 1.3–1.0 Ga Grenville Province (G on Fig. 1) (Karlstrom et al. 1999).

Cross-References

- [Archean Eon](#)
- [Craton](#)
- [Proterozoic Eon](#)
- [Shield](#)
- [Supercontinent](#)

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Canadian Shield

- [Canadian Precambrian Shield](#)

Candidate Phyla Radiation (CPR)

- [Ultrasmall Bacteria, CPR, and Patescibacteria](#)

Canyon

- [Chasma, Chasmata](#)

Cap Carbonates

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

Cap carbonates are a special type of laminated carbonate rocks (limestone and/or dolostone) associated with glacial deposits in the Neoproterozoic (► [Snowball Earth](#)). They sharply overly (“cap”) unsorted glacial sediments called tillites. Their origin is not well understood, but they may be related to a particular ocean and

atmosphere chemistry with high CO₂ concentration and alkalinity from silicate weathering or to upwelling of highly alkaline deep waters following deglaciation. They are associated with negative incursions of carbon isotopes that are widespread and can serve for correlation.

Cross-References

- [Glaciation](#)
- [Sedimentary Rock](#)
- [Snowball Earth](#)

Capsid Encoding Organism

- [Virus](#)

Carbamide

- [Urea](#)

Carbamonitrile

- [Cyanamide](#)

Carbene

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

A carbene is an organic molecule having two electrons available on a carbon atom for chemical bonding. Short-chain and long-chain carbenes are very common in interstellar chemistry, e.g., C₃, H₂CCC, and H₂CCCC (Cernicharo et al. [1991a, b, 2000](#)), and even longer chains such as H₂C₅ and H₂C₆ (McCarthy et al. [1997](#)).

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

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Carbimide

- [Cyanamide](#)

Carbodiimide

- [Cyanamide](#)

Carbodiimide (HNCNH)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[HNCNH](#)

Definition

Carbodiimide, HNCNH, is a higher-energy isomer of ► [cyanamide](#), H₂NCN. The latter is present in interstellar “hot cores,” regions in molecular clouds where massive young stars are

forming, and is an effective condensation agent in prebiotic chemistry (Nooner et al. 1973).

History

Carbodiimide was detected by radio astronomers (McGuire et al. 2012) in the Galactic Center molecular cloud Sagittarius B2(N).

Cross-References

- [Cyanamide](#)
- [Hot Core](#)
- [Molecules in Space](#)

References and Further Reading

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Carbohydrate

Heshan Grasshopper Illangkoon
Department of Chemistry, University of Florida,
Gainesville, FL, USA

Keywords

Cellulose · Formaldehyde · Formose ·
Fructose · Glucose · Glyceraldehyde ·
Glycolaldehyde · Origins of life · Primordial
soup · Ribose · Sucrose · Sugars ·
Disaccharide · Monosaccharide ·
Oligosaccharide · Polysaccharide

Synonyms

[Saccharide](#)

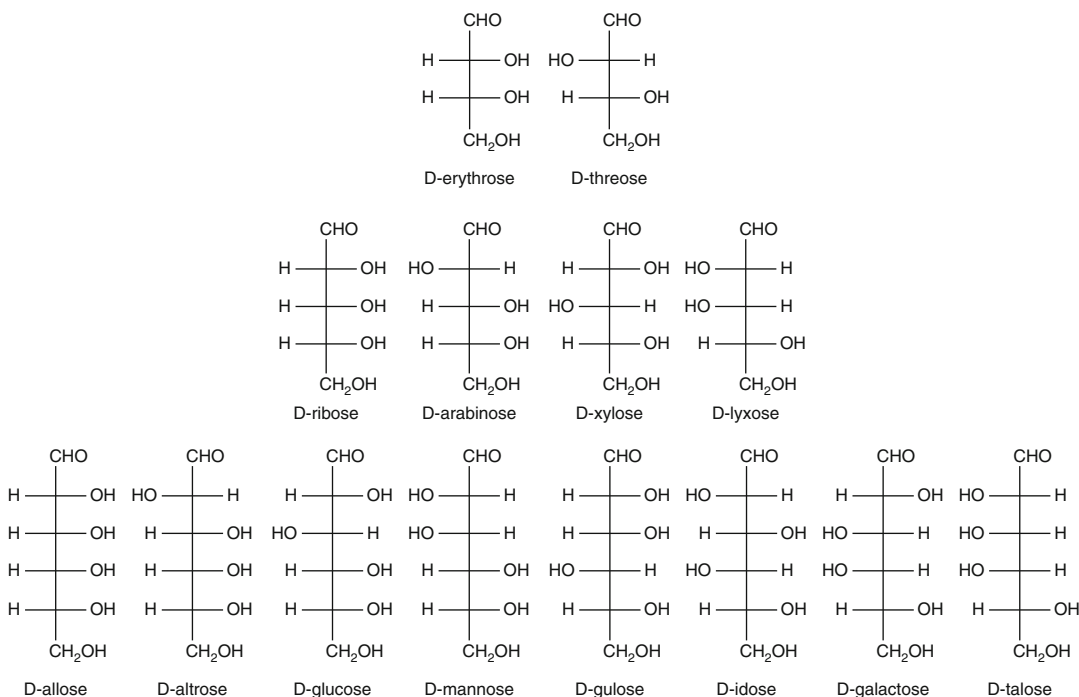
Definition

Carbohydrates are molecules composed solely of carbon, oxygen, and hydrogen with the general formula $C_n(H_2O)_n$. The ratio of carbon to hydrogen to oxygen atoms in a carbohydrate is 1:2:1. Carbohydrates are involved in cell signaling, serve as a source of energy, and provide structure to cells. Chains that alternate negatively charged phosphates with carbohydrates form the backbones of the genetic biopolymers RNA and DNA.

Overview

Carbohydrates are an essential component of life on Earth. From ► [ribose](#) being an integral component of the genetic biopolymers DNA and RNA to polymers of glucose used for cell wall support in plants, carbohydrates are involved in many crucial biological functions. The complex structures of carbohydrates can be easily visualized using ► [Fischer projections](#). Figure 1 depicts Fischer projections of aldoses, a class of carbohydrates that contain an aldehyde group. In the structures below, each line represents a covalent bond and each intersection of lines represents an unwritten carbon (C).

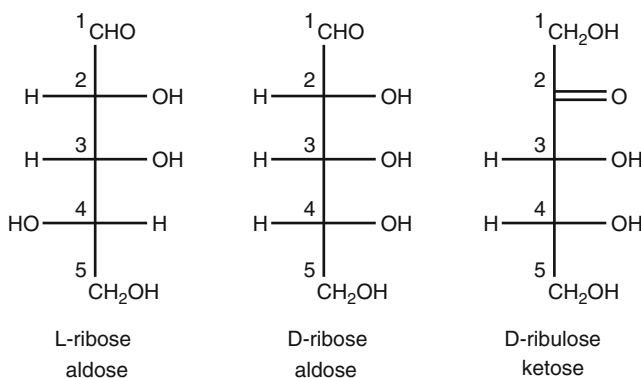
There are 2^n stereoisomers of a given sugar, where n is the number of ► [chiral](#) centers in the molecule. For instance, the aldopentoses contain five carbons, three of which are chiral centers, giving $2^3 = 8$ stereoisomers. These pentoses have the common names of ribose, arabinose, xylose, and lyxose and each come in a d or l ► [enantiomer](#). The d or l configuration of the sugar is determined by the position of the alcohol on the chiral center furthest away from the aldehyde carbon. If the alcohol is on the right of the backbone, the sugar is classified as d, while if it is on the left, it is l. In the case of aldopentoses, this chiral center is on carbon four (Fig. 2). On Earth, the d isomer prevails as the dominant carbohydrate incorporated in biological systems; however, it has been postulated that l sugars could also be used as the predominant isomer in alternate “alien” biochemistries.



Carbohydrate, Fig. 1 The four-, five-, and six-carbon d-aldoses

Carbohydrate,

Fig. 2 Carbohydrates can occur in either D or L forms. The ketose ribulose has an oxidized center at carbon two



Carbohydrates can also form cyclic structures that produce an anomeric center giving the sugar an alpha (alcohol pointing down) or beta (alcohol pointing up) label. Ribose, for example, can be found in a furanose (five-membered) or pyranose (six-membered) form. Both the alpha and beta configurations of the furanose and pyranose forms of ribose are shown in Fig. 3. The ribose found in DNA is in a furanose configuration, whereas ribose in aqueous solutions and

crystalline form is predominantly pyranose (Šišak et al. 2010).

Presence of Carbohydrates in the Universe

Astrobiologists studying the ► [origins of life](#) seek an answer to fundamental questions related to the origins of carbohydrates. Through the use of radio telescopes, scientists have determined the presence of carbohydrates and their building blocks in interstellar gas clouds. Examples of some organic

molecules reported in these clouds (Fig. 4) include ► **formaldehyde**, ► **glycolaldehyde**, and dihydroxyacetone (Snyder et al. 1969; Hollis et al. 2004; Weaver and Blake 2005; although the detection of dihydroxyacetone has been questioned – see ► **Molecules in Space**). Meteoritic bombardment could have delivered these molecules to the surface of the early Earth (Sephton 2002). Aldol reactions of glycolaldehyde and formaldehyde on a primitive Earth could also have been sources of glyceraldehyde, erythrulose, and higher carbohydrates (Fig. 5).

Prebiotic Synthesis of Carbohydrates

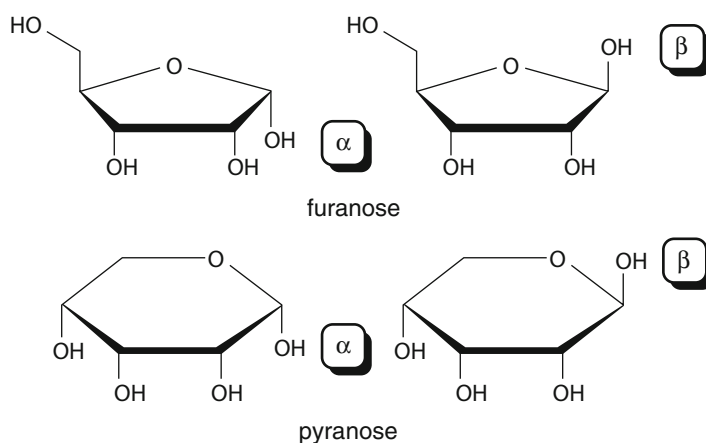
The prebiotic synthesis of carbohydrates is fundamental to astrobiology and origins of life research.

The ► **“RNA World”** hypothesis, which purports that life evolved from simple RNA molecules, presupposes the existence of a prebiotic soup with abundant building blocks, including amino acids, carbohydrates, purines, and pyrimidines.

One of the first reported instances of prebiotic carbohydrate synthesis occurred in 1861 when a German scientist, Butlerov, added formaldehyde to hot solutions of barium and calcium hydroxide forming a sweet sugary substance (Butlerov 1861). This became known as the ► **formose** reaction. A century later, Breslow discovered that the glycolaldehyde formed in this reaction initiates a series of autocatalytic reaction cycles which, over time, fix more formaldehyde to give higher carbohydrates (Breslow 1959). A side reaction in this

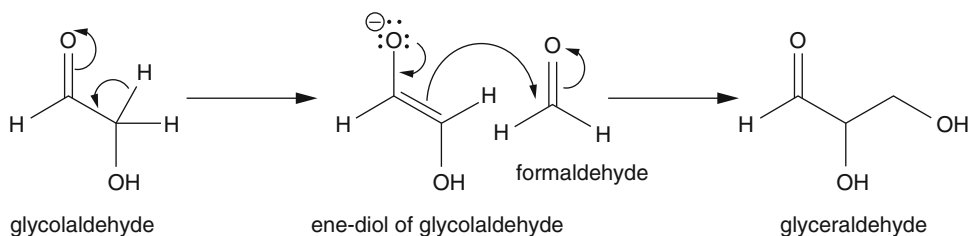
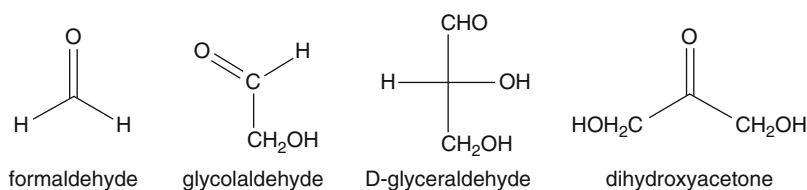
Carbohydrate,

Fig. 3 The furanose (five-membered) and pyranose (six-membered) forms of d-ribose and their alpha (α) and beta (β) anomers

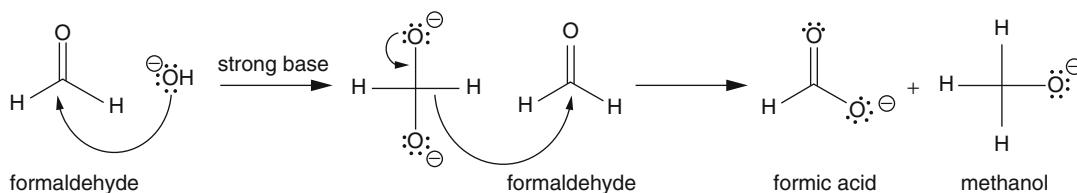


Carbohydrate,

Fig. 4 Formaldehyde and some lower carbohydrates glycolaldehyde, d-glyceraldehyde, and dihydroxyacetone



Carbohydrate, Fig. 5 An example of an aldol addition of formaldehyde to glycolaldehyde



Carbohydrate, Fig. 6 In the Cannizzaro reaction, formaldehyde reacts in strong base to give formic acid and methanol (both shown in their deprotonated forms)

experiment is the disproportionation of [formaldehyde](#) to form [methanol](#) and formic acid in a process now known as the Cannizzaro reaction (Fig. 6).

One argument against the RNA world arising from the [primordial soup](#) involves the formation of “problematic tar,” which is a seemingly useless by-product of highly reactive species (Larralde et al. 1995). The propensity of the formose reaction to form tar is an indication of the functionality and reactivity of these building blocks. The tar prevents the accumulation of genetically relevant carbohydrates and complicates in-depth product analysis. Recently, however, [borate](#) minerals have been shown to stabilize and direct the reactivity of carbohydrates, making them potentially important participants in prebiotic reactions (Ricardo et al. 2004). Here, borate binds to adjacent alcohols of sugars as they are formed. This in turn reduces their reactivity and improves carbohydrate stability, preventing further uncontrolled tar-forming reactions.

In a different approach to prebiotic carbohydrate synthesis, activated pyrimidine nucleosides are assembled, sidestepping the model of adding a nucleobase to a previously synthesized ribose sugar (Powner et al. 2009). Though this methodology does not yet account for the synthesis of purine nucleosides, it opens new avenues for research toward the prebiotic synthesis of RNA and DNA.

Cross-References

- ▶ [Aldose](#)
- ▶ [Biopolymer](#)
- ▶ [Borate](#)

- ▶ [Disproportionation](#)
- ▶ [Fischer Projection](#)
- ▶ [Formaldehyde](#)
- ▶ [Formose Reaction](#)
- ▶ [Glycolaldehyde \(HOCH₂CHO\)](#)
- ▶ [Ketose](#)
- ▶ [Methanol](#)
- ▶ [Origin of Life](#)
- ▶ [Primordial Soup](#)
- ▶ [Ribose](#)
- ▶ [RNA World](#)

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Carbon

Alan W. Schwartz
Radboud University Nijmegen, Nijmegen,
The Netherlands

Synonyms

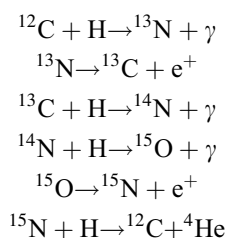
Elemental carbon

Definition

Carbon: The sixth element of the periodic table.

Overview

Carbon is the sixth element in the periodic table. Its stable isotopes include ^{12}C , the nucleus of which contains six protons and six neutrons, and ^{13}C , which contains six protons and seven neutrons. Carbon is the fourth most abundant element in the solar atmosphere, after hydrogen, helium, and oxygen. This predominance is largely due to the autocatalytic role of carbon in the stellar nucleosynthesis of elements higher than hydrogen via proton addition (Bethe 1939):



Carbon Isotopes

Carbon exists on Earth in the form of two stable (^{12}C and ^{13}C) and one unstable isotope (^{14}C). ^{12}C and ^{13}C have abundances of 98.89% and 1.108%, respectively (Wederpohl 1978). The standard atomic weight of carbon on Earth (abridged to five figures) is, therefore, 12.011 (Commission on Isotopic Abundances and Atomic Weights,

IUPAC). ^{14}C (six protons and eight neutrons) is produced in the upper atmosphere by the interaction of thermal neutrons (produced from cosmic rays) and nitrogen atoms. The isotope has a half-life for decay (into ^{14}N and a beta particle, β^-) of 5730 years and is employed in determining the age of objects having a biological origin up to about 50,000 years of age (Arnold and Libby 1949). In addition to the use of ^{14}C decay kinetics to determine the age of objects of archeological and anthropological interest, the ratio of the stable isotopes $^{12}\text{C}/^{13}\text{C}$ is an important indication of the pathway of synthesis of organic compounds. Because of the kinetic isotope effect, both biological and nonbiological synthetic processes can produce organic material containing a distinctive enrichment of the lighter isotope of carbon, ^{12}C . While the isotopic fractionation ratio ($\delta^{13}\text{C}$) was once thought to be a reliable indication of a biological carbon fixation (Schidlowski et al. 1983), this has recently been questioned (McCollom and Seewald 2006).

Electronic Structure

The electronic structure of carbon is abbreviated as $1s^2, 2s^2, 2p^2$ (two electrons in the $1s$ orbital, two electrons in the $2s$ orbital, and two electrons in the $2p$ orbital). The element can therefore accept four electrons in the outermost (valance) shell to complete an octet and form a neon-like configuration: $1s^2, 2s^2, 2p^6$. It was pointed out by Wald that the prevalence of H, O, N, and C in biochemistry can be rationalized by the fact that these elements are the smallest that can reach stable (filled, i.e., noble gas-like) electronic configurations in the valance shell by adding (i.e., sharing with other atoms) one, two, three, and four electrons, respectively, and thereby forming covalent bonds (Wald 1958).

This suggests that the same properties of these elements would similarly be responsible for a central role for organic chemistry (and biochemistry) anywhere in the universe. Wald also argued that silicon's electronic configuration (one period lower in the periodic table; $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$), while potentially also permitting the forming

of covalent bonds by accepting four electrons in the outermost shell, is substantially larger than carbon. The larger distance between the nucleus of silicon and the outer electronic orbitals results in differences in bonding energies, as well as the geometry of the orbitals, compared to carbon. The result is that C forms stable covalent bonds (single as well as multiple) with itself and with other atoms, while Si has much less tendency to do so. Thus, CO₂ is a discrete molecule and a stable gas, and C-C bonds produce stable chains of hydrocarbons. SiO₂, on the other hand, is a crystalline solid (of average composition SiO₂), which exists as an unlimited three-dimensional network, and Si-Si chains are not stable in the presence of water or O₂. Carbon is thus regarded by most astrobiologists as being central to and probably necessary for life.

Native Forms of Carbon

In spite of its importance to life and its role in the biosphere, elemental carbon is only a trace constituent in most of the Earth's crust, where it is present at an average level of 200 ppm. In sedimentary rocks, carbon is abundant but usually in compounds such as carbonates (limestone) or organic matter (petroleum, coal). In the biosphere, hydrosphere, and atmosphere, carbonic acid equilibria (carbon dioxide, carbonate, and bicarbonate) play major roles in the weathering of crustal rocks and presumably would have similar roles on other, Earth-like planets.

The primary forms of elemental carbon in Earth's crust and mantle are graphite and diamond. Diamond is thought to form under high-pressure and high-temperature conditions in the mantle and to be transported to the surface by magmatic activity. Graphite has a sheet-like network of so-called sp² (planar)-bonded carbon atoms (see below) and can be hydrogenated to produce hydrocarbons or oxidized to carboxylic acids. In contrast, diamond, which has a tetrahedral or sp³ structure, forms face-centered cubic crystals which are difficult to oxidize or reduce. The hexagonal mineral lonsdaleite, another allotrope which is said to be even harder than

diamond, is only found in strongly shocked areas such as meteorite craters, where it is thought to have formed from graphite during impact (Wederpohl 1978). Similarly, fullerenes and related "cage" forms of carbon also require exceptional conditions to form but have been identified in the unshocked Allende and Murchison meteorites as C₆₀–C₄₀₀ fullerenes (Becker et al. 2000). Graphene, a linear sheet structure consisting of hexagonal lattices of carbon, has long been recognized as a theoretical possibility, but was only synthesized in 2004 (Novoselov et al. 2004). It forms the basis for a new series of sheet structures and can be thought of as the basic unit of fullerenes. Similarly, carbon nanotubes have been described in which graphene sheets comprise the basic structural unit. For a review of these structures see Hirsch (Hirsch 2010).

Compounds of Carbon and the History of Organic Chemistry

Although the element has been known from ancient times, an understanding of its chemical nature and particularly its role in organic material did not emerge until the development of analytical methods by Lavoisier and others in the eighteenth century. Thus, Lavoisier demonstrated that carbonic acid or carbon dioxide was formed by the union of carbon and oxygen or by burning organic substances in air or oxygen (Moore 1918). The terms "organic chemistry" and "organic compound" were historically intended to indicate the nature of biologically derived compounds of carbon, which were thought to be unique to life. Today, organic chemistry is usually described as the chemistry of compounds of carbon but probably can be more accurately regarded as focusing on the chemistry of hydrocarbons (compounds composed of hydrogen and carbon) and of their derivatives with oxygen and nitrogen.

Modern organic chemistry is generally considered to have started in the mid-nineteenth century with the work of Wöhler, who synthesized the well-known animal waste product, urea. The actual story of Wöhler's work is somewhat more

complicated than the usual description. The great chemist was attempting to synthesize ammonium cyanate by studying the reaction between cyanogen and (aqueous) ammonia, one of the products of which was a white crystalline substance. The same product was also obtained by the reaction of lead cyanate and ammonia. It was in the course of purifying the latter that Wöhler obtained urea. His realization of the potential importance of the reaction led him to write to Berzelius, saying that he could make urea without using a kidney or even an animal (McKie 1944). In spite of the enthusiastic nature of this communication to Berzelius, the latter's reaction, as well as those of many of Wöhler's contemporaries, was restrained and ► [vitalism](#) only gradually died out.

During this same period, chemists became aware of the existence of meteorites containing organic compounds. Berzelius and Wöhler, among others, remarked on the presence of organic material in several carbonaceous meteorites. It is noteworthy, however, that neither Berzelius nor Wöhler thought that the organic compounds present were necessarily biological products (Nagy 1975). Today, the universality of organic chemistry has become obvious, not only through the investigation of meteorites and comets but due to observations of interstellar organic compounds.

Molecular Structure of Carbon Compounds

Bond formation between carbon atoms (or with other elements) occurs by sharing electrons and involves a process known as hybridization of molecular orbitals. In methane and related hydrocarbons, the carbon atom is located in the center of a tetrahedron, with the bonded hydrogen atoms located at the corners. This geometry was explained by Pauling:

We have thus derived the result that an atom in which only *s* and *p* eigenfunctions contribute to bond formation and in which the quantization in polar coordinates is broken can form one, two, three, or four equivalent bonds, which are directed toward the corners of a regular tetrahedron. (Pauling 1931).

The tetrahedral geometry of compounds of carbon thus results from so-called sp^3 hybridized orbitals. As a consequence of this symmetry, substitution of other atoms bonded to the central carbon atom (such as substitution of the hydrogen atoms in methane, CH_4 by atoms or groups A, B, and C to produce $CHABC$), produces an unsymmetrical molecule which displays the phenomenon of ► [chirality](#). Synthesis of such a chiral molecule by a spontaneous chemical reaction produces a mixture of isomers or enantiomers which are chemically but not physically identical. It can readily be seen by inspecting models that such simple examples of chiral enantiomers are mirror images of each other. The phenomenon of chirality was discovered historically by Pasteur, in the form of "optical activity," as determined by the property of rotating the plane of polarization of a plane-polarized beam of light. The carbon atom in this simple compound is referred to as an asymmetric center. More complex molecules, such as the biological product tartaric acid, which led Pasteur to his discovery, contain more than one chiral center and can produce even more complicated sets of chiral enantiomers.

Cross-References

- [Carbonaceous Chondrite](#)
- [Chirality](#)
- [Comet](#)
- [Delta, Isotopic](#)
- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)
- [Interstellar Chemical Processes](#)
- [Organic Molecule](#)
- [Vitalism](#)

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Carbon Concentrating Mechanisms

► Carboxysomes, Structure and Function

Carbon Cycle, Biological

J. Cynan Ellis-Evans
UK Arctic Office, Strategic Coordination Group,
British Antarctic Survey, Cambridge, UK

Keywords

Biogeochemical cycles · Carbon source ·
Fermentation · Photosynthesis · Respiration

Definition

The carbon cycle is one of the most important biogeochemical cycles on Earth and involves all five environmental spheres. Its geological components operate on a scale of millions of years, while biological carbon cycling operates over a scale of days to thousands of years. Every organism on Earth needs carbon either for structure or energy, and the primary biological processes in carbon cycling are ► [photosynthesis](#) and respiration. Incorporation of biological carbon in sedimentary deposits subsequently used as fossil fuels is now also an important process in biological carbon cycling, notably through influencing the global carbon budget and thus the Earth's climate.

Overview

Carbon is the fourth commonest element in the Universe and is present in all five Earth spheres (► [biosphere](#), geosphere, pedosphere, ► [hydrosphere](#), and atmosphere). The annual rates of biological carbon cycling are several orders of magnitude greater than geological cycling of carbon and very responsive to environmental fluctuations. Carbon is essential to life on Earth, and the biological processes of light-mediated carbon fixation (photosynthesis, chemolithoautotrophy), ► [aerobic respiration](#) of organic carbon to form inorganic CO₂, and (to a lesser extent) ► [anaerobic respiration](#) to form methane (and some CO₂) are important mechanisms for processing carbon within the five spheres. Exchange of carbon between land and atmosphere is driven by the key biological processes, but in the oceans is dominated by physical exchange as the world's oceans hold vast quantities of dissolved inorganic carbon. This reservoir of dissolved inorganic carbon (DIC) is relatively dynamic, but other reservoirs are more stable. In the case of terrestrial carbon cycling, low rates of decomposition can result in accumulation of organic carbon (e.g., peat deposits, bogs) which can under certain geological conditions form substantial coal, oil, and

gas (including methane hydrate) deposits. In the oceans, sedimentation of plankton with calcareous skeletons results in burial and limestone formation though this can also form through reaction of carbonate ions with calcium. This range of organic and particularly inorganic carbon deposits represents significant long-term sinks for atmospheric CO₂. Anthropogenic activities significantly contributing to carbon cycling include burning of fossil fuels and agro fuels and industrial processes, such as cement production (limestone decomposition). The observed buildup of CO₂ in the atmosphere since the start of the industrial revolution and associated regional warming has led to warmer ocean surface waters. Warmer waters absorb less CO₂, and so the “braking” effect of the oceans on rising atmospheric CO₂ concentrations is reduced. Warming also allows potential release of methane from temperature-sensitive methane hydrate deposits within shallow marine sediments and from thawing permafrost peat deposits on land, as well as extending the active season for soil respiration, further enhancing release of carbon dioxide and methane to the atmosphere.

Cross-References

- ▶ [Aerobic Respiration](#)
- ▶ [Anaerobic Respiration](#)
- ▶ [Biosphere](#)
- ▶ [Fermentation](#)
- ▶ [Hydrosphere](#)
- ▶ [Methanogens](#)
- ▶ [Photosynthesis](#)

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Carbon Dioxide

Thomas McCollom

Laboratory for Atmospheric and Space Physics,
University of Colorado, Boulder, CO, USA

Keywords

Carbon cycle · Carbon fixation · Carbon-silicate cycle · Greenhouse effect

Synonyms

CO₂

Definition

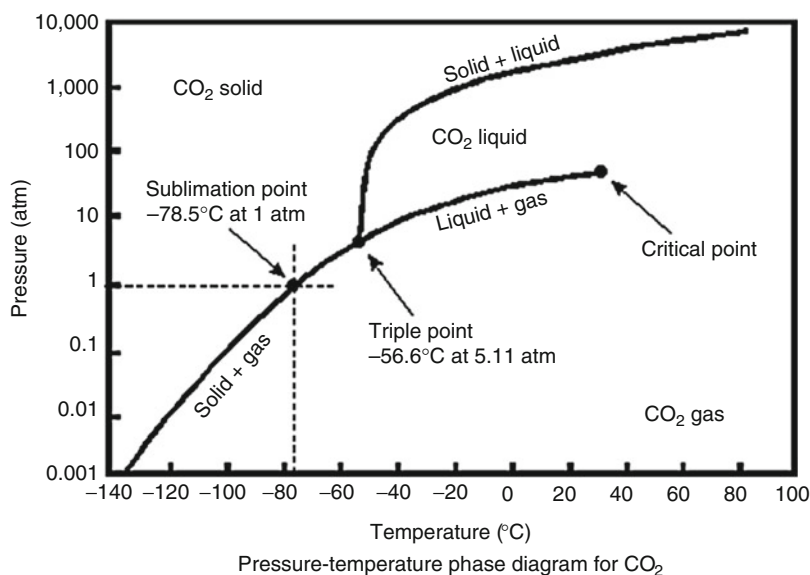
Carbon dioxide is a triatomic compound with the chemical composition CO₂. The molecule is symmetrical and nonpolar. The triple point of pure CO₂ occurs at −56.6 °C and 518 kPa (Fig. 1). As a gas, carbon dioxide is clear, colorless, and odorless.

Overview

Carbon dioxide occurs predominantly as either a gas or a solid ice in the solar system. As a gas, it is the predominant constituent of the atmospheres of Venus and Mars, as well as a minor component of the atmospheres of many other planetary bodies including the Earth. As an ice, CO₂ is a significant component of comets and the Martian polar caps. Liquid carbon dioxide requires temperatures above −56 °C and pressures greater than 5 bar (Fig. 1) to exist. Such conditions are not presently known to occur in the solar system, but might have been present on early Mars and may occur on extrasolar planets. Carbon dioxide has been found in interstellar clouds in gas and ice phases by the Infrared Space Observatory (ISO).

Carbon dioxide is also present in the interior of the Earth, where it occurs as a trace component within the crystal structures of minerals or

Carbon Dioxide,
Fig. 1 Phase diagram for
 pure carbon dioxide



occupies void spaces between minerals. At the oxidation state of the Earth's mantle, carbon dioxide together with the minerals graphite and diamond is the predominant stable form of carbon. Carbon dioxide dissolves into magmas as they form within the Earth's interior and is released into the atmosphere when the magmas cool and solidify as volcanic rocks at the surface. As a consequence, carbon dioxide is a major component of volcanic gases and is the primary form of carbon in those gases. Carbon dioxide that accumulates in the atmosphere contributes to the ► [greenhouse effect](#) that plays a significant role in warming of planetary surfaces.

Carbon dioxide dissolves readily in water, where it hydrates to form carbonic acid ($\text{H}_2\text{CO}_{3(\text{aq})}$), which in turn generates acidity through the release of protons ($\text{H}_2\text{CO}_{3(\text{aq})} \rightarrow \text{H}^+ + \text{HCO}_3^- \rightarrow 2\text{H}^+ + \text{CO}_3^{2-}$). The protons released can react with minerals to cause rock weathering, altering the rock's mineralogy and releasing cations such as Ca^{2+} and Mg^{2+} into solution. Under some circumstances, the cations released can react with dissolved CO_2 to precipitate as carbonate minerals including calcite (CaCO_3) and siderite (FeCO_3) as part of the carbon-silicate cycle. The net result is the removal of atmospheric CO_2 into carbonate-bearing rock.

Some biological organisms, the photoautotrophs and chemoautotrophs, are capable of transferring electrons to carbon dioxide (CO_2 ► [reduction](#)) to form bioorganic compounds, a process termed carbon fixation. Conversely, heterotrophic organisms consume bioorganic matter and convert much of it back to carbon dioxide in a process known as ► [respiration](#). Transformation of CO_2 through carbon fixation and respiration is a primary component of the biological carbon cycle.

Cross-References

- [Carbon Cycle, Biological](#)
- [Carbon Monoxide](#)
- [Chemoautotroph](#)
- [Greenhouse Effect](#)
- [Infrared Space Observatory](#)
- [Photoautotroph](#)
- [Reduction](#)
- [Respiration](#)

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Carbon Isotopes in the Solar System

Juha A. Karhu¹ and Andrey Bekker²

¹Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

²Department of Earth and Planetary Sciences, University of California, Riverside, Riverside, CA, USA

Keywords

Carbon isotopes · Solar system · Carbon cycle · Biosignature

Definition

Carbon has two naturally occurring stable isotopes, ^{12}C and ^{13}C . In addition, there is a radioactive isotope ^{14}C , with a half-life of 5730 ± 40 years. The radioactive ^{14}C is formed in trace amounts in the atmosphere as a result of cosmic ray bombardment.

Materials of the Milky Way Galaxy have large primordial variations in the relative abundance of the carbon isotopes. These compositions are usually reported as $^{12}\text{C}/^{13}\text{C}$ ratios, which differ from the convention adopted for Solar System materials. For Solar System materials, the range of the isotopic composition of carbon is much more limited, and the abundances of isotopes are measured and reported as parts per 1000 deviations of the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample from that of the international Vienna Pee Dee Belemnite (VPDB) reference standard. These relative deviations are expressed in δ -values:

$$\delta^{13}\text{C} = (R_{\text{sample}}/R_{\text{VPDB}} - 1) \times 1000, \quad (1)$$

where R is the abundance ratio of ^{13}C to ^{12}C . The numeric values are given in permil units followed by the ‰ symbol.

Physical, chemical, and biological processes cause fractionation in the relative abundance of ^{13}C and ^{12}C between substances. The distribution of ^{13}C and ^{12}C between two interacting

substances A and B is expressed with a fractionation factor α , which is defined as the ratio of the $^{13}\text{C}/^{12}\text{C}$ ratios of the two substances A and B:

$$\begin{aligned} \alpha_{A-B} &= \left(^{13}\text{C}/^{12}\text{C} \right)_A / \left(^{13}\text{C}/^{12}\text{C} \right)_B \\ &= (1000 + \delta^{13}\text{C}_A) / (1000 + \delta^{13}\text{C}_B). \end{aligned} \quad (2)$$

The fractionation factor is often given using a derived quantity $1000\ln\alpha$, especially when addressing equilibrium fractionation processes. Between most terrestrial substances, the fractionation factor α_{A-B} is close to 1, and the difference in $\delta^{13}\text{C}$ values gives a useful approximation of $1000\ln\alpha$:

$$\Delta_{A-B} = \delta^{13}\text{C}_A - \delta^{13}\text{C}_B \approx 1000 \ln \alpha_{A-B}. \quad (3)$$

Another derived quantity to quantify fractionation is ϵ_{A-B} , which is defined as

$$\epsilon_{A-B} = (\alpha_{A-B} - 1)1000. \quad (4)$$

Because $\alpha_{A-B} \approx 1$, also $\epsilon_{A-B} \approx \Delta_{A-B}$. The ϵ value is commonly used to designate fractionation in kinetic, nonequilibrium processes.

History

The name carbon is derived from the Latin *carbo* for “charcoal.” Aston (1920) was the first to document the ^{12}C isotope, which he considered to be the only isotope of carbon. Subsequently, King and Birge (1930) established the existence of a minor ^{13}C isotope using a mass spectrograph. Nier and Gulbransen (1939) reported carbon isotope ratios of air, organic matter, coal, graphite, diamond, meteorite, and carbonates. They noticed significant differences in carbon isotope composition among these materials, with plants, coal, air, and oil being enriched in ^{12}C with respect to carbonates. However, these measurements were not sufficiently precise and accurate to address geological problems.

Nier (1940) introduced a 60°-sector field mass spectrometer, which was further improved by McKinney et al. (1950) in the effort of Harold Urey's group to develop an oxygen isotope paleothermometer. In the same paper, they also adopted the delta notation with the isotope ratios expressed as relative permil deviations from a reference standard. The PDB scale was defined with calcite of cephalopod, *Belemitella americana*, from the Pee Dee Formation of South Carolina by Urey et al. (1951). This work set up the ground for the expansion of carbon isotope studies to many different fields, including geochemistry, paleoclimatology, hydrology, plant science, ecology, archeology, planetary studies, and astrobiology. New analytical methods have extended the analyses to exceedingly small amounts of carbon and in situ analytical techniques allow analyses to be made directly on the surface of the sample.

Overview

Carbon Isotope Fractionation

Equilibrium fractionation describes the redistribution of isotopes of an element among substances under equilibrium conditions. In a carbon isotope exchange reaction, ^{12}C and ^{13}C are exchanged between two substances. The equilibrium state is characterized by the fractionation factor α , generally given as $1000\ln\alpha$. The fractionation factor is strongly dependent on temperature, whereas the effect of pressure is small and can generally be ignored. $1000\ln\alpha$ has the largest absolute values at low temperatures and it approaches zero at high temperatures.

Kinetic fractionation occurs in unidirectional processes and reactions, where the forward and backward reaction rates are not equal. Biological processes are typically unidirectional. For example, a significant kinetic isotope fractionation is associated with the enzymatic carboxylation step of carbon assimilation by plants, in which the plants strongly favor the lighter isotope, ^{12}C .

Basic Methodology

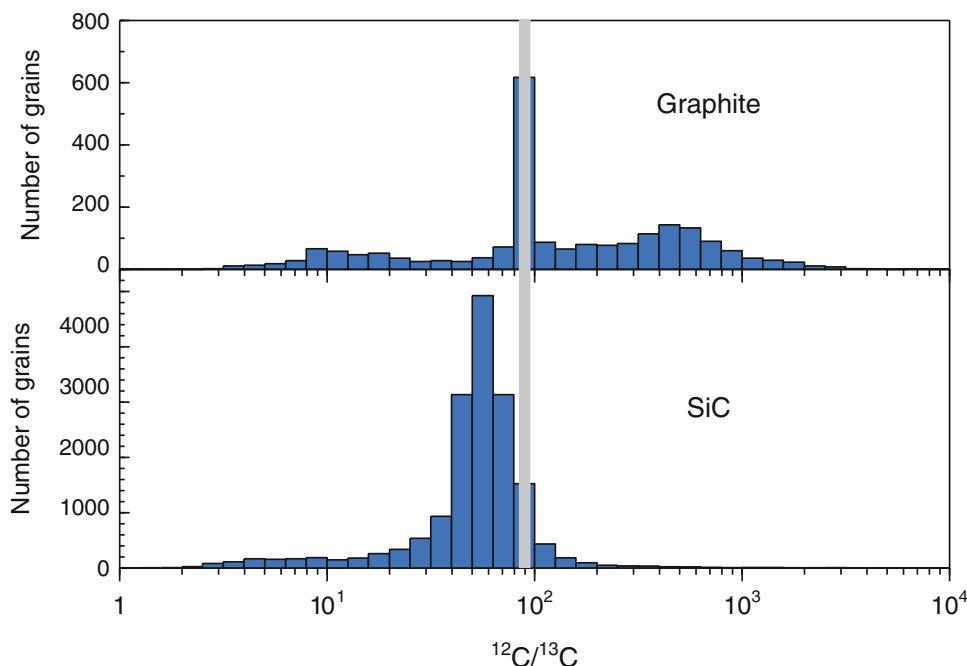
The traditional standard technique for analyzing the isotope composition of carbon involves the analysis of CO_2 on a gas source isotope ratio mass spectrometer (IRMS), where CO_2 is produced either by combustion of organic carbon or acidification of carbonates. The precision and accuracy of the analyses is commonly $<0.1\%$. More recent analytical innovations include tunable diode laser absorption spectroscopy (TDLAS) and cavity ring-down spectroscopy (CRDS). The isotope composition of carbon can also be analyzed in situ on the solid surface of a mineral by secondary ion mass spectrometry (SIMS) or by laser ablation coupled with continuous flow isotope ratio mass spectrometry (LA-CF-IRMS). Organic materials can be analyzed with an elemental analyzer connected to a continuous flow isotope ratio mass spectrometer (EA-CF-IRMS).

Key Research Findings

Presolar Stardust

One of the most astonishing findings in cosmochemistry has been the discovery of presolar stardust grains, including carbon-bearing phases such as diamond, silicon carbide, and graphite (Nittler 2003; Zinner 2014). The evidence for their interstellar, primordial origin is provided by the enormous range in their carbon isotope ratios in comparison to substances formed in the solar system. Presolar graphite and silicon carbide grains have $^{12}\text{C}/^{13}\text{C}$ ratios ranging from 2.1 to 7200 for graphite and from 1.0 to 9500 for silicon carbide (Fig. 1). For comparison, the $^{12}\text{C}/^{13}\text{C}$ ratios in Solar System materials have a much smaller total range of isotope ratios from 84 to 94 (Fig. 1).

The huge carbon isotope range in the stardust grains cannot be explained by physical or chemical fractionation processes. Instead, it is likely to record nucleosynthetic processes within stars as well as during supernova explosions (Nittler 2003). Among all solar system substances, only



Carbon Isotopes in the Solar System, Fig. 1 Distribution of the $^{12}\text{C}/^{13}\text{C}$ ratios in presolar graphite and silicon carbide (SiC) grains. The data are compared

to the total range of $^{12}\text{C}/^{13}\text{C}$ ratios in solar system materials, shown as a grey band. Source of the presolar grain data is the presolar database (Hynes and Gyngard 2009)

these grains carry information about the carbon isotope composition of the presolar stellar environment. Except for the rare stardust grains, the isotopic composition of carbon in the Solar System has been effectively processed and homogenized in the presolar molecular cloud and the early Solar System. In the Milky Way Galaxy, the $^{12}\text{C}/^{13}\text{C}$ ratios of the molecular clouds show an increasing trend with distance from the Galactic center (Milam et al. 2005). Accordingly, planetary bodies formed in different regions of the Galaxy can be expected to have distinct mean carbon isotope compositions.

Bulk $\delta^{13}\text{C}$ of the Solar System

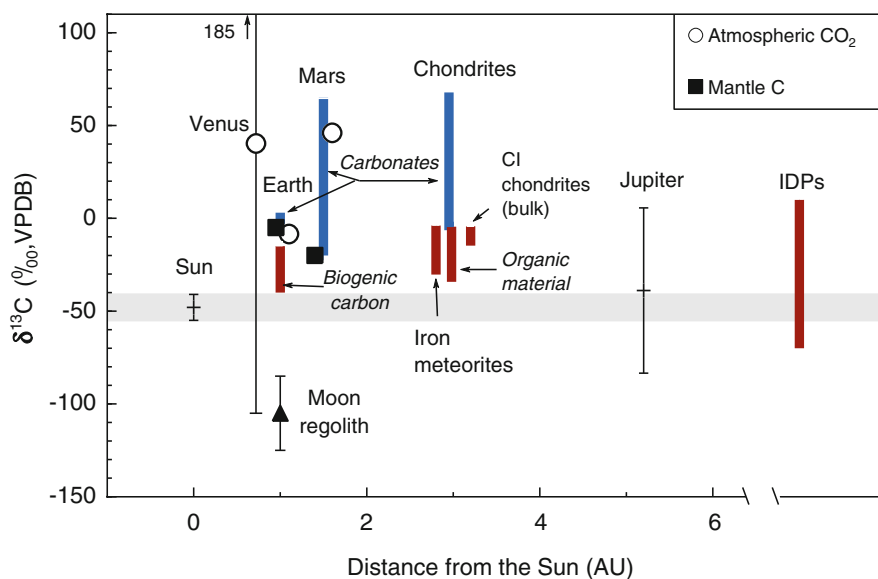
Based on the data from a shuttle-carried Fourier Transform Spectrometer, Lyons et al. (2018) determined that the photosphere of the Sun has a $\delta^{13}\text{C}$ value of $-48 \pm 7\%$ (Fig. 2). Since about 99.8% of the total mass of the solar system is in the Sun, this value also represents the best

estimate for the bulk isotope composition of carbon in the Solar System.

Similar results, although with larger uncertainty, have been obtained for the atmosphere of Jupiter using mass spectrometric methods on the Galileo probe (Niemann et al. 1998) and with SIMS analyses of the interplanetary dust particles (IDPs) (Messenger et al. 2003; Fig. 2). IDPs are thought to be derived from comets and asteroids and represent the most primordial solar system materials, which did not experience significant postaccretional alteration.

CO_2 in Planetary Atmospheres

Atmospheric CO_2 has an important role in maintaining planetary surface temperatures by the greenhouse effect. Record of the isotope composition of carbon in atmospheric CO_2 can provide very useful information about the geological evolution of the atmospheric CO_2 and the carbon cycle on the planet.



Carbon Isotopes in the Solar System, Fig. 2 $\delta^{13}\text{C}$ values of solar system materials. Mean values are shown with error bars (1σ), ranges of data are shown by bars. Separately displayed are the mantle carbon isotope composition for Earth and Mars, and the $\delta^{13}\text{C}$ values of atmospheric CO_2 for Earth, Mars, and Venus. The isotopic composition of carbon in the Sun corresponds to the bulk composition of the solar system, which is shown by a grey horizontal bar. Solar wind implanted C in the lunar regolith

On Earth, the small carbon pool of atmospheric CO_2 is relatively close to carbon isotope equilibrium with a much larger reservoir of dissolved bicarbonate in the surface oceans. The abundance of CO_2 in the atmosphere has increased during the past 200 years from about 280 to 400 ppm. The shift has been accompanied by a decrease in the $\delta^{13}\text{C}$ value of atmospheric CO_2 from ca. -6.5‰ to the present-day value of -8.5‰ (Rubino et al. 2013). Both changes have been caused by anthropogenic fossil fuel emissions.

Information about the isotopic composition of carbon in the atmospheres of Mars and Venus has been acquired by probes and rovers sent to the surface of the planets and by spectroscopic measurements (Fig. 2). A tunable laser spectrometer on board of the Curiosity rover determined the $\delta^{13}\text{C}$ value of CO_2 in the Martian atmosphere to be $+46 \pm 4\text{‰}$ (Webster et al. 2013). The result was confirmed by an ICP mass spectrometer on-board of the same rover. The ^{13}C -enriched composition of the Martian atmospheric CO_2 has

been linked to a catastrophic early loss of atmospheric gases to space, with a preferential escape of molecules with the lighter isotope, ^{12}C (Webster et al. 2013). The Martian carbonate data and the Martian mantle value represent analyses of the SNC meteorites (Grady et al. 2004; Niles et al. 2010). Sources of data: Lyons et al. (2018), Deines and Wickman (1975), Bézard et al. (1987), Niemann et al. (1998), Messenger et al. (2003), Hashizume et al. (2004), Schidlowski (2001), Deines (2002), Grady et al. (2004), Niles et al. (2010), Rubino et al. (2013), Webster et al. (2013), and Marty et al. (2013).

been linked to a catastrophic early loss of atmospheric gases to space, with a preferential escape of molecules with the lighter isotope, ^{12}C (Webster et al. 2013).

The $\delta^{13}\text{C}$ value of CO_2 in the Venusian atmosphere is poorly known. Bézard et al. (1987) determined spectroscopically a $^{12}\text{C}/^{13}\text{C}$ ratio of 86 ± 12 for CO_2 (Fig. 2). The isotope composition of carbon in CO_2 has also been measured using mass spectrometers carried by planetary probes, but due to analytical problems, these values might be biased (Hoffman et al. 1980; Bézard et al. 1987).

Meteorites

With a few exceptions, the meteorites are thought to have their origin in the asteroid belt between Mars and Jupiter. Among them, chondrites are primitive meteorites, which have not been significantly modified by planet building processes. In chondrites, carbon is mainly present as organic matter, with $\delta^{13}\text{C}$ values ranging from -22.6 to

+14.0‰ in the bulk material (Marty et al. 2013). In the most primitive CI chondrites (standing for carbonaceous chondrite Ivuna, Tanzania), the range of $\delta^{13}\text{C}$ values is smaller, from -14.7 to -4.3 ‰ (Fig. 2). Carbonates in carbonaceous chondrites are highly enriched in ^{13}C , with more than 70% range in $\delta^{13}\text{C}$ values and the highest value of +67.8‰, while organic matter has a smaller range in $\delta^{13}\text{C}$ values from -34.2 to -4.5 ‰ (Marty et al. 2013).

Carbon-bearing phases in iron meteorites have $\delta^{13}\text{C}$ values in the range from -3.9 to -30.3 ‰ (Deines and Wickman 1975). In separate phases, the $\delta^{13}\text{C}$ values fall in the range from -4.8 to -8.2 ‰ for nodular graphite, -18.1 to -19.2 ‰ for cohenite (iron carbide mineral) and -19.7 to -22.1 ‰ for taenite (Fe-Ni alloy) (Deines and Wickman 1975).

SNC Meteorites (Shergottites, Nakhilites, and Chassignites)

Numerous lines of evidence indicate a Martian origin for the SNC meteorites. Their comprehensive analysis has yielded much information about isotope composition of carbon-bearing phases on Mars. Trace carbon associated with primary magmatic rocks (basalts) of SNC meteorites suggests that the $\delta^{13}\text{C}$ value of Martian mantle carbon is -20 ± 4 ‰ (Grady et al. 2004; Fig. 2), implying disequilibrium with the Martian atmosphere.

Most SNC meteorites also contain carbonates, which are characterized by a surprisingly large span of $\delta^{13}\text{C}$ values from -20 to $+65$ ‰ (Niles et al. 2010; Fig. 2). The lowest $\delta^{13}\text{C}$ values are similar in the isotope composition to the Martian mantle carbon, whereas the highest values exceed those measured for the Martian atmosphere, but are similar to the $\delta^{13}\text{C}$ values measured in carbonaceous chondrites (see above). It appears that both the mantle and the atmosphere have been sources of carbon for the Martian carbonates.

Earth

While carbon is the fourth most abundant element in the solar system (after hydrogen, helium, and oxygen), it is fourteenth in abundance in the Earth crust. The mantle and the crust are the most important and relatively well-characterized terrestrial

pools of carbon. The metallic iron core is an additional, poorly characterized reservoir, with the amount of carbon potentially exceeding that in the mantle and crust (Wood et al. 2013; Horita and Polyakov 2015). No samples from the core are available, and therefore, the size and isotopic composition of this reservoir are inferred only on theoretical and experimental arguments.

Mantle carbon has a $\delta^{13}\text{C}$ value of -5 ± 3 ‰ (Deines 2002; Horita and Polyakov 2015). Recent evidence from superdeep diamonds has revealed considerable heterogeneity in the carbon isotope composition of the deep convecting mantle, with the most negative C isotope values typical for diamonds derived from the transition zone or having a subducted oceanic crust origin (Shirey et al. 2013; Burnham et al. 2015). The superdeep diamonds seem to have $\delta^{13}\text{C}$ values spanning the whole range of crustal carbon, which has been interpreted to reflect deep subduction of crustal materials (Shirey et al. 2013; Burnham et al. 2015). Since the efficiency of subduction of carbonate and organic carbon is different under high temperature and pressure conditions (Duncan and Dasgupta 2017), the new observations highlight substantial uncertainty regarding the estimate of the mean $\delta^{13}\text{C}$ value for the mantle carbon.

Crustal carbon, predominantly in sedimentary and metasedimentary rocks, is ultimately derived from the mantle and generally thought to have the same average $\delta^{13}\text{C}$ value of -5 ‰. However, the crust is much more heterogeneous than the mantle in carbon isotope composition, with carbonates having $\delta^{13}\text{C}$ values close to 0‰ (but in rare cases as high as +28‰) and organic carbon/graphite having $\delta^{13}\text{C}$ values close to -30 ‰ (but in rare cases values as low as -70 ‰ have been observed).

Consideration of carbon isotope fractionation between carbon minerals and liquid iron has led to a suggestion that the $\delta^{13}\text{C}$ value of carbon in the core could be significantly lower than that in the mantle (Wood et al. 2013; Horita and Polyakov 2015), possibly in the range from -15 to -10 ‰. It follows then that the generally accepted $\delta^{13}\text{C}$ value for the mantle of -5 ‰ does not necessarily represent the mean isotope composition of all terrestrial carbon.

Early Fractionation of the Solar System Carbon

The carbon isotope data (Fig. 2) provide evidence for a systematic ^{13}C -enrichment in meteorites and terrestrial planets in comparison to the bulk composition of the Solar System. The large-scale difference in the $\delta^{13}\text{C}$ values suggests early fractionation either in the presolar molecular cloud or during the formation of the Solar System. Lyons et al. (2018) argued for inheritance of the variable carbon isotope composition from the molecular cloud where the fractionation was possibly induced by photochemical self-shielding reactions during CO dissociation (Clayton 2002).

Applications

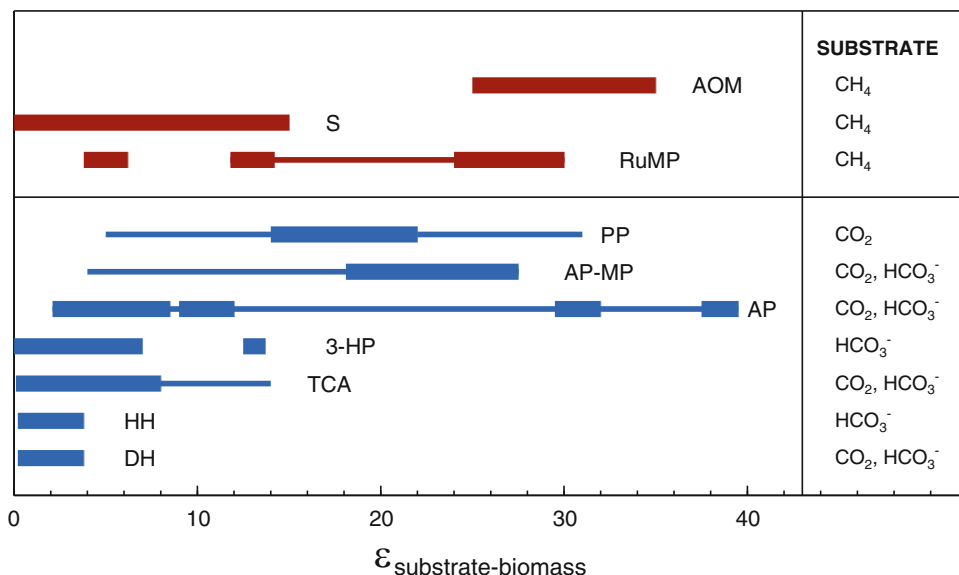
Biogeochemical C Cycle on Earth

Earth is a tectonically active planet, with carbon reservoirs at the surface of the Earth, in the crust,

the mantle, and, possibly, the core. Carbon cycles on different timescales among these reservoirs. Due to associated fractionations and a distinct isotope composition of different reservoirs, carbon isotope studies provide a powerful tool for understanding how the carbon cycle operated in the past and works at the present.

The most significant fractionation in the terrestrial carbon cycle is associated with the photosynthetic assimilation of CO_2 by autotrophic algae and bacteria, strongly favoring the light isotope, ^{12}C (Fig. 3). The amount of fractionation varies according to the carbon-fixation pathway, environmental conditions, and the possible heterotrophic processing of the photosynthetically fixed carbon.

Enzyme-catalyzed fixation of carbon from CO_2 by the *Bacteria* and *Archaea* follows six different cycles/pathways, each with a distinct C isotope fractionation (Berg et al. 2010): (1) reductive pentose phosphate cycle (=Calvin cycle; PP) using



Carbon Isotopes in the Solar System, Fig. 3 Carbon isotope fractionation ($\epsilon_{\text{substrate-biomass}}$) for autotrophic pathways of carbon fixation from CO_2 or HCO_3^- to biomass and for methanotrophic pathways of carbon fixation from CH_4 to biomass according to Zerkle et al. (2005) and Berg et al. (2010). The carbon fixation pathways from CO_2 or HCO_3^- are the reductive pentose phosphate cycle (PP), the acetyl-CoA pathway (AP), the 3-hydroxypropionate cycle (3-HP), the reductive TCA cycle (TCA), the

hydroxypropionate-hydroxybutyrate cycle (HH), and the dicarboxylate- hydroxybutyrate cycle (DH). Also shown is the fractionation associated with the AP pathway forming methane or acetate as a metabolic product (AP-MP). Carbon fixation pathways from methane are bacterial methanotrophy using the RuMP pathway (RuMP), methanotrophy using the Serine Pathway (S), and the anaerobic methanotrophy pathway (AOM)

RubisCO enzyme; (2) reductive acetyl-coenzyme A pathway (=acetyl-CoA) pathway (AP); (3) 3-hydroxypropionate bicycle (3-HP); (4) reductive citric acid cycle (=tricarboxylic acid; TCA); (5) hydroxypropionate-hydroxybutyrate cycle (HH); and (6) dicarboxylate-hydroxybutyrate cycle (DH). Only the first two cycles reach up to 30‰ fractionation, the next two generate up to 12–14‰ fractionation, while the last two produce smaller 0.2–3.8‰ fractionation. The most negative $\delta^{13}\text{C}$ values in the biosphere are associated with the sulfur-oxidizing bacteria using the AP pathway and methanotrophic bacteria (Fig. 3). Importantly, Fig. 3 illustrates that it is difficult, if not impossible, to infer specific metabolic activity from C isotope data alone, although combined with other geochemical and isotopic proxies C isotope data could be informative to fingerprint the ancient community.

Carbon enters the atmosphere-hydrosphere-biosphere system with volcanic gases from the mantle and with the weathering flux from the supracrustal rocks in the continental crust. Both these fluxes are believed to have a $\delta^{13}\text{C}$ value of about -5‰ . Carbon leaves the atmosphere-hydrosphere-biosphere system in the form of sedimentary carbonates and organic matter.

On geologic timescales, a steady state is generally assumed for the carbon cycle. Under these conditions, carbon isotope mass balance can be applied to define the fraction of organic carbon in carbon burial:

$$\delta^{13}\text{C}_i = f_{\text{org}}\delta^{13}\text{C}_{\text{org}} + (1 - f_{\text{org}})\delta^{13}\text{C}_{\text{carb}}, \quad (5)$$

where i refers to the input flux of C, f_{org} to the fractional burial flux of organic carbon, and $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ indicate the isotope composition of carbon buried as organic matter and sedimentary carbonates, respectively.

For most of the geological history, sedimentary carbonates have been characterized by $\delta^{13}\text{C}$ values of $0 \pm 3\text{‰}$, and the isotope composition of sedimentary organic matter has been within the $\delta^{13}\text{C}$ range from -40 to -15‰ , with an average value of about -25‰ (Schidlowski 2001). Applying these values to Eq. 5 gives $f_{\text{org}} = 0.2$ as the organic carbon burial fraction. In the

absence of life, nearly all carbon would have been buried as sedimentary carbonates with a $\delta^{13}\text{C}$ value of -5‰ . This value is not typical even for the oldest preserved sedimentary carbonates, and therefore, the isotope record of sedimentary carbon appears to provide strong evidence for the burial of carbon in isotopically distinct carbonate and organic carbon forms in roughly constant proportion from the time of the oldest preserved sediments at about 3.8 Ga (Schidlowski 2001).

The carbon isotope mass balance model assumes the same isotopic composition for the input fluxes from the mantle and weathering. Isotopic composition of carbon in mantle-derived carbonate melts (carbonatites) and diamonds suggests no secular evolution in the $\delta^{13}\text{C}$ values of mantle-derived carbon over the geological history of the Earth (Deines 2002). However, the $\delta^{13}\text{C}$ values of the weathering flux were not necessarily the same in the Precambrian when atmospheric O_2 levels were lower (Bekker and Holland 2012; Daines et al. 2017). In the present-day oxidizing weathering environments, all organic carbon from the upper continental crust is oxidized to CO_2 , which is then available to biogeochemical carbon cycling in the atmosphere-hydrosphere-biosphere system (Holland 1984). Under low atmospheric O_2 content, a fraction of the sedimentary organic carbon, proportional to the atmospheric $p\text{O}_2$, would be recycled as reduced carbon to sediments, resulting in a higher $\delta^{13}\text{C}$ value of the weathering flux. Therefore, the application of the carbon isotope mass balance model with the above assumptions may be misleading to describe carbon cycling at low atmospheric O_2 conditions, such as those that prevailed during the Precambrian (Bekker and Holland 2012; Daines et al. 2017). In contrast, these considerations ultimately suggest an operation of the biogeochemical carbon cycle at much lower gross primary productivity levels, consistent with independent evidence from multiple oxygen isotope composition of terrestrial and marine sulfates (Crockford et al. 2018).

The isotope composition of all biogenic carbon is depleted in ^{13}C relative to that of inorganic carbon or mantle carbon (Fig. 3). However, the

low $\delta^{13}\text{C}$ values should not be used as unequivocal evidence for biological origin. Primitive meteorites and interstellar dust particles contain organic matter with the lowest $\delta^{13}\text{C}$ values reaching -34.2% in chondrites (considered to be geochemically similar to the bulk Earth) and -15% in CI carbonaceous chondrites (taken to be the most primitive meteorites) (Marty et al. 2013). These values are thought to have been derived from abiogenic exchange reactions in the presolar molecular cloud and the protoplanetary nebula. In addition, various hydrothermal reactions are known to produce reduced carbon with carbon isotope ratios comparable to biogenic organic carbon (e.g., Horita and Berndt 1999; Sherwood Lollar et al. 2006). These reactions include metal-catalyzed Fischer-Tropsch synthesis in high temperature and pressure environments, metamorphic heating of carbonate- or graphite-bearing rocks, and the serpentinization reactions within ultramafic rocks. To establish biogenic origin, carbon isotope values of reduced carbon should be interpreted within its geological framework, such as environmental conditions at the time when it formed, and along with the constrained impact of biogenic activity on the local environment.

Future Directions

Future planetary missions and probes will provide carbon isotope measurements and bring rock samples from planets and asteroids back to Earth. New data will greatly improve our understanding of the processes responsible for the distribution of carbon isotopes in our Solar System, and carbon isotope determinations on minerals, bulk rocks, atmospheric gases, and organic compounds will provide key parameters for the continuing search for extraterrestrial life.

Cross-References

- Abundances of Elements
- Biogeochemical Cycles
- Carbon Cycle, Biological

- Great Oxidation Event
- Lomagundi Carbon Isotope Excursion
- Oxygenation of the Earth's Atmosphere

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Carbon Monosulfide (CS)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

CS

Definition

The diatomic molecule carbon monosulfide, CS, is widespread in interstellar and circumstellar ► [molecular clouds](#), in our ► [Milky Way](#) and in external galaxies. Its emission at millimeter

wavelengths is frequently used to estimate the density in these regions, since these pure rotational transitions require densities greater than about 10^5 molecules per cubic centimeter to be excited by collisions. Various isotopic variants have been observed astronomically, including those with ^{13}C , ^{34}S , and ^{33}S , as well as the most abundant $^{12}\text{C}^{32}\text{S}$. CS is also observed in cometary comae.

History

Interstellar CS was first detected by radio astronomers in 1971.

Cross-References

- [Comet](#)
- [Milky Way](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Sulfur](#)

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Carbon Monoxide

Thomas McCollom
Laboratory for Atmospheric and Space Physics,
University of Colorado, Boulder, CO, USA

Synonyms

[CO](#)

Definition

Carbon monoxide is a diatomic compound with the chemical composition CO. At terrestrial atmospheric pressure, the melting point of pure

carbon monoxide is $-205\text{ }^{\circ}\text{C}$ and the boiling point is $-191.5\text{ }^{\circ}\text{C}$.

Overview

Carbon monoxide is not known to occur as a pure substance in most planetary environments, but instead occurs primarily as a minor component in gas and ice mixtures. Carbon monoxide is the most abundant constituent after molecular hydrogen in interstellar space (see ► [Molecules in Space](#)), and spectroscopic observations indicate it composes several percent of the icy component of ► [comets](#) (which is predominantly water ice). These observations indicate carbon monoxide was a significant reservoir of carbon during formation of the solar system. In planetary bodies, carbon monoxide primarily occurs as a trace component in atmospheres (~ 0.1 parts per million on the present Earth) and in volcanic gases.

Transformations between carbon monoxide and ► [carbon dioxide](#) (CO_2) proceed fairly readily through photochemical reactions in planetary atmospheres and through mechanisms such as the so-called water-gas shift reaction in geologic environments ($\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$). The latter is an oxidation-reduction reaction, and at the prevailing oxidation state of the Earth's interior, carbon dioxide is strongly favored by chemical thermodynamics relative to carbon monoxide. Consequently, $\text{CO}_2\text{:CO}$ ratios in volcanic gases on Earth are typically in a range of $10^3\text{--}10^5$. Carbon monoxide may also be generated from dehydration of ► [formic acid](#) and vice versa ($\text{HCOOH} \leftrightarrow \text{CO} + \text{H}_2\text{O}$).

Carbon monoxide readily forms complexes with transition metals, such as iron carbonyl [$\text{Fe}(\text{CO})_5$] (carbonyl is the name given to the CO radical). Formation of carbonyls from carbon monoxide can also occur on the surface of transition metal-bearing minerals and alloys. Carbonyls are highly reactive, and carbonyls derived from carbon monoxide have been hypothesized to be a key reactant for the in situ formation of prebiotic organic compounds in several scenarios for the ► [origin of life](#) (e.g., Huber and Wächtershäuser 1997). One such reaction that is frequently

invoked for the formation of organic matter in the early solar system is Fischer-Tropsch synthesis, a surface-catalyzed process for conversion of gaseous mixtures of CO and H₂ to hydrocarbons and other functionalized organic compounds such as fatty acids. Potential environments for the surface-catalyzed conversion of carbon monoxide to prebiotic organic compounds by the Fischer-Tropsch synthesis or other processes include dust grains in the early solar system, volcanic fumaroles, and hydrothermal systems.

Cross-References

- [Carbon Dioxide](#)
- [Comet](#)
- [Fischer-Tropsch-Type Reaction](#)
- [Formic Acid](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Origin of Life](#)
- [Prebiotic Chemistry](#)

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Carbon Nitride

- [Cyanogen](#)

Carbon Source

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Carbon source refers to any carbon-containing molecule (carbohydrate, amino acid, fatty acid, CO₂)

used by an organism for the synthesis of its organic molecules. Carbon is a basic element for sustaining life as we know it and the main element in all classes of macromolecules. All cells require carbon as a major nutrient. On a dry weight basis, a typical cell is 50% carbon. Depending on their carbon source, organisms are either heterotrophs, requiring one or more organic compounds as their carbon source, or autotrophs, where CO₂ is the carbon source.

Cross-References

- [Biosynthesis](#)
- [Carbon Cycle, Biological](#)
- [Carbon Dioxide](#)
- [Chemotroph](#)
- [Macronutrient](#)
- [Metabolism](#)
- [Phototroph](#)

Carbonaceous Chondrite

Tilman Spohn¹ and Frank Sohl²

¹International Space Science Institute, Bern, Switzerland

²Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

Synonyms

[Carbonaceous meteorite](#); [CC](#)

Definition

Carbonaceous chondrites constitute a subcategory of ► [chondrites](#) – which in turn are stony ► [meteorites](#). Carbonaceous chondrites are the most primitive meteorites identified thus far and are mostly regarded as remnants of the first solid bodies to accrete in the ► [solar nebula](#). The main components of carbonaceous chondrites are ► [chondrules](#) and ► [CAIs](#) (Ca-Al-rich inclusions), which are embedded in a matrix of micrometer-sized dust

particles. Since carbonaceous chondrites contain the highest concentration of volatile elements and molecules (e.g., ► [organic refractory matter](#)) of the chondrites, they are thought to have formed at the lowest temperatures. Their chemical composition is very similar to that of the Sun (albeit depleted in ► [hydrogen](#) and helium), and thus they can be considered (apart from ► [comets](#)) to be the most primitive material present in our ► [solar system](#).

Cross-References

- [CAIs](#)
- [Chondrite](#)
- [Chondrule](#)
- [Comet](#)
- [Meteorites](#)
- [Solar Nebula](#)
- [System Solar Formation, Chronology of](#)

Carbonaceous Chondrites, Organic Chemistry of

Conel Michael O'Donel Alexander¹ and Sandra Pizzarello²

¹Earth and Planets Laboratory, Carnegie Institution for Science, Washington, DC, USA

²Department of Chemistry & Biochemistry, Arizona State University, Tempe, AZ, USA

Keywords

Amino acids · Asteroids · Carbonaceous · Chondrites · Comets · Enantiomeric excess · Interplanetary dust particles · Interstellar medium · Isotope anomalies · Meteorites · Molecular cloud · Nucleic acids · Organic matter · Protoplanetary disk

Definition

Carbonaceous Chondrites (CCs) are stony fragments of primitive asteroids that never became

hot enough to melt and differentiate. As such, they preserve with varying degrees of fidelity a record of the dust present in the solar protoplanetary disk when and where they formed. CCs have varying but near solar nonvolatile chemical compositions and contain carbon in the range 0–4 weight percent (wt. %) as well as water/OH (0–13 wt.% in hydrated minerals) and all other biogenic elements (e.g., nitrogen, phosphorous, sulfur). Most of the CC carbon is in organic materials that include both kerogen-like insoluble macromolecular materials and soluble organic compounds, such as amino acids. The macromolecular materials dominate, but the relative proportions of the organic components change within and between groups. Meteorites are generally categorized as falls or finds depending on whether their falls to Earth were observed or not. Falls are more desirable for organic analyses since they have been less exposed to terrestrial contamination. Nevertheless, both Japanese and American institutions have established programs that search for meteorite finds in Antarctica because the cold temperatures and their storage in the ice means that they can remain relatively pristine for long periods of time. Based on their physical, chemical, and isotopic properties, the CCs have, so far, been subdivided into eight recognized groups: CI, CM, CR, CK, CH, CB, CO, and CV, where the second letter generally refers to the type meteorite for a group (Ivuna, Mighei, Renazzo, Karoonda, High metal, Bencubbin, Ornans, and Vigarano, respectively). The separate groups are probably fragments from different parent asteroids. Some CCs, such as the recent falls Tagish Lake and Sutters' Mill, have features that are distinct from any of these groups, are simply classified as C ungrouped, and probably come from less well sampled asteroids.

Overview

The CCs are stony meteorites whose bulk non-volatile elemental compositions are to varying degrees similar to that of the Sun. All the CCs experienced at least some degree of aqueous

alteration and/or thermal metamorphism in their parent asteroids that modified or even destroyed the organic materials they originally contained. The least heated CCs contain abundant carbon (~1–4 wt.%, depending on the group) that is mostly in organic materials. This organic material, which is classified procedurally as either solvent soluble organic material (SOM) or insoluble organic material (IOM), provides a record of organic chemistry in the early Solar System at about the time the Earth was forming and before the inception of terrestrial life (Alexander et al. 2017; Glavin et al. 2018).

High-resolution mass spectroscopy indicates that some CCs contain at least tens of thousands of individual soluble compounds, and those identified to date include: water-soluble carboxylic-, dicarboxylic-, amino-, hydroxy-, keto-, and pyridine carboxylic-acids; sugar alcohols and acids, aldehydes and ketones; amines and amides; purine bases and pyrimidine bases; and solvents-soluble aliphatic, aromatic, and heteroatom containing hydrocarbons. Many CC compounds have counterparts in the biosphere, for example, 12 detected amino acids are also found in terrestrial proteins: *glycine*, *alanine*, *proline*, *valine*, *leucine*, *isoleucine*, *serine*, *threonine*, *tyrosine*, *phenylalanine*, *aspartic-*, and *glutamic acids*.

Another similarity between terrestrial and meteoritic amino acids is their chirality and the occurrence in some of L-enantiomeric excesses (Glavin et al. 2020). To date, this chiral asymmetry has only been found in a few CC amino acids, is not constant even for the same amino acid in different members of the same group, and is of unknown origin. Nevertheless, it shows the presence in abiotic environments of possible chiral influences and enhances the astrobiological significance of meteoritic compounds. Contrary to the compositional selectivity and homochirality of biomolecules, however, most meteoritic compounds do not show chiral preferences and are found with almost complete structural diversity for a given carbon number, for example, close to 100 amino acids have been identified to date in meteorites compared to the 23 that are the

constituents of terrestrial proteins (Pizzarello and Shock 2010).

The IOM is in bulk a structurally complex, macromolecular material with an elemental composition in the least heated samples of $\sim\text{C}_{100}\text{H}_{79}\text{N}_4\text{O}_{15}\text{S}_3$, which is similar to the averages of the refractory organic materials in the dust from comets Halley and 67P/Churyumov-Gerasimenko (Alexander et al. 2017; Isnard et al. 2019). Degradative, pyrolytic, and spectroscopic studies all point to the IOM being composed of small aromatic units that are linked by short, highly branched aliphatic chains. In situ observations show that the IOM is dispersed in chondrite matrices as chemically and isotopically diverse particles that are typically $<1\text{ }\mu\text{m}$ across. There are no apparent physical/spatial associations between the IOM particles and any minerals that could, for instance, have played a role in their formation.

Although the origins of the CC soluble and insoluble materials have yet to be established, both are likely to be the products of long cosmic histories. Their isotopic compositions show enrichments in ^2H (deuterium) and ^{15}N that point to the synthesis of the organic materials or their precursors in very cold, radiation-rich environments such as would have been found in the protosolar molecular cloud and the outer solar protoplanetary disk. Once in the CC asteroidal parent bodies, internal heating by the decay of short-lived radionuclides and impacts drove the melting of ices and alteration processes akin to low-temperature serpentinization on Earth. While not well understood, the presence of aqueous fluids almost certainly resulted in the modification of the original soluble organic inventories (e.g., formation of amino acids by Strecker synthesis and Michael addition). Experiments and observations from meteorites indicate that the IOM would also have been chemically and isotopically modified during this period of aqueous activity, including the release of water- and solvents-soluble compounds (e.g., Yabuta et al. 2007). In many CCs, further heating led to their progressive dehydration, recrystallization, and destruction of their organic materials.

Cross-References

- [Aliphatic Hydrocarbon](#)
- [Amino Acid](#)
- [Aromatic Hydrocarbon](#)
- [Asteroid](#)
- [Comet \(Nucleus\)](#)
- [Enantiomeric Excess](#)
- [Globule, Nanoglobule](#)
- [Interplanetary Dust Particle](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Meteorite, Murchison](#)
- [Meteorites](#)
- [Protoplanetary Disk](#)
- [Racemization](#)
- [Serpentinization](#)

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Carbonaceous Meteorite

- [Carbonaceous Chondrite](#)
- [Meteorite, Murchison](#)

Carbonate Lake

- [Soda Lake](#)

Carbonate on Mars

Nicholas Arndt

Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Synonyms

[Calcareous sediment](#); [Limestone](#)

Definition

The term carbonate refers either to a mineral or to a rock. Examples of carbonate minerals are:

1. Calcite (CaCO_3) and dolomite ($\text{MgCa}(\text{CO}_3)_2$), which are common constituents of limestones and other calcareous sediments
2. Siderite (FeCO_3), which also occurs in ► [sedimentary rocks](#)
3. Magnesite (MgCO_3), an alteration product of ultramafic rock
4. Malachite $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$, smithsonite (ZnCO_3), rhodocrosite (MnCO_3), withérite (BaCO_3), and cerussite (PbCO_3), which result from surficial alteration of metallic ore deposits.

The term “carbonate” is also applied to sediments or ► [sedimentary rocks](#) such as limestones or dolostones that are composed predominantly of carbonate minerals. In the Precambrian, particularly the Proterozoic, carbonate minerals precipitated on microbial mats by their photosynthetic activity and resulting alkalinity of the surface are common. Most

Phanerozoic carbonates are composed to a large degree of the shells, tests, and spicules or their fragments of marine organisms, cemented by secondary carbonates. Rarely, carbonates precipitate chemically directly from sea- or lake water. Dolomite, a widespread carbonate, has variable origins, but its precipitation is also known to be biologically mediated. Carbonate sediments are rare in Archean sequences but common as cements. Recent studies on Mars dust, performed by Martian rovers, showed that the dominant carbonate mineral is magnesite; which may provide evidence for the presence of water at the surface early in the history of [▶ Mars](#).

Cross-References

- ▶ [Mars](#)
- ▶ [Sedimentary Rock](#)

Carbonate, Extraterrestrial

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Definition

The term carbonate can either refer to carbonate minerals, which contain the carbonate ion CO_3^{2-} , or to carbonate rocks, which contain carbonate minerals. On Earth, the vast majority of carbonate rocks are of sedimentary origin, while igneous carbonates (carbonatites) are extremely rare. Furthermore, the formation of carbonate minerals on Earth generally takes place within an aqueous solution, either through abiotic precipitation or biomineralization. Hence, the presence of carbonates on other planets (especially Mars) is viewed as an indicator for the former presence of liquid water. Extraterrestrial carbonates have been identified in a wide range of localities on Mars as well as in several Martian meteorites. They include magnesium carbonate detections in the Nili Fossae region, carbonates intermixed with iron/magnesium-smectites (phyllosilicates) in the Libya Montes

region, magnesium-rich carbonates at Gusev crater, and calcium-/iron-rich carbonates at various spots in Tyrrenia Terra. The spectral signatures share similarities with carbonaceous chondrites.

Cross-References

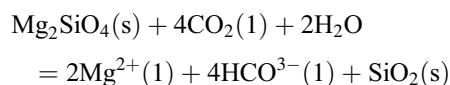
- ▶ [Mars](#)
- ▶ [Mineral](#)
- ▶ [Phyllosilicates, Extraterrestrial](#)
- ▶ [Sulfates, Extraterrestrial](#)

Carbonation

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale
Supérieure de Lyon, Lyon Cedex 7, France

Definition

A *carbonation* reaction describes the breakdown of silicates by dissolved carbon dioxide. For example, the reaction of olivine carbonation reads



Carbonation enhances the drawdown of volcanic CO_2 by [▶ weathering](#); it thus limits the partial pressure P_{CO_2} and therefore the greenhouse effect. In addition, the alkalinity liberated in the reaction (HCO_3^-) keeps the pH of the ocean high enough for the carbonate ion to be abundant and enhances the precipitation of calcium carbonates.

Cross-References

- ▶ [Weathering](#)

Carbonization

- ▶ [Pyrolysis](#)

Carbonyl

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

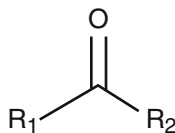
Definition

In organic chemistry, a carbonyl is a functional group consisting of a carbon atom doubly bonded to an oxygen atom (Fig. 1). Some examples of carbonyl-group-containing compounds include carboxylic acids and their derivatives (e.g., amides, esters, and anhydrides), aldehydes, and ketones. The term carbonyl can also refer to a ligand in an organometallic complex (e.g., iron pentacarbonyl, $\text{Fe}(\text{CO})_5$).

Since oxygen is more electronegative than carbon, the oxygen atom in a carbonyl group pulls electron density toward itself and away from carbon, making the bond polar. The carbonyl carbon thus tends to be electrophilic and more reactive with nucleophiles. The electronegative oxygen can react with an electrophile.

Protons bonded to carbon atoms alpha to a carbonyl group are often considerably more acidic (by $<3pK_a$ units) than typical aliphatic C-H bonded protons. The carbonyl group is in tautomeric equilibrium with an enol configuration. Deprotonation of this enol produces an enolate anion, which is nucleophilic, and can alkylate electrophiles such as other carbonyls.

Carbonyl, Fig. 1 General Structure of Carbonyl Compounds



Cross-References

► [Aldehyde](#)

Carbonyldiamide

► [Urea](#)

3-(6-Carboxy-3,4-dihydroxy-5-phosphanyloxan-2-yl)oxy-4,5-dihydroxy-6-phosphanyloxyoxane-2-carboxylic Acid (IUPAC)

► [Alginate](#)

Carboxylic Acid

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Meguro-ku, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry, carboxylic acids are organic acids that contain a carboxyl functional group. The general formula of a carboxylic acid is R-COOH . Carboxylic acids are proton donors. Some common examples are ► [formic acid](#), H-COOH , and ► [acetic acid](#), CH_3COOH . There are many carboxylic acids of biological importance, for example, fatty acid esters are important components of many cell membranes, proteins are polymers of amino acids, and many compounds in intermediary metabolism are carboxylic acids. Common prebiotic syntheses of carboxylic acids proceed via the hydrolysis of precursor nitriles.

Because they are both hydrogen-bond acceptors and hydrogen-bond donors, they are able to participate in hydrogen bonding. Carboxylic acids tend to have higher boiling points than water, partly because of their tendency to form hydrogen-bonded dimers. Carboxylic acids are polar: short-chain aliphatic carboxylic acids (e.g., those containing one to five carbon atoms) are soluble in water, whereas higher carboxylic acids are less soluble due to the increasingly hydrophobic nature of their aliphatic components.

Carboxylic acids form various derivatives in combination with other functional group-containing compounds, for example, esters in combination with alcohols, amides in combination with amines, and anhydrides in combination with another carboxylic acid.

Cross-References

- [Acetic Acid](#)
- [Amide](#)
- [Ester](#)
- [Formic Acid](#)
- [Nitrile](#)

Carboxylic Acids, Geological Record of

Ross H. Williams
CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology/
University of Maryland, College Park, MD, USA
NASA Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, MD, USA

Keywords

Carbonyl · Fatty acids · Hydroxyl · Organic acid · Carboxyl · Lipids

Synonyms

[Fatty acids](#)

Definition

► [Carboxylic acids](#) are a class of organic compounds that contain one or more carboxyl groups per molecule. Each carboxyl group, which is a combination of ► [carbonyl](#) and hydroxyl groups, has the formula -C(=O)OH (or -COOH). Carboxylic acids are polar and proton donors. Carboxylic acids are widespread in nature, often combined with other functional groups, and ubiquitous in biology, recent sediments, and carbonaceous meteorites. As they degrade during diagenesis and thermal maturation in the rock record, they generally transform into esters, carboxylates (i.e., hydroxyl group replaced with salts or anions), and, eventually, alkanes.

Overview

Carboxyl groups are polar. The carbonyl group is a hydrogen-bond acceptor, and the hydroxyl group is a hydrogen-bond donor. Consequently, carboxylic acids participate in hydrogen bonding, particularly with each other and with minerals such as phyllosilicates, oxyhydroxides, and other oxides. In addition, the “self-association” of carboxylic acids that results from hydrogen bonding generates stabilized dimeric pairs in nonpolar media. The dimers have decreased volatility. The bonds must be broken chemically or thermally for the carboxyl group to be reactive to other geochemicals. The stabilization of dimers and the nonreactive nature of the alkyl side chain (or other carbon skeleton) contribute to the refractory nature of carboxylic acids during diagenesis compared to more polar organic molecules.

Carboxylic acids having more than five carbons in an alkyl chain are not soluble in water unless at high temperatures and exhibit both hydrophilic (carboxyl) and hydrophobic (alkyl) regions in the same molecule. The amphiphilic nature of these molecules leads to the formation of nonbiological monolayers on the water and mineral surfaces or micelles, sphere-shaped clusters, in solution. Biology takes advantage of the amphiphilic nature of carboxylic acids to form fatty acid lipid bilayers of

cellular ► [membranes](#). Formation of nonbiological monolayers was likely critical for the formation of the earliest cellular life.

Carboxylic acids are weak acids that only partially dissociate into H⁺ cations and RCOO⁻ anions in pH neutral aqueous solution. In the presence of a base, carboxylic acids become carboxylates. These moieties are important in geological and biogeochemical processes because they can be siderophores, chelating with metals, such as ferric iron.

The carbon atom of a carboxyl group is in a relatively high ► [oxidation](#) state and can be partially reduced by sulfur or other organic molecules during diagenesis under reducing conditions. ► [Oxidation](#) of the carboxyl carbon commonly occurs in oxidizing environments to form carbon dioxide (decarboxylation reaction). Depending on the geochemical or biological reaction, the alkyl side chain may end up reduced to an alkane or oxidized, often with the addition of an anion or salt. In both cases, decarboxylation results in the loss of a carbon from the carbon skeleton, and the product can then be preserved in the rock record. Consequently, a series of carboxylic acids preserved in a geological record is often associated with a corresponding series of alkanes with one less carbon.

Cross-References

- [Acid Hydrolysis](#)
- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Carbonyl](#)
- [Carboxylic Acid](#)
- [Cell Wall](#)
- [Complex Organic Molecules](#)
- [Fatty Acids, Geological Record of](#)
- [Kerogen](#)
- [Membrane](#)
- [Oxidation](#)

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Carboxysomes, Structure and Function

Jeffrey Blanchard¹ and Farah Abdul-Rahman²

¹Biology Department, University of Massachusetts Amherst, Amherst, MA, USA

²University of Massachusetts Amherst, Amherst, MA, USA

Keywords

Carbon dioxide · Calvin Cycle · Ribulose-1,5-bisphosphate carboxylase/oxygenase

Synonyms

[Bacterial microcompartments](#); [Carbon concentrating mechanisms](#); [Polyhedral bodies](#)

Definition

Carboxysomes are intracellular proteinaceous compartments found in cyanobacteria and some ► [chemoautotrophs](#) that encapsulate the enzymes carbonic anhydrase and ribulose-1,5-bisphosphate carboxylase/oxygenase (► [RuBisCO](#)). The function of the carboxysome is to concentrate CO₂ with close proximity to RuBisCO, eliminating the competitive reaction with oxygen. Thus, carboxysomes are the site of carbon dioxide (CO₂) fixation.

History

In 1956 the first carboxysomes (then termed polyhedral bodies) were visualized in a cyanobacterium

(Drews and Niklowitz 1956). Following the discovery of similar structures in several other cyanobacteria and chemoautotrophs, carboxysomes were purified in 1973 and shown to contain the enzyme, ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) (Shively et al. 1973). Because RuBisCO plays a central role in carbon fixation, they were given the name carboxysomes.

Overview

Carboxysomes are intracellular organelles composed of a proteinaceous shell that encapsulates the enzyme carbonic anhydrase and ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) (Cameron et al. 2013). Unlike other types of organelles, no lipids are associated with carboxysomes. Carboxysomes are icosahedral in shape, akin to bacterial phages and capsid viruses. However, there is no other evidence of an evolutionary connection between carboxysomes and any known viruses.

X-ray crystallography of individual shell proteins revealed hexamers as the basic micro-compartment shell structure building block and showed how these hexamers assemble to form the walls of polyhedral shell (Kerfeld et al. 2005). Subsequent structural studies determined that another universally conserved shell protein forms pentameric structures that are located in the vertices of the icosahedra (Tanaka et al. 2008). These structural studies have led to beautiful structural models of carboxysomes that suggest mechanisms for the passage of molecules through the pores formed by hexameric and pentameric structures (Yeates et al. 2008).

Carboxysomes fall under the broader class of structures, the bacterial microcompartments, which encompasses several functional types. Bacterial microcompartments share evolutionarily related shell proteins which encapsulate different enzymes. Other types of bacterial microcompartments have been shown to utilize 1,2-propanediol, ethanolamine, and choline (Abdul-Rahman et al. 2013).

Carboxysomes are the site of carbon dioxide (CO₂) fixation. Bicarbonate (HCO₃[−]) is

transported into the shell through nanopores, where the shell-associated enzyme, carbonic anhydrase, converts HCO₃[−] to CO₂. RuBisCO packed inside the carboxysome converts the substrates CO₂ and ribulose-1,5-bisphosphate into two 3-phospho-D-glycerate (3-PG) molecules. 3-PG then exits the carboxysome and can be used as a metabolic intermediate in the Calvin-Benson-Bassham cycle.

RuBisCO has low affinity for CO₂ and is capable of binding O₂. The oxygenation of ribulose-1,5-bisphosphate produces phosphoglycolate which can accumulate to toxic levels and inhibit photosynthesis (Yeates et al. 2008). Thus, the shell serves to both concentrate CO₂ around RuBisCO and block oxygen from enzymatically competing with CO₂.

Two types of carboxysomes have been characterized, the α - and β - carboxysomes, named for the form of RuBisCO they encapsulate. The β -carboxysome is found exclusively in cyanobacteria, while the α -carboxysome is found in marine cyanobacteria as well as in some autotrophic [proteobacteria](#). The carboxysome's presence in all cyanobacteria, with the exception of *Cyanobacterium UCYN-A* which lacks genes for carboxysomes and the Calvin cycle (Tripp et al. 2009), indicates it is an essential structure for CO₂ fixation in the phylum.

The great oxidation event (~2.4 billion years ago) altered the atmosphere with the appearance of free atmospheric oxygen and is attributed to the emergence of photosynthetic cyanobacteria that release oxygen as a by-product (Session et al. 2009). Cyanobacterial mutants that lack one or more shell proteins cannot survive under normal atmospheric CO₂ levels and can only grow in high (5%) CO₂ (Ogawa et al. 1994). The ability of cyanobacteria to grow without carboxysome shells at higher CO₂ concentrations suggests that these structures would not be required if the atmosphere's current makeup had higher CO₂ levels.

Cross-References

► [Oxygenation of the Earth's Atmosphere](#)

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CASA*, Poland

Franco Ferrari and Ewa Szuszkiewicz
CASA*, Faculty of Mathematics and Physics,
University of Szczecin, Szczecin, Poland

Synonyms

[Centre for Advanced Studies in Astrobiology and Related Topics \(CASA*\)](#)

Definition

The center is structured as a consortium of laboratories based in Poland and coordinated by CASA*. The consortium consists of five founding institutions. Three institutions are in Warsaw: the Space Research Centre, the Nicolaus Copernicus Astronomical Centre, and the Institute of Paleobiology of the Polish Academy of Sciences. The fourth institution is the Nicolaus Copernicus University in Toruń. Finally, the headquarters of CASA* are at the University of Szczecin.

The scopes of CASA* are:

1. To stimulate and promote the research in astrobiology and related topics in Poland
2. To conduct and coordinate interdisciplinary research projects at the Polish level
3. To promote the cooperation of Polish groups working in astrobiology with the other countries of the European Union and in particular to establish a Polish contact point with the *European Space Agency* (ESA) and the *European Astrobiology Network Association* (EANA), which is the main reference for astrobiologists in the European Union
4. To establish a center of excellence in astrobiology research and related topics in Central Europe
5. To start courses in astrobiology in Poland

The research carried out by the teams participating in CASA* covers most of the disciplines of astrobiology including astronomy, astrophysics, astrochemistry, physics, genetics, space medicine, ► [radiation biology](#), microbiology, biogeology, biosedimentology, and ► [geomicrobiology](#). CASA* makes available for its members computing facilities and the structures of the Laboratory for Polymer Research of the University of Szczecin. CASA* is participating in EANA and in the Committee on Space Research of the Polish Academy of Sciences. The center has also representatives in several COST Actions of the European Union and in a number of international projects.

History

Originally CASA* has been founded in 2003 as a virtual center (Szuszkiewicz 2004). It is organized as a consortium since 2007.

The members of CASA* have been active in organizing courses and conferences for students and young researchers in Poland and have participated in the activities of the Astrobiology Lecture Course Network (ABC-Net) supported by ESA. The teaching activity has resulted in the publication of the first book in astrobiology written in Polish entitled *Astrobiology: From cosmic dust to DNA*, published by the Szczecin University Press (Ferrari and Szuszkiewicz 2006).

Cross-References

- EANA
- ESA
- Geomicrobiology
- Radiation Biology

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Cassini

Therese Encrenaz
Observatoire de Paris – Section de Meudon,
LESIA, Meudon, France

Definition

Giovanni Domenico Cassini (or Jean-Dominique Cassini) (1625–1712) was born in Perinaldo, near

Naples, and was Professor at Bologna. In 1669, he became a member of the French Académie des Sciences, and in 1671, he became the first Director of the Observatoire de Paris, from which the Paris Meridian was defined. Its first scientific aims were metrology, celestial mechanics, and positional astrometry. Cassini made important discoveries regarding solar-system objects: determination of Mars' rotation, Jupiter's rotation, Jupiter's satellites' revolutions, identification of several of Saturn's satellites (Iapetus, Rhea, Thetys, and Dione), as well as the Cassini Division within Saturn's rings. Cassini also recorded observations of the ► [zodiacal light](#). The Cassini space mission, launched in 1997 and in operation in the ► [Saturn](#) system between 2005 and 2017, was named after him.

Cross-References

- Planetary Rings
- Saturn

Cassini Division

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

The Cassini Division is a gap between the A and B rings of ► [Saturn](#). It was first identified by Giovanni Domenico ► [Cassini](#) in 1675 and can be observed with a small telescope. It extends between 117,500 and 122,000 km from the center of Saturn. Observations by the Cassini orbiter have shown that the Cassini division is not devoid of matter, as previously thought, but it consists of a region where the density of particles is lower than that in the main rings themselves. The existence of the Cassini division is probably due to a gravitational interaction with ► [Mimas](#), as the Cassini division is in resonance with the orbit of this satellite. There are other divisions in Saturn rings (Encke division, Keeler division).

Cross-References

- [Mimas](#)
- [Planetary Rings](#)
- [Saturn](#)

Cassini Mission

- [Cassini-Huygens Space Mission](#)

Cassini Spacecraft

- [Cassini-Huygens Space Mission](#)

Cassini State

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

When an orbiting body is affected by tides, its spin axis, spin rate, and orbital plane can reach an equilibrium state in which obliquities (tilts) are nonzero. Cassini states are observed in the Earth-Moon system, Triton-Neptune system, and possibly, Europa-Jupiter system. In these cases, the satellite's obliquity is locked at a small nonzero value, but in general, with large inclinations, the obliquity could be large.

Cross-References

- [Tides, Planetary](#)

Cassini Titan's Probe

- [Huygens Probe](#)

Cassini, Giovanni Domenico

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Cassini, Giovanni Domenico [Jean-Dominique] (1625–1712) was an Italian astronomer born in Perinaldo in June 8, 1625. In 1669, Cassini set out for Paris (in 1673, became a naturalized Frenchman) where he will be appointed the first director of the Observatory of Paris, starting that way a family dynasty of prominent astronomers in prerevolutionary France. His astronomical works ranged from studies of comets (that he considered analogous to planets but traveling in paths of greater eccentricity) to the movements of Jupiter's moons and Saturn's satellites and ring. Cassini found the Saturnian satellites, Iapetus (1671), Rhea (1672), and Tethys and Dione (1684) and noted the division of the rings of Saturn.

In 1997 in a joint effort between NASA, ESA, and ASI, the Cassini Mission was launched to study the structure and physical properties and dynamics of Saturn and its satellites, mainly Titan.

Cassini-Huygens Space Mission

Athena Coustenis
Laboratoire d'Etudes Spatiales et
d'Instrumentation en Astrophysique (LESIA),
Observatoire de Paris, CNRS, UPMC Univ. Paris
06, Univ. Paris-Diderot, Meudon Cedex, France

Keywords

Cassini-Huygens · Cassini orbiter · Huygens probe · Kronian satellites · Rings · Saturn · Titan · Enceladus

Synonyms

Cassini mission; Cassini spacecraft; Huygens probe

Definition

Cassini-Huygens is a large ► NASA-ESA- ► ASI mission, composed of the ► Saturn orbiter (► Cassini) and the ► Titan lander (► Huygens). Cassini-Huygens reached Saturn in 2004 after a trip that lasted about 7.5 years and has since then been investigating the Saturnian environment, carrying out the first detailed survey of the ► planet, its rings, and the 62 currently known satellites, with a focus on ► Titan. The Cassini instruments have returned a great amount of data that have revolutionized our view of the Saturnian system. The orbiter is foreseen to remain operational until 2017.

History

An ambitious and international mission to explore the Saturnian system was initially proposed to the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) in 1982 by a team of European and US scientists. After extensive discussions between ESA and NASA, the initial concepts eventually evolved by 1989 into Cassini-Huygens, a mission composed of an American orbiter and a European descent probe. This made it the first truly international planetary mission, in addition to its other unique features. The Italian Space Agency (ASI) is responsible for the spacecraft's radio antenna and portions of three scientific instruments. Cassini-Huygens arrived in the Saturnian system in July 2004. The Huygens probe executed its mission in January 2005. After two extensions, the Cassini orbiter continues its exploration of the Saturnian system until 2017. For a thorough overview of the mission and its objectives, see "The Cassini-Huygens Mission" (Russell 2004).

Overview

Trajectory and Operations

The Cassini-Huygens mission is a fruitful collaboration between ESA, NASA, and ASI which has been investigating the Saturnian system since 2004, bringing spectacular new insights on the primary planet, its rings, and the exchanges within the system and within the Solar System. Particular attention was devoted to the natural satellites, of which Titan, the largest moon, is a special target. The mission has thus been instrumental in enhancing our understanding of the environment around Saturn, in particular as to the habitability potential in bodies around giant planets.

The Cassini-Huygens spacecraft consists of two main elements: the NASA Cassini orbiter, named after the Italian-French astronomer Giovanni Domenico Cassini, who gave his name to the ► Cassini Division in the rings and discovered several of Saturn's major satellites, and the ESA-provided Huygens probe, named after the Dutch astronomer, mathematician, and physicist Christian Huygens, who discovered Titan in 1655. The Cassini-Huygens mission was launched on October 15, 1997, on a Titan IV-Centaur rocket from Cape Canaveral and performed flybys of ► Venus, ► Earth, and ► Jupiter before entering into orbit around Saturn on July 1, 2004 (Fig. 1).

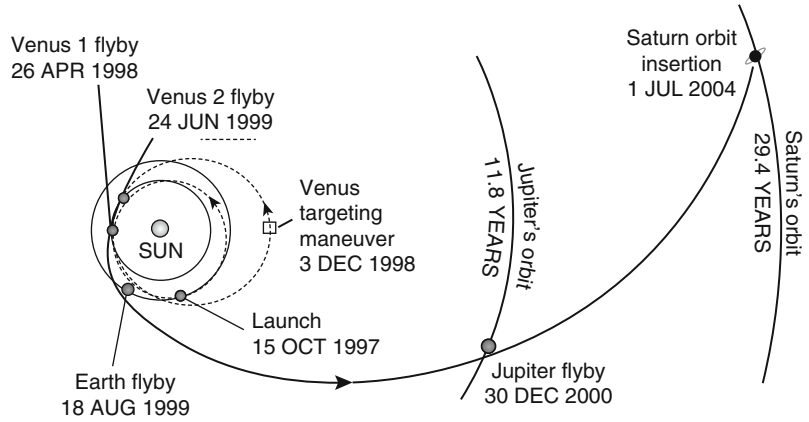
One particular target of Cassini-Huygens was Titan, also visited in situ by the ► Huygens probe: on December 25, 2004, the Huygens probe separated from the orbiter and reached Titan on January 14, 2005, when it descended through the atmosphere, landed on the moon's surface, and relayed scientific information for a total of more than 5 h (Lebreton et al. 2008). Mission control activities for Cassini are conducted from the Space Flight Operations Facility at the Jet Propulsion Laboratory (► JPL), where the project is headquartered.

The Spacecraft and Its Payload

The spacecraft, including the orbiter and the probe, is the largest and most complex interplanetary spacecraft built to date. The orbiter

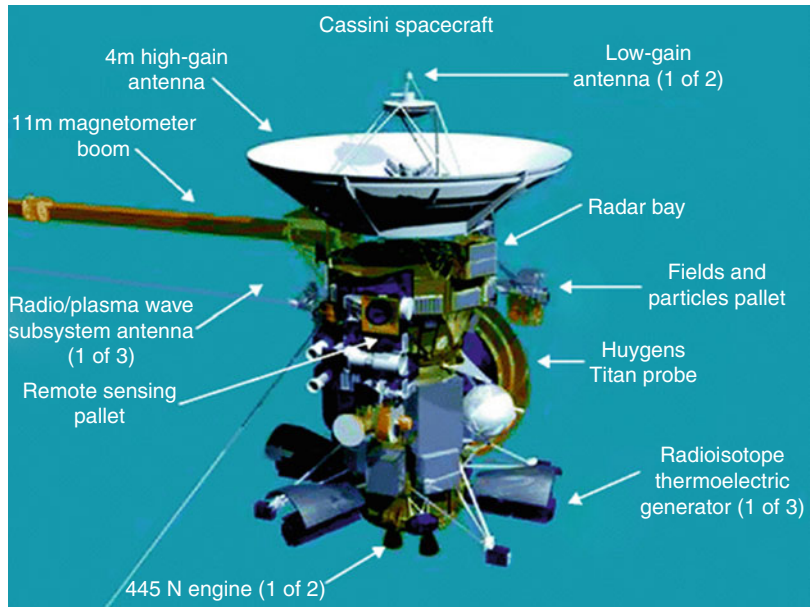
Cassini-Huygens Space

Mission, Fig. 1 The trajectory of the Cassini-Huygens mission from launch to Saturn orbit insertion



Cassini-Huygens Space

Mission, Fig. 2 Diagram of the Cassini spacecraft carrying the Huygens probe



has a mass of 2,150 kg (plus fuel), and the probe has a mass of 350 kg. The Cassini spacecraft is more than 6.8 m high and more than 4 m wide (Fig. 2). The complexity and mass of the spacecraft is warranted by the ambitious program of scientific observations the spacecraft is performing. Due to this, the spacecraft was not injected into a direct trajectory to Saturn but made use of gravity-assisted maneuvers at Venus, Earth, and Jupiter. These maneuvers increased the duration of the voyage, which lasted about 7.5 years, but at the same time allowed to test the instruments during the different flybys, to improve their calibration, and also to make some interesting

observations at Jupiter in conjunction with the ► [Galileo mission](#) in orbit around the gas giant in December 2000. This brief conjunction of the two probes, complemented by simultaneous observations from the Earth-orbiting Hubble Space Telescope and Chandra X-ray Observatory, provided an unprecedented opportunity for the intimate study of the Solar System's largest planet and enhanced our understanding of Jupiter's radio emission and aurorae and their interaction with the solar wind. Jupiter's magnetosphere and radiation belts and the interactions between the magnetosphere and ► [Io](#), ► [Ganymede](#), and ► [Europa](#) were also explored.

The main body of the orbiter is nearly cylindrical and consists of a lower equipment platform, a propulsion module, and an upper equipment platform, topped by a 4-m diameter high-gain antenna. Attached about halfway up the trunk is a remote sensing pallet, which hosts cameras and other remote sensing instruments, and a fields and particles pallet, which carries instruments that study magnetic fields and charged particles. In order to point the instruments in the correct observing direction, the entire spacecraft must be turned, although three of the instruments possess their own single-axis articulation capability.

Cassini's orbiter instrumentation (Fig. 2) consists of a synthetic-aperture RADAR mapper, a charge-coupled device ► **imaging** system, a visible/infrared mapping spectrometer, a composite infrared spectrometer, a cosmic dust analyzer, a radio and plasma wave experiment, a plasma spectrometer, an ultraviolet imaging spectrograph, a magnetospheric imaging instrument, a magnetometer, and an ion/neutral mass spectrometer. Telemetry from the communications antenna and other special transmitters is also used to make observations of the atmospheres of Titan and Saturn and to measure the gravity fields of the planet and its satellites. On its orbit around Saturn, Cassini finds itself between 8.2 and 10.2 astronomical units (AU) from the Earth. Because of this, it takes between 68 and 84 min for radio signals to travel from Earth to the spacecraft, and vice versa.

More details and updates on the Cassini-Huygens mission can be found at <http://saturn.jpl.nasa.gov/>; <http://sci.esa.int/cassini-huygens/>; http://www.nasa.gov/mission_pages/cassini/main/.

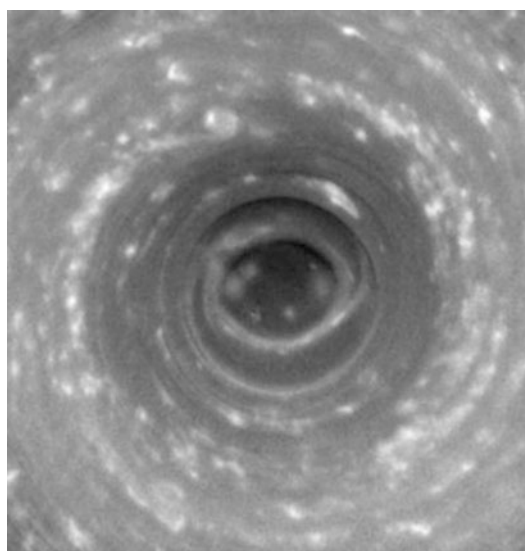
Major Discoveries

The Cassini-Huygens mission has brought a host of new and exciting discoveries in the Saturnian system (Coustenis and Taylor 2008; Lorenz and Mitton 2008; Brown et al. 2009; Dougherty et al. 2009). They concern the distribution and composition of the rings, the nature of the kronian satellites and their interactions with the system, the planet's atmospheric envelope, and its ► **magnetosphere**. But also, the Cassini-Huygens discoveries have completely revolutionized our

perception of the astrobiological and habitable potential in a giant planet system, with strong implications also for exoplanetary worlds.

Given the long duration of the mission, the complexity of the payload onboard the Cassini Orbiter, and the amount of data gathered on the primary planet, the satellites, and rings, it would be impossible to describe all the new discoveries made (the reader can find detailed reviews in the books edited by Dougherty et al. 2009; Brown et al. 2009). We will therefore cite here only a few of the major breakthroughs showing how Cassini's data have opened up a whole new chapter in Solar System exploration and in particular have contributed to our understanding of the astrobiological aspects of many of the Saturnian bodies (Lunine and Raulin 2010; Coustenis and Encrenaz 2013).

In studying the primary planet, Cassini found lightning on Saturn whose power is said to be approximately 1,000 times that of lightning on Earth (Dougherty et al. 2009). In addition, in October 2006, the probe detected an 8,000 km diameter hurricane with a six-sided eyewall at Saturn's South Pole (Fig. 3). The storm's eye is

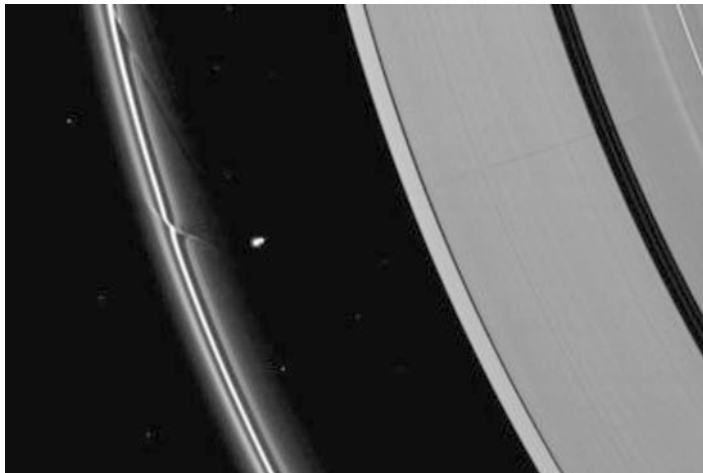


Cassini-Huygens Space Mission, Fig. 3 This Cassini image shows a large hurricane-like storm at Saturn's south pole. The dark eye of the "hurricane" spans about 8,000 km and it is surrounded by rings of clouds that tower about 30–75 km above it. Contrary to the Earth, Saturn's storm is fixed in place – above the South Pole – and is not powered by an ocean, since Saturn is a gaseous planet

about 2,000 km across with cloud speeds as fast as 530 kph. Scientists believe that the storm is the strongest of its kind ever seen. This observation is particularly notable because eyewall clouds had not previously been seen on any planet other than Earth. In addition, in counterpart, a strong six-sided jet stream was found at Saturn's north pole known as "the hexagon" and photographed again recently to span 32,000 km.

Saturn is probably best known for its system of ► **planetary rings**, which makes it the most visually remarkable object in the solar system. They extend from 6,630 to 120,700 km above Saturn's equator, average approximately 20 m in thickness, and are composed of 93% ► **water** ice with a smattering of ► **tholin** impurities and 7% ► **amorphous carbon**. The particles that make up the rings greatly vary in size. On September 20, 2006, a Cassini photograph revealed a previously undiscovered planetary ring, outside the brighter main rings of Saturn and inside the G and E rings. Apparently, the source of this F ring is the result of the crashing of a meteoroid off two of the moons of Saturn (Dougherty et al. 2009). Indeed, the interactions and material exchange between the rings and the satellites provide a significant

breakthrough in our understanding of the Saturnian system provided by the Cassini spacecraft (Fig. 4). Thus, on October 6, 2009, another discovery was announced of a tenuous outer disk of material in the plane of ► **Phoebe's** orbit. The ring is from 128 to 207 times the radius of Saturn and is thought to originate from micrometeoroid impacts on the satellite Phoebe, which orbits at an average distance of 215 Saturn radii. The ring material should thus share Phoebe's retrograde orbital motion and after migrating inward would encounter ► **Iapetus'** leading face, which could help explain the dramatic two-faced nature of this satellite. While the infalling material cannot be directly responsible for the observed pattern of light and dark regions on Iapetus, it is believed to have initiated a runaway thermal self-segregation process in which ice sublimates from warmer regions and condenses onto cooler regions. This leaves contrasting areas of dark ice-depleted residue and bright ice deposits. Another important discovery was that the source of the material in the E ring, the second outermost and very wide, was probably the water-laden plumes emanating from the "tiger stripes" of the south polar region of the cryovolcanic satellite



Cassini-Huygens Space Mission, Fig. 4 Cassini captures the effects of the small moon Prometheus on two of Saturn's rings in this image taken on July 30, 2009, at a distance of approximately 1.8 million kilometers from Saturn. A long, thin shadow cast by the moon stretches across the A ring on the right. The gravity of the small

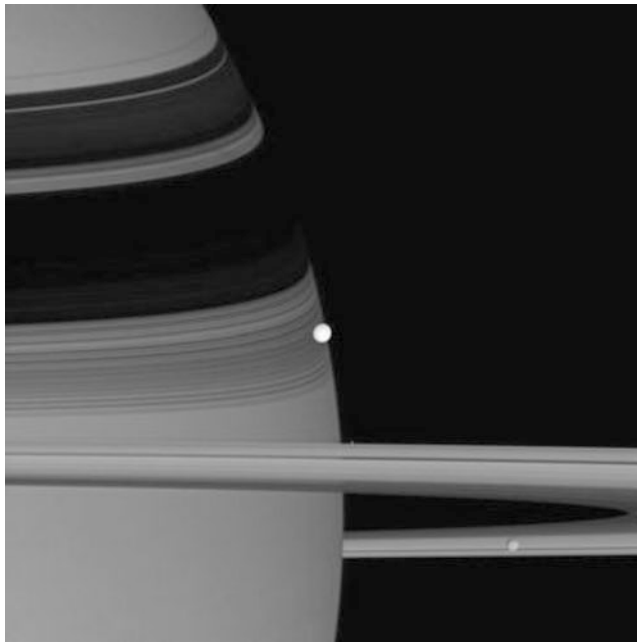
moon Prometheus periodically creates streamer-channels in the F ring, as can be seen on the left of the image. Prometheus is overexposed in this image. Bright specks in the image are background stars. This view looks toward the northern, dark side of the rings from about 28° above the ring plane

Enceladus. Besides the main Cassini division, other gaps have been found in the rings where particle density drops significantly. A couple of them have identified origins by known moons embedded within them, while others are at locations of known ► [orbital resonances](#) with ► [Saturn](#)'s other moons. Finally, still some gaps remain unexplained to date.

So far, the mission has discovered and confirmed several new satellites, bringing the number up to 62. In the satellite system, the Cassini orbiter has produced a large range of new results, demonstrating that these small bodies are far from being icy, dead worlds but rather active bodies with resurfacing and cryovolcanic features. The moons of Saturn are a diverse collection (Fig. 5). Cassini has explored their icy landscapes in unprecedented detail, solving long-standing mysteries and sharing many new surprises: ► [Iapetus](#) has an enormous ridge along its equator, in addition to its two sides of remarkably different

brightness. ► [Rhea](#) may have its own faint rings. And sponge-looking Hyperion is so porous that impacts tend to just punch into the surface, and its gravity is so low that what material does get ejected tends to leave the moon altogether.

A big surprise came from February 2010 observations of ► [Mimas](#), the satellite characterized by the 130-km wide Herschel crater dominating its surface, showing large temperature differences across the surface with no surface brightness features to explain it. The differences are believed to be due to Mimas' thermal inertia being considerably higher in the colder regions than the hotter. In such a case, heat could soak into the Mimas interior more easily, rather than raise the temperature of the surface. This supposes that the thermal conductivity of the satellite has to be at least ten times greater in the cold regions with respect to the warmer regions, while there are no apparent differences in the visible-wavelength observations. These facts and the giant crater,



Cassini-Huygens Space Mission, Fig. 5 On June 28, 2007, the Cassini cameras captured this trio of icy moons against Saturn's atmosphere and rings (Dougherty et al. 2009). Enceladus is located on the planet's shadow-draped limb at the center; Pandora is a bright speck hovering near the rings; and Mimas is seen at lower right. The

view was obtained at a distance of approximately 291,000 km from Enceladus, looking toward the sunlit side of the rings from about a degree below the ringplane. Scale in the image ranges from 17 km per pixel on Enceladus to 32 km per pixel on Saturn in the background

Herschel, residing within this cold region remain a mystery.

Cassini also discovered the presence of organics (hydrocarbons mainly) on several of Saturn's satellites seen through their signatures in several of the instruments' data, not only on Titan and ► [Enceladus](#), but also on Iapetus and Phoebe and ► [Dione](#), with Cassini VIMS showing that the dark material in the Saturn system could be organics (Dougherty et al. 2009).

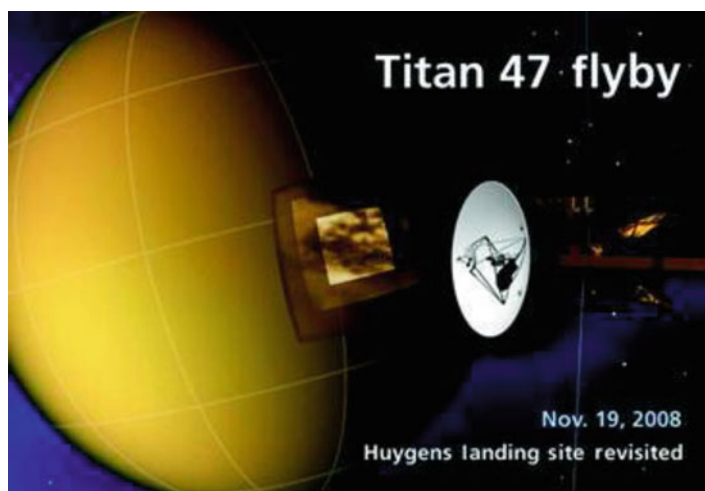
More surprises came from the combined investigations of the orbiter and of the Huygens probe in the case of Titan as shown for example in Fig. 6 for the Huygens landing site (Coustenis and Taylor 2008; Lorenz and Mitton 2008; Mueller-Wodarg et al. 2014) but also from very close Cassini flybys of Enceladus (Brown et al. 2009). In some ways, the moons Titan and Enceladus have turned out to be unique revelations of the Cassini mission, making the Saturnian system's exploration very relevant to the search for ► [life](#) and habitable conditions in the Solar System. Titan, with its thick organic-laden atmosphere, clouds, dunes, and rivers and lakes of liquid ► [methane](#)-ethane on its surface (Stofan et al. 2007; Brown et al. 2008; Raulin et al. 2012), is a rich laboratory for chemistry and processes that may resemble early Earth but with different materials in play (Coustenis and Taylor 2008). Furthermore, the presence of an internal liquid water ocean is more substantiated with new

measurements. And with its towering south polar plume of icy particles and water vapor, Enceladus is a geologically active moon, certainly a strong candidate for liquid water underneath its surface and energy sources, and incredibly important for the study of potentially habitable environments. Both of these moons are compelling targets for future exploration in that context, but in the meantime, Cassini-Huygens is providing us with major insights bearing high relevance to Astrobiology, the ► [origin of life](#), and habitability.

Titan

The Cassini orbiter and the Huygens descent probe were designed to be part of a common strategy to uncover the mysteries shrouding the enigmatic satellite of Saturn, ► [Titan](#). Titan is an organic paradise that is certain to tell us much about the chemical evolution that may lead to life. Water ice and ► [carbon dioxide](#) ice have been reported to exist currently on the surface. Transient episodes of melting of the water ice by either geologic activity or impacts would expose organics to aqueous alteration, as well as contact with carbon dioxide, leading potentially to reaction pathways that mimic those that occurred on the prebiotic Earth. No other place in the solar system has this type of ongoing chemistry. The Cassini-Huygens era of investigation has furthered our understanding of Titan as the largest ► [abiotic](#) organic factory in the Solar System.

Cassini-Huygens Space Mission, Fig. 6 Artwork showing the Cassini orbiter observing the Huygens probe landing site with VIMS and UVIS in 2008



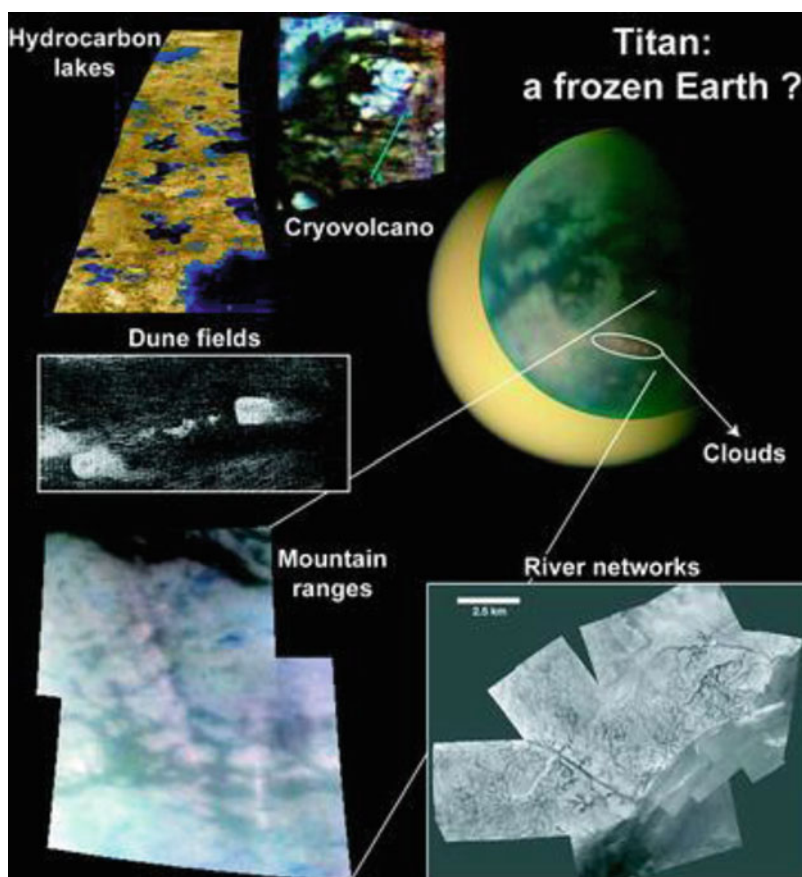
Some essential breakthroughs related to Astrobiology within the realm of Saturn are summarized hereafter and on Fig. 7.

Titan's Atmosphere

With the current picture of Titan's organic chemistry, the chemical evolution of the main atmospheric constituents – ► [dinitrogen](#) (N_2) and methane – produces complex refractory organics through ► [photolysis](#) and ► [photochemistry](#). Measurements throughout the Titan atmosphere, both remotely and in situ, have indicated the presence of numerous hydrocarbon and ► [nitrile](#) gases, as well as a complex layering of organic ► [aerosols](#) that persists all the way down to the surface of the moon. The organic chemistry detected in the higher atmosphere by the Ion and Neutral Mass Spectrometer (INMS; Waite et al. 2007) provided feedback and useful information for all studies and models of the satellite's

chemical composition, complemented by measurements in the ► [stratosphere](#) made by the Composite Infrared Spectrometer (CIRS; Coustenis et al. 2010) and by the chemistry inferences from the Gas Chromatograph-Mass Spectrometer (GC-MS; Niemann et al. 2005), as well as density and temperature data retrieved by the Huygens Atmospheric Structure Instrument (HASI; Fulchignoni et al. 2005) during the descent to the surface near Titan's equator. The highly complex organic species in the ionosphere found by INMS are the precursors of the hydrocarbons and nitriles found in the stratosphere, which form aggregates and eventually condense out on the surface. Some of these chemical components are molecules of prebiotic interest (like hydrogen cyanide and HCN, Raulin et al. 2008). Thus, it appears that Titan is a chemical factory in which the formation of complex positive and negative ions is initiated in the high thermosphere as a

Cassini-Huygens Space Mission, Fig. 7 Some of the major discoveries that the Cassini-Huygens mission made on Titan: transient atmospheric phenomena (clouds) and several geomorphological features (dunes, cryovolcanoes, channels, mountains, and lakes) are shown in this composite. (Credit: G. Tobie)



consequence of magnetospheric-ionospheric-atmospheric interactions involving solar EUV, UV radiation, and energetic ions and electrons. Furthermore, seasonal variations of the atmospheric temperature and chemical composition have been recorded by the Cassini instruments.

The products accumulate on the surface, together with condensed volatile organic compounds such as HCN and benzene. The abundance of methane and its organic products in the atmosphere, seas, and dunes exceeds by more than an order of magnitude the carbon inventory in the Earth's ocean, biosphere, and fossil fuel reservoirs. Indeed, the measured value of the irreversible conversion of the methane in the atmosphere into higher-order organic/nitrile compounds that eventually end up deposited on the surface of Titan is near that of our terrestrial reference, indicating that methane is resupplied and converted at a rate that prevents the buildup of the heavier isotopologue over time as is the case of ► [nitrogen](#). However, the source of the atmospheric methane remains a mystery today although various models and hypotheses have been advanced, including its periodic outgassing from the interior via cryovolcanism.

The Cassini cameras and spectrometers, as well as the Huygens instruments, showed the presence of clouds and storms in Titan's atmosphere and described the distribution of the aerosols (haze) throughout the atmosphere. Most of the clouds detected in the past years were in Titan's southern hemisphere, as expected given the season on Titan that has been essentially probed (summer in the south), which means that solar heating is concentrated there. In recent years, however, they have been found to be building up also in the north as the season changes. Furthermore, temporal and even seasonal variations in the thermal structure and the chemical composition of Titan have been recorded by the Cassini instruments. During the Cassini mission, Titan's season moved from northern winter to northern spring, returning to the same configuration as during the Voyager encounter sometime in 2010. The same enhancement in the northern polar composition was found for most gases, but since mid-2012, a reversal has been monitored as the south pole is

now coming into winter exhibiting stronger signatures of gases and haze. The seasonal variations of the haze, whose vertical structure has changed with the detached layer dropping in altitude significantly in recent years, can be attributed to a varying Hadley circulation. Another important discovery was that the stratospheric zonal winds and temperatures in both hemispheres of Titan are symmetric about a pole that is offset from the surface pole by $\sim 4^\circ$.

Cassini-Huygens has also provided important information on the origin and evolution of Titan's atmosphere by measuring the noble gas concentrations (like argon for the first time) and their isotopic abundances, as well as the nitrogen and carbon stable isotopic ratios. These measurements also provide important clues about the overall role of escape, chemical conversion, outgassing, and recycling in the evolution of Titan's atmosphere.

Titan's Surface

Only with Cassini-Huygens did it become possible to acquire a clear picture of Titan's complex and exciting terrain. One of the most efficient applications of the synergy between the orbiter and the probe is the mapping of Titan's surface. While the Cassini orbiter provided detailed views of Titan's surface with its camera, mapping spectrometer, and radar, the Huygens probe, descending through the atmosphere on January 14, 2005, returned extraordinarily detailed images with resolutions ranging from 10 m at 10 km down to centimeters at the surface (Fig. 7). The Huygens Atmospheric Structure Instrument (HASI) gave the conditions of pressure, density, and temperature throughout Titan's atmosphere and in particular on Titan's surface to be 1.5 bar and 93.7 K (Fulchignoni et al. 2005), serving as a reference for many studies.

For the surface discoveries, the context is provided by the Cassini radar (RADAR), the Visual and Infrared Mapping Spectrometer (VIMS), and the Imaging Science Subsystem (ISS) data (Porco et al. 2005), while the ground truth was obtained by several of the Huygens instruments at the probe's ► [landing site](#), like the images and spectra of Descent Imager/Spectral Radiometer (DISR; Tomasko et al. 2005) or the composition

measurements of the GC-Ms (Niemann et al. 2005). Radar observations suggest that the ultimate fate of this aerosol precipitation is the generation of expansive organic-laden dunes (Lorenz et al. 2006; Radebaugh et al. 2008) that were observed around Titan's equator for the first time by Cassini (Fig. 7). These dunes are remarkable in being exactly the same size and shape as linear (longitudinal) dunes on Earth such as those found in the Namibian and Saharan desert and are essentially found near Titan's equator. Indeed, the mid latitude regions around the equator on Titan were found to be rather uniformly dark with some extensive bright regions (mostly elevated structures like mountains and ridges), while the poles are relatively bright but also filled with large dark areas now recognized as hydrocarbon "lakes" (mostly in the north pole) formed possibly by precipitation through the atmosphere. Few craters were detected on Titan's surface, which then appears rather young.

Radar-bright channels (probably cobbled streambeds like that at the Huygens landing site) have been observed at low and mid-latitudes, while channels incised to depths of several hundred meters are seen elsewhere, and at high latitudes, radar-dark, meandering channels are seen that suggest a lower-energy environment where deposition of fine-grained sediment occurs (Soderblom et al. 2007a; Lorenz et al. 2008a). Fluvial modification of the surface was very evident at the Huygens landing site (Tomasko et al. 2005). Radar and near-infrared imagery has revealed channels on much larger scales than those seen by Huygens.

Furthermore, in July 2006, Cassini found the first proof of hydrocarbon lakes near Titan's north pole (Stofan et al. 2007), which was confirmed in January 2007 (Mitri et al. 2007; Hayes et al. 2008). In March 2007, additional images near Titan's north pole discovered hydrocarbon "seas." These very dark features at the high northern latitudes of Titan were finally shown to be liquid-filled (most probably with ethane-rich mixtures; Brown et al. 2008; Raulin 2008, 2012; Cordier et al. 2012) basins – "lakes." The features range in size from less than 10 km² to at least 100,000 km². They are confined to the region

poleward of 55°N. To date, some 655 such features have been identified and mapped (Fig. 7). Other small lakes exist more to the south, like the Ontario Lacus. In 2010, specular reflections of the Sun off of Titan's northern lakes ("sunglints") were reported, while Cassini looked back toward a crescent Titan at high phase angle. The data were used to set some constraints on possible surface waves on a north polar lake (Jingpo Lacus), and since then observed specular reflections have been quite useful in corroborating the presence of large extents of liquid hydrocarbons in Titan's surface. The major seas on Titan, which are very extended in size, are namely Kraken Mare (surface area of at least 400,000 km² centered at 68 N, 310 W), Ligeia Mare (79 N, 248 W), and Punga (85 N, 339 W). Although some of these "seas" or "lakes" or even "oases" are found at mid latitudes, most are located in the northern hemisphere at Titan's current season, but they are expected according to some models to build up in the south, following the atmospheric evolution, as the season changes. In 2013, a study even reported the possible presence of blocks of hydrocarbon ice floating on the surface of these lakes.

Thus, the diversity of the terrains on Titan depicted by the Cassini-Huygens instruments includes a host of geologic features (Fig. 7):

- Erosional features such as channels and dendritic networks, possible lakes and seas, fluvial erosional deltas and other erosional and depositional constructs such as dunes (Radebaugh et al. 2008), possible glacial-flow constructs, etc.
- Impacts: the very low crater frequency is indicative of active geological surface processes
- Volcanotectonic features: domes, possible cryovolcanic flows, and bright spots (Sotin et al. 2005; Nelson et al. 2007; Lopes et al. 2013) as well as mountain chains (Radebaugh et al. 2007), many of these features may be active regions on Titan's surface

The features Cassini-Huygens discovered on Titan's surface were more complex than any expected, with landforms that seem to resemble the landscapes on Earth, including hills, dunes, a

deflated lakebed, but all composed of completely different constituents, many of which could be ices and organic material. The ambient conditions and direct measurement of methane evaporating from under the landed probe imply that the working erosive agent is liquid methane, not liquid water.

The surface of Titan, as revealed by the Cassini orbiter and the Huygens probe, offers us an opportunity to stretch our current models in an effort to explain the presence of dunes, rivers, lakes, cryovolcanoes, and mountains in a world where the rocks are composed of water ice rather than silicates and the liquid is methane or ethane rather than liquid water.

Titan's tectonism involves a number of very-large-scale linear features seen optically, notably the dark dune-filled basins. Some linear mountain ranges have been detected, several forming a chevron pattern near the equator, with a large bright terrain (Xanadu) extending over 3400 km in diameter. RADAR/SAR (synthetic-aperture radar (*SAR*)) imagery shows Xanadu to be extremely rugged.

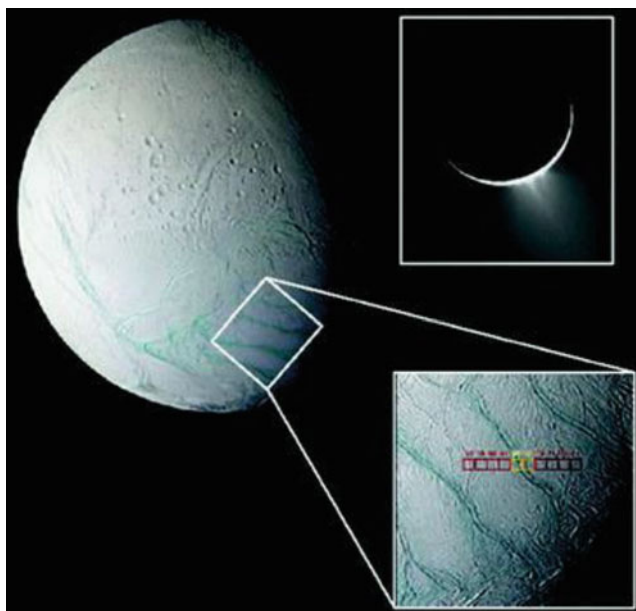
As said before, the N_2 - CH_4 by-products in Titan's atmosphere eventually end up as sediments on the surface, where they accumulate presently at a rate of roughly 0.5 km in 4.5 Gyr. Since no large source was detected by Cassini to

resupply methane, cryovolcanic outgassing has been hypothesized, yet over what timescales and through which internal processes is unknown. Cassini-Huygens also found that the balance of geologic processes – impacts, tectonics, fluvial, aeolian – is somewhat similar to the Earth's, more so than for Venus or Mars. Titan may well be the best analogue to an active terrestrial planet in the sense of our home planet, albeit with different working materials (Solomonidou et al. 2013; Mueller-Wodarg et al. 2014).

In addition, the detection of Argon 40, and observations of what appear to be flows from cryovolcanoes, suggests that the interior of Titan is geologically active; theoretical calculations suggest a heat flow at present of about 8% that of the Earth, sufficient to mobilize water as liquid in the interior as the working fluid for ► [cryovolcanism](#). Cryovolcanism is a process of particular interest at Titan because of the known astrobiological potential of liquid water erupting onto photochemically produced organic molecules. Several likely cryovolcanic structures have been identified in Cassini near-infrared and radar images (Fig. 8). Although definitive evidence for active volcanism has not yet been produced, there are apparent surface changes in Cassini data that require explanation.

Cassini-Huygens Space Mission, Fig. 8

Cassini's major breakthroughs in our understanding of the Enceladus environment are connected to the southern polar region, where the magnetometer and the cameras detected plumes of gas and ice particles emanating from a series of warm fractures, dubbed the "tiger stripes"



Titan's overall density (1.88 g/cm^3) requires it to have roughly equal proportions of rock and ice. After its accretion, Titan was probably warm enough to allow differentiation into a rocky core with a water/ice envelope, but whether an iron or iron-sulfur core formed during the subsequent evolution remains uncertain. In addition, the presence of an internal liquid water ocean for Titan is supported by models, radar and gravity Cassini measurements, and the HASI experiment. The extremely low-frequency electric signal recorded by HASI was interpreted as a Schumann resonance between the ionosphere and a modestly conducting ocean roughly 50 km below the surface. Thermal evolution models suggest that Titan may have an icy crust between 50 and 150 km thick, lying atop a liquid-water ocean a couple of hundred kilometers deep, with some amount (a few to 30%, most likely $\sim 10\%$) of ammonia dissolved in it, acting as an antifreeze. Beneath lies a layer of high-pressure ice. Cassini's measurement of a small but significant non-synchronous contribution to Titan's rotation is most straightforwardly interpreted as a result of decoupling of the crust from the deeper interior by a liquid layer (Lorenz et al. 2008b). The presence of ammonia, from which Titan's nitrogen atmosphere was presumably derived, distinguishes Titan's thermal evolution from that of Ganymede and Callisto. The recent detection of periodic tidal stresses on Titan requires that its interior be deformable over timescales of the orbital period in a way that is consistent with a global ocean at depth (Iess et al. 2012). All of these indications make Titan a very likely habitable environment.

Enceladus

When Cassini had its first encounter with [▶ Enceladus](#) on February 17, 2005, the magnetometer instrument saw a bending of Saturn's magnetic field, with the plasma being slowed and deflected as it passed Enceladus. Data collected during the March 9, 2005, flyby provided further evidence of the existence of an atmosphere around the southern pole of Enceladus. The cosmic dust analyzer recorded thousands of hits from tiny particles of dust or ice coming from a cloud around the moon and feeding the adjacent E ring.

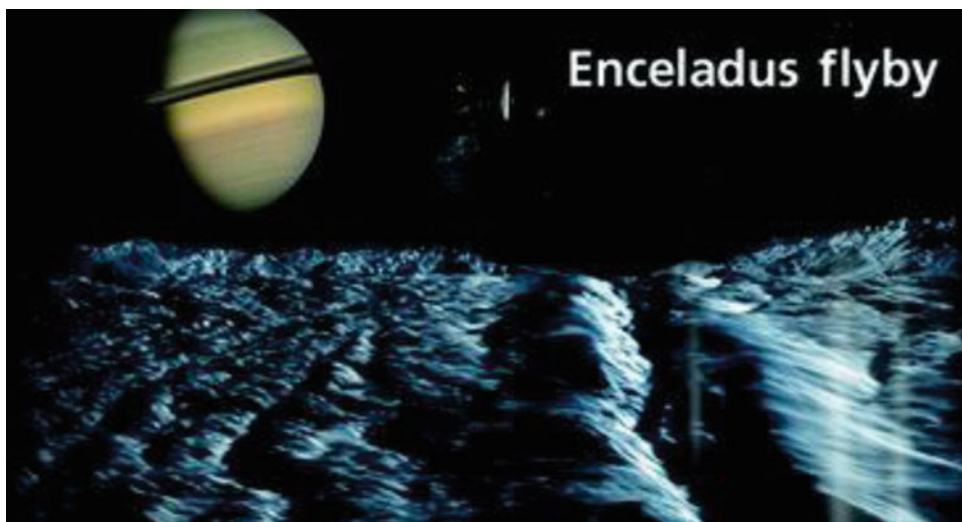
The Cassini spacecraft provided definitive proof that Enceladus is currently geologically active when multiple Cassini instruments detected plumes of gas and ice particles emanating from a series of warm fractures centered on the south pole, dubbed the "tiger stripes" (Fig. 8).

Cassini data strongly suggested the presence of liquid-water reservoirs that erupt in geysers on Saturn's moon Enceladus. Images had also shown particles of water in its liquid state emitted by icy jets and towering plumes. Several flybys of Enceladus followed bringing more data and revealing an extremely intriguing world (Fig. 9).

In March 2008, Cassini swept by Enceladus' south pole at an altitude of 52 km and plunged into a south polar plume, scooping up particles and gases to sample their composition. The gases that were "tasted" by Cassini's INMS bore a strong resemblance to the gases that issued from comets. All of the "fields and particles" Cassini instruments (the ones that measure the abundance, compositions, and motions of plasma, ions, atoms, molecules, particles, and magnetic fields in situ, wherever Cassini travels) have been sampling the plumes (Fig. 9).

Enceladus is thus the second cryovolcanically active icy satellite that has been identified (Triton is the only other known active icy satellite, but the process driving its cryovolcanism may not be linked to an internal heat source) and can be used to study active processes that are thought to have once played an important role in shaping the surfaces of other icy satellites. These processes include tidal heating, cryovolcanism, and ice tectonism, which all can be studied as they currently happen on Enceladus. Moreover, the plume source region on Enceladus samples a warm, chemically rich, environment that may facilitate complex organic chemistry and biological processes. CIRS on Cassini has demonstrated that the Enceladus south pole was the warmest portion of this moon, considerably much warmer than the equator (Spencer 2013).

Enceladus is arguably a place in the solar system where exploration is most likely to find a demonstrably habitable environment, and several researches point to the possibility that Enceladus' plumes, tectonic processes, and possibly a liquid-



Cassini-Huygens Space Mission, Fig. 9 One of the Cassini flybys of Enceladus when the spacecraft flew at quite low altitudes into the satellite's plumes (artistic impression)

water reservoir beneath the surface may create a complete and sustainable geochemical cycle that may allow it to support life. While other moons in the solar system have liquid-water oceans covered by kilometers of icy crust, in the case of Enceladus, the pockets of liquid water may be no more than tens of meters below the surface. Cassini has thus discovered a new potential ► [habitat](#) in our Solar System, well outside the traditional ► [habitable zone](#), which needs to be extended to include these “deep habitats.”

Future Directions

The primary mission for *Cassini* ended on July 30, 2008. However, given the excellent condition of the orbiter, the mission was extended to 2010. On February 3, 2010, NASA announced another extension for Cassini, this one for 6-1/2 years until 2017. The extension enables another 155 revolutions around the planet, 54 flybys of Titan, and 11 flybys of Enceladus.

However, even after these extensions, several questions and scientific themes remain that cannot be addressed by Cassini in its current configuration or with its present instrumentation. The two major themes in Titan exploration – the methane cycle as an analogue to the terrestrial hydrological cycle (Atreya et al. 2006) and the chemical

transformations of ► [complex organic molecules](#) in the atmosphere and the surface – render Titan a very high priority if we are to understand how volatile-rich worlds evolve and how organic chemistry and planetary evolution interact on large spatial and temporal scales. Both are of keen interest to planetology and astrobiology.

To answer the several remaining vital questions that Cassini has raised for Titan and for Enceladus, a new mission (the Titan Saturn System Mission, TSSM) was proposed and studied in 2008 by both ESA and NASA. This ambitious mission could bring the required long-term exploring capabilities combining an orbiter and two in situ elements (a montgolfière balloon and a lander) with state-of-the-art technology and instruments (see www.lesia.cosmicvision/tssm/tssm-public). After this study, other, simpler but also exciting, mission concepts have also been proposed for a return to the Saturnian system within the next two or three decades to study Titan with orbiters, lake landers, balloons, airplanes, etc.

Cross-References

- [Aerosols](#)
- [Cassini](#)
- [Cassini Division](#)

- ▶ [Complex Organic Molecules](#)
- ▶ [Enceladus](#)
- ▶ [Giant Planets](#)
- ▶ [Habitable Zone](#)
- ▶ [Hubble Space Telescope](#)
- ▶ [Huygens](#)
- ▶ [Huygens Probe](#)
- ▶ [Iapetus](#)
- ▶ [Isotopic Ratio](#)
- ▶ [Landing Site](#)
- ▶ [Magnetosphere](#)
- ▶ [Methane](#)
- ▶ [Mimas](#)
- ▶ [Organic Material Inventory](#)
- ▶ [Origin of Life](#)
- ▶ [Photochemistry, Atmospheric](#)
- ▶ [Photolysis](#)
- ▶ [Planetary Rings](#)
- ▶ [Rhea](#)
- ▶ [Satellite or Moon](#)
- ▶ [Saturn](#)
- ▶ [Terrestrial Analog](#)
- ▶ [Tholins](#)
- ▶ [Titan](#)
- ▶ [Volatile](#)

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Catabolism

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Catabolism is the subset of metabolic networks by which organic compounds are degraded to simpler organic or inorganic compounds. Catabolism includes oxidation reactions – coupled to the reduction of coenzymes such as NAD⁺ or FAD – and sometimes substrate-level phosphorylation steps leading to ATP synthesis.

Cross-References

- [Anabolism](#)
- [Metabolism](#)

Catalyst

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In chemistry, catalysts are compounds that increase the rate of a reaction but are not consumed in the reaction, as a reagent would be. They can therefore generally participate in reactions multiple times. The term “catalyst” is derived from the Greek word *καταλύειν*, meaning to dissolve or loosen. Catalysts may be metals, mineral surfaces, ► [enzymes](#), ► [ribozymes](#), or small organic molecules, among other possibilities.

Catalysts operate by changing the rate-limiting free energy change to the transition state relative to that of the corresponding uncatalyzed reaction, resulting in a larger reaction rate at a given temperature. The physical mechanism of catalysis can be complex. Catalysts may affect the reaction environment or bind to the reagents to polarize bonds forming intermediates that do not occur in the cognate uncatalyzed reactions. Catalysts have no effect on the chemical equilibrium of a reaction because the rates of both the forward and reverse reactions are affected.

In catalyzed reactions, as in uncatalyzed reactions, the overall reaction rate depends on the frequency of collision of the reactants in the rate-limiting step. The catalyst usually acts in this limiting step, and rate changes are proportional to the amount of catalyst present. As catalysts are not consumed in a reaction, only small amounts may be needed to increase the rate of the reaction significantly. In reality, however, catalysts are sometimes inhibited, deactivated, or destroyed

via secondary processes. Substances that reduce the activity of catalysts are called inhibitors if the reduction is reversible and poisons if the reduction is irreversible.

Catalysts can be heterogeneous or homogeneous, depending on whether they exist in the same phase as the substrate. Heterogeneous catalysts act in a different phase than the reactants, for example, solids that act on liquid or gaseous substrates. Homogeneous catalysts function in the same phase as the reactants, for example, cytosolic enzymes are examples of homogeneous catalysts.

Cross-References

- [Clay](#)
- [Enzyme](#)
- [Protein](#)
- [Ribozyme](#)

Catena, Catenae

Roland J. Wagner
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Synonyms

[Crater chain](#)

Definition

A catena is a linear, slightly curved, or sinuous chain of circular to elliptical depressions. The depressions can be surrounded by raised rims and are contiguous or separate. A crater chain may originate from volcanic or impact processes. Depressions in volcanic catenae are generally rimless. Raised rims and a more-or-less uniform size distribution of the depressions are characteristic of impact crater chains. Impact catenae are created

(a) either by fragments of a projectile that disintegrated prior to impact or (b) by material ejected when a crater is formed, forming chains of secondary craters.

Cross-References

- [Crater, Impact](#)
- [Fumarole](#)
- [Olympus Mons](#)
- [Patera, Paterae](#)

Cavitation Zone

- [Spallation Zone](#)

Cavus, Cavi

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

A cavus is a hollow, irregular steep-sided depression occurring usually in arrays or clusters (definition by the International Astronomical Union; <http://planetarynames.wr.usgs.gov/jsp/append5.jsp>). It is used as a descriptor term for naming surface features on ► [Mars](#).

Cross-References

- [Mars](#)

CC

- [Carbonaceous Chondrite](#)

CCD

Daniel Rouan

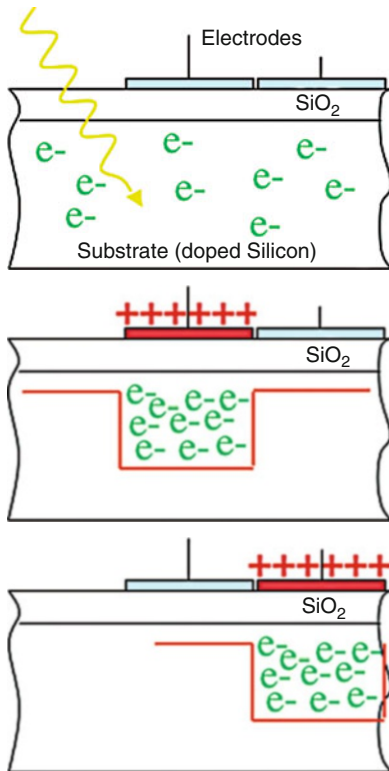
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

Charge-coupled device

Definition

CCD is the abbreviation for charge-coupled device. A CCD is a photoelectronic imaging



CCD, Fig. 1 The principle of charge transfer from one pixel to the next one in a CCD. *Top:* photons penetrate the substrate and create electrons. *Middle:* the electrons are attracted and stored below an electrode polarized with a positive voltage and isolated from the substrate, thanks to a thin layer of silicon oxide. *Bottom:* a voltage is applied to the next electrode and reset on the first one so that electrons travel one step. The procedure is repeated until all pixels are read at the end of the chain

device commonly used for astronomical observations in the visible domain. A CCD is a solid-state silicon-based detector where each of the numerous pixels (up to ten million) stores in a potential well the electrons produced by photons (one to one). At the end of the exposure, charges are transferred from one pixel to the next, up to the output amplifier, by manipulation of voltages applied to surface electrodes (see Fig. 1). Back-illuminated (or thinned) CCDs feature an excellent quantum efficiency for wavelengths up to $\lambda = 1 \mu\text{m}$. Because of their better efficiency and the convenience of obtaining directly a digital image at the output, CCDs definitely replaced photographic plates for use in astronomy in the 1980s, especially since it has been possible to tile side by side several CCDs (up to several tens) and produce cameras with a wide sensitive surface.

Cross-References

► [Imaging](#)

CD

► [Circular Dichroism](#)

Celestial Equator

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The celestial equator is the projection of the Earth's equator on the sky, represented as a great circle on the imaginary celestial sphere. As a result of the Earth's axial tilt, the celestial equator is inclined by $\sim 23.5^\circ$ with respect to the ecliptic plane. The celestial equator is the origin of ► [declination](#), one of the two coordinates used to locate an object on the sky.

Cross-References

- [Coordinate Systems](#)
- [Declination](#)
- [Ecliptic](#)

Cell

Angeles Aguilera

Laboratorio de Extremófilos, Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Keywords

Cell structure · Endosymbiotic theory · Microscopy · Organelles

Definition

The cell is the smallest unit of living matter capable of performing all the activities necessary for life (Alberts et al. 1994). In fact it is the smallest structure with a complete metabolism because it has all the physical and chemical components needed for its own maintenance and growth. All living organisms are made of cells. The simplest forms of life are individual cells that propagate by division, while more complex organisms are multicellular, that is, their bodies are cooperatives of many kinds of specialized cells that could not survive for long time by themselves.

History

The first person to use the word “cell” was Robert Hook (1665) who described what he called the *cella* in a piece of cork (Fig. 1). He used this term because the cork appeared to be composed of thousands of small chambers that resembled the individual sleeping rooms in monasteries. However, Antonie Philips van Leeuwenhoek (1632–1723) using his handcrafted microscopes was the first to observe and describe single-celled microbial organisms, which he originally referred to as *animalcules*. After Van Leeuwenhoek, in 1838 a botanist, Matthias Jakob Schleiden, and a

zoologist, Theodor Schwann, formally proposed “The Cell Theory” stating that: (1) all organisms are composed of one or more cells, (2) all cells come from preexisting cells, (3) vital functions of an organism occur within cells, and (4) all cells contain the hereditary information necessary for regulating cell functions and for transmitting information to the next generation of cells. Their theory, which nowadays seems so obvious, was a milestone in the development of modern biology. The cell theory was extended in 1855 by Rudolf Virchow, who stated that new cells come into existence only by the division of previously existing cells. Cells cannot arise by spontaneous generation from nonliving matter (Campbell and Reece 2002).

Overview

At first sight, cells exhibit a staggering diversity. Some lead a solitary existence, others live in communities; some have defined geometric shapes, others have flexible boundaries; some swim, some are sedentary. However, all cells have several basic features in common: they are bounded by a plasma membrane that physically separates them from the outside environment. Within the membrane is a semifluid substance, cytosol, composed mostly of water (70–90 %). In the cytosol is where a variety of specialized structures named ► [organelles](#) are located. All cells contain also chromosomes, carrying genes for synthesizing all the proteins needed for cell growth, repair, and reproduction.

Despite all the different cell morphologies, it is surprising that there are only two types of cells. Based on differences in compartmentalization, cells can be divided into prokaryotic cell, the simplest, and the more complex eukaryotic cell (Fig. 2). By definition, prokaryotes are those organisms whose cells are not subdivided by membranes into a separate nucleus and cytoplasm. All prokaryote cell components are located together in the same compartment; the genetic material (DNA) is concentrated in a region called the nucleoid, but no membrane separates this region from the rest of the cell. On the contrary, eukaryotic cells contain a membrane-bound

Cell, Fig. 1 Portraits of Robert Hook and Antonie Philips van Leeuwenhoek, two of the founders of cell biology and microbiology. Below them, the portraits of Matthias Jakob Schleiden and Lynn Margulis, known for their cell theory and endosymbiotic theory respectively

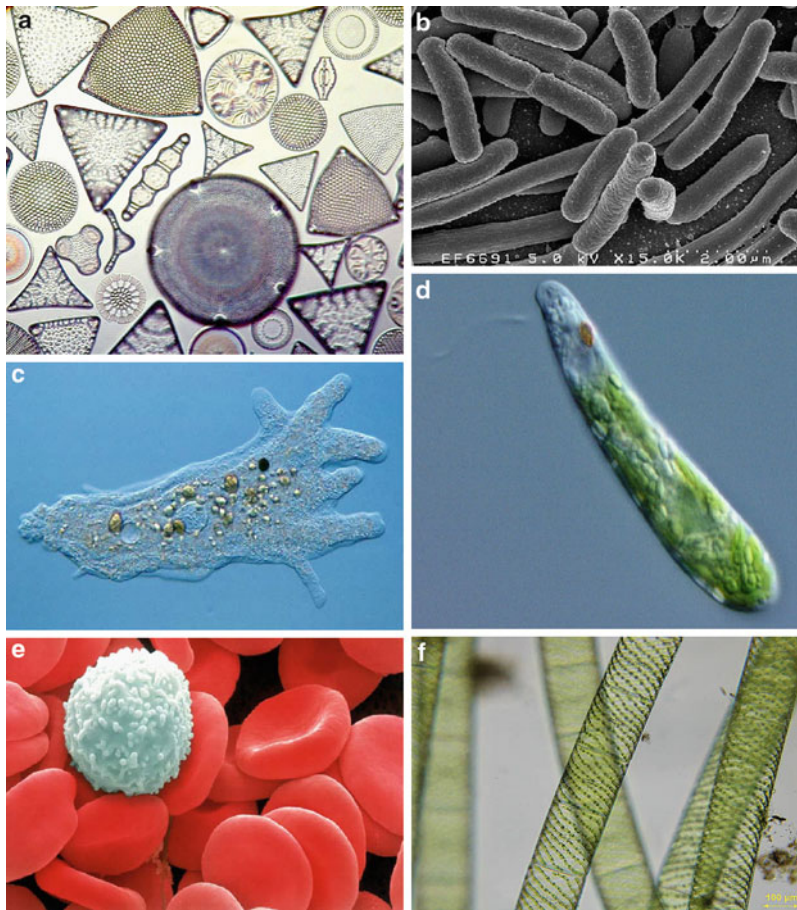


organelle named nucleus where the genetic material is contained. Only bacteria and archaea are prokaryotic cells. Protists, plants, fungi, and animals are eukaryotic cells (Bolsover et al. 1997).

Prokaryotic cells are simpler and generally smaller than eukaryotic cells and are thought to have evolved first (Fig. 3). Fossils show that prokaryotic organisms antedate by at least 2 billion years the first eukaryotes, which appeared some 1.5 billion years ago. It is likely that eukaryotes evolved from prokaryotes. The most plausible explanation of this process is known as the endosymbiotic theory, first articulated by the Russian botanist Konstantin Mereshkowsky in 1905. The endosymbiotic theory was advanced and substantiated with microbiological evidence by Lynn Margulis in a 1967 paper, *The Origin of Mitosing*

Eukaryotic Cells. The basis of this theory concerns the origins of mitochondria and plastids (e.g., chloroplasts), which are organelles of eukaryotic cells. According to this theory, these organelles originated as separate prokaryotic organisms that were taken inside the cell as endosymbionts. Mitochondria developed from proteobacteria (in particular, Rickettsiales or close relatives) and chloroplasts from cyanobacteria (Margulis 1967).

In addition, prokaryotic cells also lack most other membrane-bound organelles typical of eukaryotic cells. In some prokaryotic cells the plasma membrane is folded inward to form a complex of internal membranes (the mesosome) along which the relations of cellular respiration are thought to take place. Photosynthetic



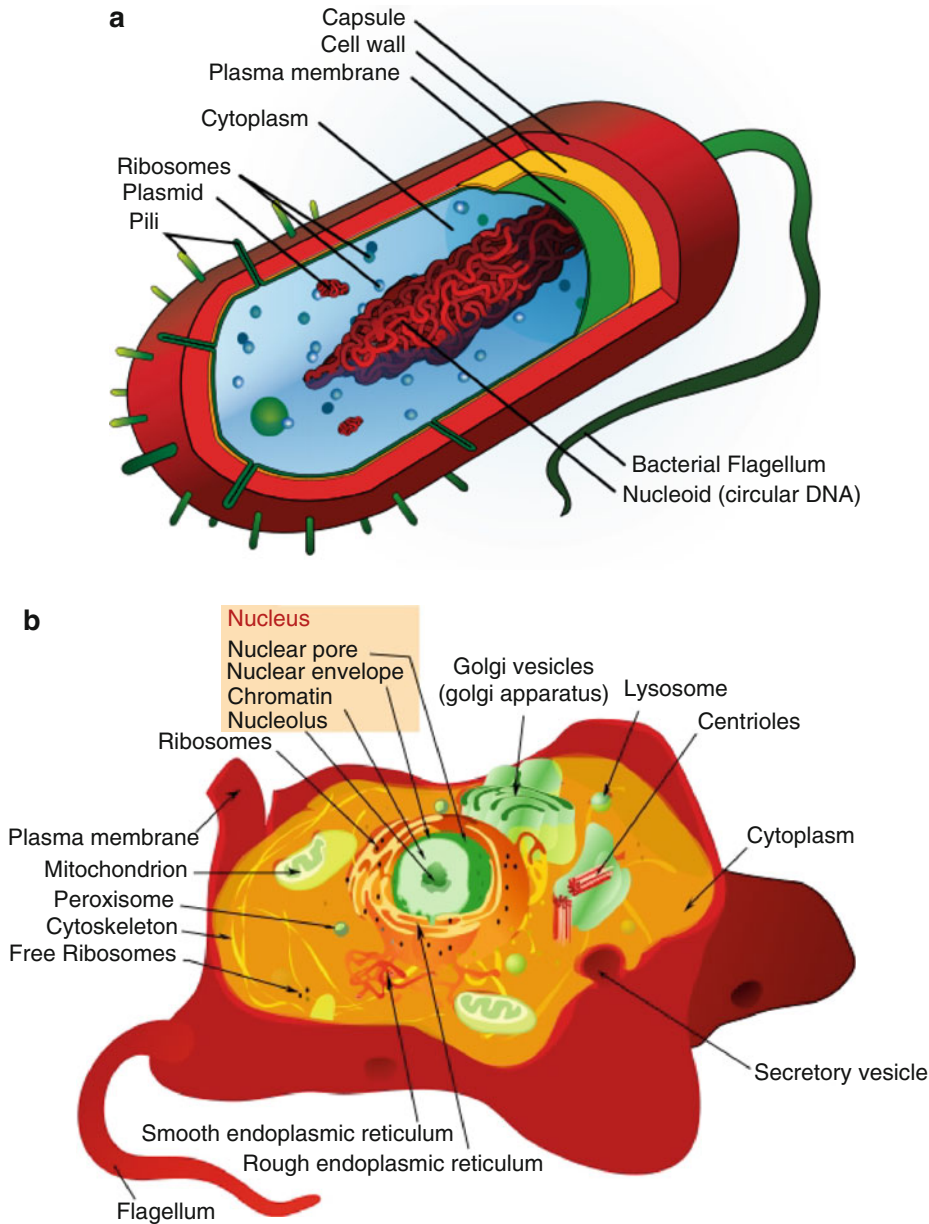
Cell, Fig. 2 Although all the cells have several basic features in common, there is a great variety of specific cellular body plans. Some cells are organisms in their own right, and some make up the bodies of multicellular organisms. (a) Mixed diatoms, these algae are single-cell or colonial and are surrounded by a rigid siliceous envelope named theca. (b) Bacterial cells belonging to the species *Escherichia coli* a rod-shaped bacterium that is commonly found in the lower intestine of warm-blooded organisms. (c) Amoeba cell, this small protozoan uses tentacular protuberances called pseudopodia to move and phagocytose smaller unicellular organisms, which are enveloped inside the cell's cytoplasm in a food vacuole, where they are slowly broken down by enzymes. (d) *Euglena* cell, a photosynthetic protist with at least

150 described species. The cells are cylindrical with a rounded anterior and tapered posterior. The chloroplasts are well-developed and can glide and swim using their flagella. (e) White and red blood cells also referred to them as leucocytes and erythrocytes principal cells of the immune system involved in defending the body against both infectious disease and foreign materials and cells involved in delivering oxygen to the body tissues via the blood flow through the circulatory system. (f) *Spirogyra* cells, a filamentous green algae named for the helical or spiral arrangement of the chloroplasts. It is commonly found in freshwater areas, and there are more than 400 species of *Spirogyra* in the world. *Spirogyra* measures approximately 10–100 μm in width and may stretch centimeters long

prokaryotes contain chlorophyll associated with flat membranes called lamellae. On the contrary, eukaryotic cells have many types of membrane-bound organelles that partition the cytoplasm into compartments.

Typically, each prokaryotic cell has a single chromosome carrying a full set of genes providing

it with the genetic information necessary to operate as a living organism. Each chromosome has 3,000–4,000 genes although some have as few as 500. A typical prokaryotic cell is rod shaped and about 2–3 μm long and 1 μm wide (1 μm = 0.001 mm). However, bacteria are not limited to a rod shape; spherical, filamentous, or spirally twisted



Cell, Fig. 3 Schematic representation of the cell composition. (a) Prokaryotic cells, (b) eukaryotic animal cells. Despite their apparent differences, both cell types have a lot in common. They perform most of the same kinds of functions, and in the same ways. All are enclosed by plasma membranes, filled with cytoplasm, and loaded with small structures called ribosomes. They have DNA

which carries the archived instructions for operating the cell. Physiologically they are very similar in many ways. For example, the DNA in the two cell types is precisely the same kind of DNA, and the genetic code for a prokaryotic cell is exactly the same genetic code used in eukaryotic cells

bacteria are also found. Eukaryotic cells are generally much bigger than prokaryotes. Size is a general aspect of cell structure that relates to function. At the lower limit, the smallest cells

known are bacteria called Mycoplasmas, which have diameters between 0.1 and 1.0 μm . Eukaryotic cells are typically ten times bigger than bacteria.

There are two distinct types (Domains) of prokaryotes, the ► **Bacteria** and ► **Archaea**, which are no more genetically related to each other than either group is to the eukaryotes. Both show the typical prokaryotic structure where the nucleus and other internal membranes are lacking. Despite this visual similarity to bacteria, archaea possess genes and several metabolic pathways that are more closely related to those of eukaryotes: notably the proteins involved in transcription and translation. Other aspects of archaean biochemistry are unique, such as their reliance on ether lipids in their cell membranes and cell wall. The cell wall of bacteria is always made of peptidoglycan, a molecule unique to this group or organisms. Archaea often have cell walls, but peptidoglycan is never present. Thus, the only well defined cellular structures presented by prokaryotes, the cell membrane and cell wall, are chemically quite different in these two groups or organisms. Initially, archaea were seen as extremophiles that lived in harsh environments, such as hot springs and salt lakes, but they have since been found in a broad range of habitats, such as soils, oceans, and marshlands. Archaea are particularly numerous in the oceans, and the archaea in plankton may be one of the most abundant groups of organisms on the planet (Clark 2005).

In addition to the plasma membrane, a eukaryotic cell has extensive and elaborately arranged internal membranes, which partition the cells into compartments. The nucleus is surrounded by a double membrane, the nuclear membrane, which separates the nucleus from the cytoplasm, but allows some communication with the cytoplasm via nuclear pores. The nucleus contains most of the genes in the eukaryotic cell (although some genes are located in the mitochondria and chloroplasts). The genome of eukaryotes usually consists of 10,000–50,000 genes carried on several ► **chromosomes**. In a cell that is not dividing, DNA is organized along with proteins forming an irregular network of strands termed chromatin. When the cells began the process of nuclear division (mitosis), the chromatin coils and condenses into discrete chromosomes containing several thousand genes arranged in a specific linear

order. Most eukaryotes are diploid, with two copies of each chromosome. Consequently, they possess at least two copies of each gene.

Besides nucleus, eukaryotic cells contain a variety of ► **organelles**, which are subcellular structures that carry out specific tasks. Some of them are separated from the rest of the cytoplasm by membranes but others are not. Many of the different membranes of the eukaryotic cell are forming an extensive complex of branching tubules, named endoplasmic reticulum (ER) that is continuous with the nuclear envelope and permeates the cytoplasm. The ER manufactures membranes and performs many other biosynthetic functions such as synthesis of lipids, metabolism of carbohydrates, and detoxifications of drugs and toxins. The ER also functions as a system for transporting materials from one part of the cell to another and perhaps to the outside environment as well. The Golgi apparatus is a stack of flattened membrane sacs and associated vesicles that is involved in the secretion of the proteins manufactured along the ER. The proteins are released from the ER in sealed-off little vesicles that fuses with the membranes of the Golgi complex. Within the Golgi complex the proteins are modified in various ways (i.e., adding carbohydrates forming glycoproteins). The Golgi apparatus in plant cells produces polysaccharides used to construct the cell wall.

Other organelles related to cell metabolism are the lysosomes, membrane-bound structures specialized for digestion that contain hydrolytic enzymes that cells use to digest macromolecules. About 40 different enzymes have been identified in lysosomes. In addition, mitochondria and ► **chloroplasts** are the main energy transducers of cells. Mitochondria are generally rod-shaped organelles bounded by a double membrane. They resemble bacteria in their size and shape; it is thought that mitochondria are indeed evolved from bacteria that took up residence in the primeval ancestor of eukaryotic cells. Like bacteria, mitochondria contain a circular molecule of DNA similar to a bacterial chromosome, although much smaller. Mitochondria are the site of most of the chemical reactions that convert the chemical energy present in inorganic compounds to another

form of energy, ATP, that cells can use for work. These organelles are the sites for cellular respiration, the catabolic process that generates ATP by extracting energy from sugars, fats, and other compounds with the help of oxygen. This contrasts with bacteria, where the respiration chain is located in the cytoplasmic membrane, as no mitochondria are present (Davis et al. 1990).

► **Chloroplasts** are also membrane-bound organelles that produce and store food materials in algae and plant cells. Chloroplasts contain the light-absorbing pigment chlorophyll, along with enzymes and other molecules that function in the photosynthetic production of reduced carbon molecules by trapping light energy. Like mitochondria, chloroplasts contain a circular DNA molecule and are thought to have evolved from a photosynthetic bacteria. Chloroplasts also contain a variety of yellow and orange pigments known as carotenoids. Although a unicellular alga may have only a single large chloroplast, cells of complex plants may possess 20–100 of these organelles.

Besides for the presence of chloroplasts, plant cells differ from animal cells in several other ways. Although all cells are limited by plasma membranes, plant cells are also surrounded by ► **cell walls** of cellulose, which limits any change of position and shape. In addition, most plants have one large or several small compartments called vacuoles, used for storing nutrients and waste products, and certain organelles such as centrioles and lysosomes are absent.

There are still other structures that support the cells, connect them with other cells, and help them move. Cytoskeletal elements, such as microtubules or microfilaments, give cells their shape and allow the movement. Centrioles are tiny organelles that function in nuclear division, usually located within a dense area of cytoplasm, the centrosome. Cells are able to swim or move by using their cilia and flagella, which are specialized arrangements of microtubules (Maton et al. 1997).

Cell Origin and Evolution

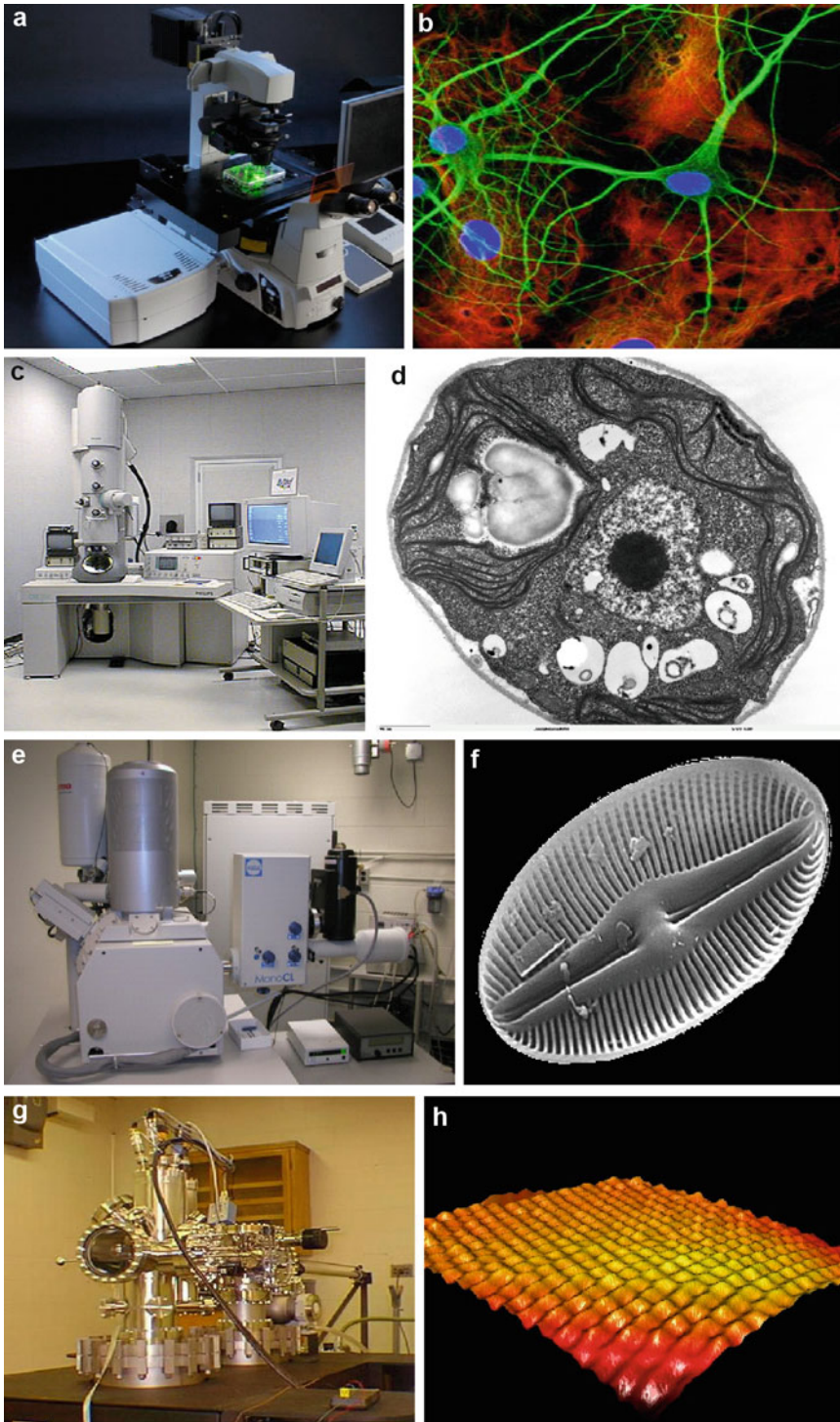
Synthesis and accumulation of biologically relevant molecules in the early Earth would have been the first step in the path to the primitive cells. It is generally assumed that RNA was the first

information storage molecule and that DNA came later. The primitive cell vaguely resembled a bacterium (Bada and Lazcano 2010).

Life began remarkably early in Earth's history, and those first organisms were ancestral to the great diversity of life we observe today. The Earth was formed about 4.5 billion years ago. However, the oldest fossils of organisms known are 3.5 billion years old. These microfossils resemble certain bacteria that still exist today. For bacteria so complex to have evolved by 3.5 billion years ago, it is a reasonable hypothesis that life originated much earlier, when Earth began to cool to a temperature at which liquid water could exist. The fossil record supports the presumption that prokaryotes were the earliest organisms. Photosynthesis probably evolved very early also in prokaryotic history. The photosynthetic bacteria that generate and release oxygen to the atmosphere, named cyanobacteria, probably evolved over 2.7 billion years ago. The accumulation of atmospheric oxygen was gradual and had an enormous impact on life since oxygen attacks chemical bonds and was toxic for many of the existing prokaryotic groups. Although some prokaryotic species survived in habitats that remained anaerobic, a variety of different adaptations to the oxydizing atmosphere evolved, including cellular respiration, using oxygen to obtain energy from organic and inorganic molecules.

The oldest fossils of eukaryotes are 2.1–2.7 billion years old, and look like simple single-celled algae. This range of time places the earliest eukaryotes during a time when the oxygen evolution was changing Earth's environments dramatically. Development of chloroplasts may be part of the explanation for this temporal correlation.

It seems reasonable to suggest that eukaryotes evolved from a single prokaryotic ancestor that gradually accumulated greater structural complexity. But evidences show that the eukaryotic cell originated from a symbiotic coalition of multiple prokaryotic ancestors not just one. The theory of serial endosymbiosis proposes that mitochondria and chloroplasts were formerly small prokaryotes living within larger cells (Margulis 1967; Davis et al. 1990). The proposed ancestors of mitochondria were aerobic



Cell, Fig. 4 Microscopes and their images. (a) A confocal microscope creates sharp images of a specimen that would otherwise appear blurred when viewed with a conventional optical microscope. This is achieved by excluding most of

the light from the specimen that is not from the microscope's focal plane. (b) A glia neuron cell viewed using confocal microscopy. (c) Transmission electron microscope (TEM) uses a high energy electron beam transmitted

heterotrophic prokaryotes, related to alpha-proteobacteria, that became endosymbionts. The proposed ancestors of chloroplasts were photosynthetic prokaryotes related to cyanobacteria. These ancestors probably gained entry to the host cell as undigested prey or parasites. Evidences supporting this idea are the structural similarity between bacteria, mitochondria, and chloroplasts; both organelles are able to replicate by a splitting process reminiscent of binary fission in bacteria, and each organelle contains a genome consisting of a single circular DNA molecule not associated with histones or other proteins, as in most prokaryotes. Furthermore, the organelles contain all the enzymatic equipment necessary to transcribe and translate their DNA into proteins. During the evolution from endosymbiont to organelle, the vast majority of the original bacterial genes has been lost or transferred to the host nucleus; so the organellar genomes are very reduced in comparison to their closest free-living counterparts.

Basic Methodology

Living cells are composed of many progressively smaller components. Most levels of biological organization are imperceptible to the human senses, so that to study them we must make use of a variety of instruments and indirect techniques. Microscopy is the most useful technique to study cell structure and related issues. The light microscope, gradually improved since Hooke's time, uses visible light as the source of illumination. During the last decades, the development of the electron microscope has enabled researchers

to study the fine detail, called ultrastructure of cells. Nowadays, the scanning tunneling electron microscope allows us to study the relationship between molecules.

Magnification is the ratio of the size of the image to the size of the specimens. Whereas the ordinary light microscope can magnify a structure about 1,000 times, the electron microscope can magnify up to 250,000 times or even more. Besides, the electron microscope has far superior resolving power, which is the ability to reveal fine detail, and is expressed as the minimum distance between two points that can be distinguished as separate and distinct points.

Optical and electron microscopy involve the diffraction, reflection, or refraction of electromagnetic radiation/electron beams interacting with the subject of study, and the subsequent collection of this scattered radiation in order to build up an image. This process may be carried out by wide-field irradiation of the sample (e.g., standard light microscopy and transmission electron microscopy) or by scanning of a fine beam over the sample (e.g., confocal laser scanning microscopy and scanning electron microscopy) (Fig. 4).

Optical or light microscopy involves passing visible light transmitted through or reflected from the sample through a single or multiple lenses to allow a magnified view of the sample. The resulting image can be detected directly by the eye. To be viewed with the light microscope, specimens must be very thin. Single cell organisms can be observed *in vivo*. There are important limitations to the standard optical microscopy: the technique can only image dark or strongly refracting objects efficiently, diffraction limits resolution to approximately 0.2 μm ,



Cell, Fig. 4 (continued) through a very thin sample to image and analyze the microstructure of materials with atomic scale resolution. The electrons are focused with electromagnetic lenses and the image is observed on a fluorescent screen, or recorded on film or digital camera. **(d)** A TEM image of the green algae *Chlamydomonas*. We can observe the ultrastructure of the nuclei, chloroplasts, and pyrenoid. **(e)** Scanning electron microscope (SEM), while TEM allows us to study the inner structure of objects (tissues, cells, viruses) and SEM is used to visualize the

surface of tissues, macromolecular aggregates, and materials. **(f)** An SEM image of a diatom, brown algae. We can see the silica theca that surround the cells with their characteristic patterns specific for each species. **(g)** The scanning tunneling microscope (STM) provides a picture of the atomic arrangement of a surface by sensing corrugations in the electron density of the surface that arise from the positions of surface atoms. **(h)** An STM image of palladium crystals

and out of focus light from points outside the focal plane reduces image clarity. Live cells generally lack sufficient contrast to be studied successfully. Internal structures of the cell are colorless and transparent.

The electron microscope uses a beam of electrons as a source of illumination instead of light. The microscope has a greater resolving power than a light-powered optical microscope, because it uses electrons that have wavelengths about 100,000 times shorter than visible light (photons), and can achieve magnifications of up to 1,000,000 times. The electron microscope uses electrostatic and electromagnetic “lenses” to control the electron beam and focus it to form an image. Two types of electron microscopes in common use are the transmission electron microscope and the scanning electron microscope (Murphy 2002).

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Cell Membrane](#)
- [Cellular Theory, History of](#)
- [Cytoplasm](#)
- [Eukarya](#)
- [Evolution, Biological](#)
- [Prokaryote](#)

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Cell Communication

- [Quorum Sensing](#)

Cell Membrane

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Cytoplasmic membrane](#); [Plasma membrane](#)

Definition

The ► [cell](#) membrane is the boundary that envelops all cells and provides a semipermeable barrier for their separation from the extracellular environment. It is constituted by a 5–8-nm-thick lipid bilayer – mainly composed of amphiphilic phospholipids – in which membrane proteins are interspersed. The cell membrane is involved in different cellular processes including active and passive traffic of substances, signal transduction, and cell adhesion and fusion. In addition to the cell membrane, inside the eukaryotic cytoplasm, there are membrane-enclosed ► [organelles](#). These specialized compartments include the nucleus, mitochondria, plastids, Golgi apparatus, vacuoles, vesicles, lysosomes, peroxisomes, and endoplasmic reticulum. Mitochondria, present in almost all eukaryotes, and plastids, present in photosynthetic eukaryotes, are double-membrane organelles, a feature indicative of their endosymbiotic origin. ► [Bacteria](#) and archaea lack membrane-enclosed compartments, with certain exceptions

such as the magnetosomes present within the nucleocytoplasm of magnetotactic bacteria and the cell compartments observed in bacteria from the phylum Planctomycetes. Some ► [virus](#) families – the so-called lipid coated viruses – are also surrounded by a membrane during their extracellular phase, derived from the host cell previously infected.

Cross-References

- [Amphiphile](#)
- [Archaea](#)
- [Bacteria](#)
- [Cell](#)
- [Cell Wall](#)
- [Eukarya](#)
- [Lipid Bilayer](#)
- [Membrane](#)
- [Membrane Potential](#)
- [Organelle](#)
- [Virus](#)

Cell Models

David Deamer
Department of Chemistry, University of
California, Santa Cruz, Santa Cruz, CA, USA

Keywords

Compartments · Encapsulation · Lipid vesicles · Permeability · Replication · Translation

Synonyms

[Artificial cells](#); [Protocell](#); [Synthetic cells](#)

Definition

Cell models are laboratory versions of simple cellular structures that exhibit some of the properties of the living state. They consist of a compartment, usually microscopic lipid vesicles,

with encapsulated functional polymers such as enzymes and nucleic acids.

History

The idea that it might be possible to assemble model cells can be traced back to 1965, when Alec Bangham discovered that phospholipids spontaneously self-assemble into closed compartments (now called liposomes) when dispersed in aqueous phases (see review by Bangham 1993). The boundary of such compartments is a ► [lipid bilayer](#) that is relatively permeable to water and small molecules like water but much less permeable to ionic solutes such as sodium and potassium ions. Efraim Racker took the next step toward cell models when he and his coworkers showed that it was possible to use detergents such as deoxycholic acid to disperse membranous components of cells (see Racker 1970). When the detergent was removed, small vesicles formed that contained the original lipids and functional proteins. Using this method, Racker and his colleagues were able to reconstitute electron transport reactions of mitochondrial and chloroplast membranes.

Similar techniques were soon applied to other biological structures and functions. For instance, Oesterhelt and Stoekenius (1971) reconstituted the proton pump of purple membranes isolated from a species of *Halobacterium* (now recognized as archaeon, rather than a bacterium) that uses the energy of a proton gradient to synthesize ATP. Racker and Stoekenius then collaborated to produce a system of reconstituted membrane vesicles containing both the proton pump of *Halobacterium halobium* and the ATP synthase of mitochondria (Racker and Stoekenius 1974). The hybrid structures could synthesize ATP using light as an energy source, which strongly confirmed Peter Mitchell's chemiosmotic hypothesis that proton gradients could drive ATP synthesis (Mitchell 1976).

When it was realized that lipid vesicles could incorporate enzymatic functions, the next step toward model cells became feasible, in which a polymerase encapsulated in liposomes would be

able to synthesize a nucleic acid. This was first attempted by Chakrabarti et al. (1994) and Walde et al. (1994) both reporting that encapsulated polynucleotide phosphorylase could synthesize an RNA homopolymer from its substrate, in this case ADP.

Overview

The point of this brief history is that relatively complex biological functions can be reconstituted by ► [self-assembly](#) of their dispersed components, so it is reasonable to consider the possibility that similar techniques might allow artificial cells to be fabricated under laboratory conditions. If this turns out to be possible, perhaps it will help define “life” and even elucidate the major steps that led to the origin of cellular life nearly four billion years ago.

Basic Methodology

What would such a system do? This question can be answered by listing the properties and functions of model cells that could conceivably be assembled in the laboratory. For the purposes of this list, it is assumed that all the nutrients and energy needed for growth and replication will be provided so that a complex metabolism will not be required:

1. Self-assembly of lipid molecules generates cellular compartments defined by boundary membranes.
2. Macromolecules are encapsulated in the compartments, yet smaller substrate molecules can cross the membrane barrier.
3. The macromolecules have the potential to grow by polymerizing the substrate molecules.
4. The membrane itself can grow by addition of lipid molecules.
5. Some of the encapsulated polymers are catalysts that can speed the growth process, and the catalysts are reproduced during growth by polymerization.
6. Genetic information is contained in the sequence of monomers in a second set of polymers and is used to direct the growth of catalytic polymers.
7. The catalytic polymers catalyze the polymerization of the genetic molecules.
8. Following a certain amount of growth, the membrane-bounded system of macromolecules divides into smaller structures, each containing the catalysts and copies of genetic information.
9. Genetic information is passed between generations by duplicating the gene sequences and sharing them between daughter cells.
10. Occasional mistakes (mutations) occur during replication or transmission of genetic information so that the system can evolve through selection.

Key Research Findings

Several research groups are beginning to study systems of genetic and catalytic molecules that are steps toward fulfilling this list of properties. For instance, Mansy et al. (2008) demonstrated that it was possible to encapsulate a short DNA template in fatty acid vesicles, then add activated nucleotides outside. The nucleotides were sufficiently permeable to enter the vesicle interior and support the sequence-dependent elongation of the DNA. In a related advance, Lincoln and Joyce (2009) developed a pair of ribozymes, each of which could catalyze the synthesis of the other by a ligation reaction that joined two smaller non-catalytic oligonucleotides. This system is not encapsulated and does not replicate a complete base sequence but illustrates in principle how an evolving system of paired ribozymes could function. The Rasmussen Group in Denmark has stepped away from biologically inspired molecular systems and is attempting to assemble a very different version of model cells (DeClue et al. 2009). In their system, the reactions occur on the surface of vesicles, rather than the interior, thereby bypassing the requirement for membrane transport of the nutrients. Furthermore, they are attempting to drive the polymerization reaction

by an input of light energy, rather than supplying activated monomers.

Another approach to model cells is to encapsulate ribosomes and translation systems in lipid vesicles. Luigi Luisi and his coworkers at the Eidgenössische Technische Hochschule in Zurich, Switzerland, made the first attempt to assemble a translation system in lipid vesicles by encapsulating ribosomes and an RNA homopolymer that codes for phenylalanine (Oberholzer et al. 1995). The phenylalanine was attached to transfer RNA so that it was ready to be used by ribosomes for peptide synthesis. However, the lipid bilayer was impermeable to the transfer RNA, so peptide bond formation was limited to the small number of tRNA-amino acid complexes that were encapsulated within the vesicles. This limitation makes the point that model cells need to have some way to transport nutrients inward across their boundary membrane.

Noireaux and Libchaber (2004) reported an elegant solution to the permeability problem. They disrupted *E. coli* cells and captured samples of the bacterial cytoplasm in lipid vesicles. The samples included ribosomes, transfer RNAs, and the hundred or so other components required for protein synthesis. The researchers then chose two genes to translate, one for green fluorescent protein (GFP), a marker for protein synthesis, and a second gene for a pore-forming protein called alpha hemolysin. If the system had worked as planned, the GFP would have accumulated in the vesicles as a visual marker for protein synthesis and the hemolysin would have allowed externally added “nutrients” in the form of amino acids and ATP to cross the membrane barrier and supply the translation process with energy and monomers. The system was functional, and the newly synthesized hemolysin allowed synthesis of GFP to continue for as long as four days. The GFP in the vesicles was monitored by its green fluorescence. A more recent example of a model cell system is the encapsulated “genetic cascade” fabricated by Ichihashi et al. (2010), in which a gene on a plasmid was transcribed by RNA polymerase to mRNA, which in turn directed the synthesis of green fluorescent protein.

The model cells containing ribosomes clearly demonstrate one fundamental property of life: they can use genetic information to synthesize a protein. Although they can grow by synthesizing one or more specific proteins, no other cellular components are produced. To approach the definition of a living system, the vesicles would need to incorporate genetic information required for a hundred or more different proteins and RNA species, over half of which are the components of the ribosomes themselves. They would need genes for polymerase enzymes so that the DNA could be replicated as part of the growth process, and a way for lipid to be synthesized, because the membranous boundary must grow to accommodate the internal growth. Transport proteins must be synthesized and incorporated into the lipid bilayer; otherwise, the vesicles have no access to external sources of nutrients and energy. A whole set of regulatory processes must be in place so that all of these functions are coordinated. Finally, when the vesicles grow to approximately twice their original size, there must be a way for them to divide into daughter cells that share the original genetic information.

It seems impossible that the first forms of life sprang into existence with such a complex system of interacting molecules. There must have been something simpler, a kind of scaffold life that was left behind in the evolutionary process leading to today’s life. Can we reproduce that scaffold? This is the challenge for research on model cells and the origin of life.

Applications

A functioning system of artificial cells will represent a major breakthrough in biotechnology. At present, the pharmaceutical industry must use recombinant DNA techniques and bacterial cultures to synthesize protein products. Model cells are simplified versions of bacterial cells, and if they can be designed to produce a desired protein in large quantities, the result would be a much more efficient, flexible, and inexpensive system for producing important therapeutic agents. See review by Pohorille and Deamer (2002).

Future Directions

One promising approach to model cells is suggested by the results reported by Lincoln and Joyce (2009). It is possible that a pair of ribozymes will be found that can catalyze their own complete synthesis using genetic information encoded in their base sequences. If the ribozymes could then function in a membrane-bounded compartment using nucleotides present in the external medium, the system could rightly be claimed to have the essential properties that are lacking so far in artificial cell models: reproduction of the catalysts and genetic information in a cellular compartment.

Cross-References

- [Cell](#)
- [Lipid Bilayer](#)
- [Nucleic Acids](#)
- [Protocell](#)
- [Self-Assembly](#)

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Cell Motility

- [Motility](#)

Cell Wall

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

The cell wall is an external layer that surrounds some types of ► [cells](#). It has structural, protective, and functional roles (filtering capacities for the selective uptake of substances for cell metabolism). It is located outside the cell membrane. The cell wall is found in bacteria, plants, fungi, algae, and some Archaea. The main functions of cell walls are (1) to provide tensile strength and limited plasticity to the cell, (2) to provide mechanical support, (3) cutinized, it is used to prevent water loss, (4) to provide mechanical protection, and (5) to contribute to cell-cell communication. The structure of the cell wall differentiates Gram-positive from ► [Gram-negative bacteria](#), a property of important phylogenetic value.

Cross-References

- [Cell](#)
- [Cell Membrane](#)
- [Gram-Negative Bacteria](#)
- [Gram-Positive Bacteria](#)
- [Peptidoglycan](#)
- [Protoplast](#)

Cell, Minimal

Rosario Gil

Institute for Integrative Systems Biology, Universitat de València – CSIC, Paterna (València), Spain

Keywords

Minimal genome · Synthetic biology · Top-down approach · Bottom-up approach

Definition

A minimal cell is a hypothetical biological system that possesses only the necessary and sufficient attributes to be considered alive. Therefore, it must be able to maintain its own structures (homeostasis), self-reproduce, and evolve in a supportive, protected, and stable environment.

Overview

A minimal living cell must still retain all essential genes needed to perform all essential functions, that is, a minimal genome. However, there is no conceptual or experimental support for the existence of *one* form of minimal cell. Different essential functions can be defined depending on the environment, and numerous versions of minimal genomes can be envisaged to perform such functions even in the same conditions (Koonin [2003](#)). Computational and experimental studies (mostly bacterium centered) to define the characteristics of a minimal cell (reviewed in Feher et al. [2007](#); Moya et al. [2009](#)), converge in the conclusion that different minimal hypothetically viable cells can be conceived, possessing a universal genetic machinery supported by a diversity of minimal ecologically dependent metabolic charts (Gil et al. [2004](#)).

Defining the minimal genome does not fully define a minimal cell. Several levels of complexity (topological genome architecture, transcriptome, proteome, metabolome, and interactome) that are not taken into account in minimal genome studies (Fisunov et al. [2011](#)) can be explored through theoretical computer models based on the massive amount of molecular and cellular biology data available (Di Ventura et al. [2006](#); Shuler et al. [2012](#); Goldberg et al. [2018](#); Martínez and Reyes-Valdés [2018](#)). However, to date, no single computational method can fully explain complex phenotypes in terms of molecular components and their interactions, and it is difficult to determine and model all parameters involved (Karr et al. [2012](#)).

Nowadays, one of the main goals of synthetic biology is the generation of minimal cells, to improve our basic understanding of living

systems and to be used as containers for introducing genetic modules to customize cells for biotechnological purposes (Moya et al. 2009). There are two complementary and alternative ways to do so, namely *top-down* and *bottom-up* approaches. The *top-down* strategies, also called genome-driving cell engineering (O'Malley et al. 2008), start from simple modern cells and intend to simplify them further through the removal of non-essential genetic elements. The *bottom-up* approaches aim at constructing the simplest system that could be considered alive from scratch (Luisi 2002), by putting together the essential non-living components: a self-replicating nucleic acid, a metabolic machinery, and an encapsulating structure (Stano and Luisi 2011). Although no such system has been built yet, the field is experiencing a notable progress, allowing to design more refined cell-like compartments (Stano 2019). In addition to the above-mentioned approaches, there is a third integrative strategy known as *middle-out* approach. Using it, scientists at the J. Craig Venter Institute (JCVI) were able to design, synthesize, and transplant into a pre-existing cell, the smallest genome of a free-living organism, generating *Mycoplasma mycoides* strain JCVI-syn3.0, the first semi-synthetic almost-minimal cell (Hutchison et al. 2016).

Research based on extant cells to define a hypothetical minimal cell is not related to the study of the origin of life because it is impossible to identify which one of the putative alternatives was adopted by primitive cells. In contrast, some *bottom-up* research programs are motivated by the possibility of better understanding this topic, by recreating some of the steps that precellular systems might have followed under primitive Earth conditions (Pereto and Catala 2007).

Cross-References

► [Genome, Minimal](#)

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Cellular Automata

Marco Tomassini
Information Systems Department, University of
Lausanne, Lausanne, Switzerland

Keywords

Automata · Complex systems · Discrete
dynamics · Simulation

Synonyms

[Tessellation automata](#)

Definition

Cellular automata (CA) are dynamical systems in which space and time are discrete. A cellular automaton consists of an array of cells, each of which can be in one of a finite number of possible states, updated synchronously in discrete time steps, according to a local, identical interaction rule. The state of a ► [cell](#) at the next time step is determined by its own current state and the current states of a surrounding neighborhood of cells (Wolfram 1994).

Overview

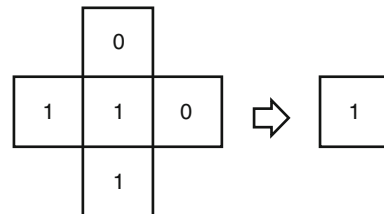
Cellular automata were originally conceived by Ulam and von Neumann in the 1940s to provide a formal framework for investigating the behavior of

complex, extended systems (von Neumann 1966). In particular, von Neumann asked whether we could use purely mathematical-logical considerations to discover the specific features of automata that make them formally analogous with self-constructing and self-replicating biological systems.

Thanks to their simplicity and appeal, over the years, CA have been applied to the study of general phenomenological aspects of the world, including communication, computation, construction, growth, reproduction, competition, and evolution. CA have also been used successfully as an easy way to program models for studying phenomena of interest in several scientific fields, including physics, biology, and computer science.

Basic Methodology

As an example, let us consider the *parity rule* for a two-state, five-neighbor, two-dimensional CA. Each cell is assigned a state of 1 at the next time step if the combined parity of its current state and the states of its four neighbors in the *N*, *E*, *S*, and *W* directions is odd and is assigned a state of 0 if the parity is even. There are 32 different combinations for the states of the neighbors, including the central cell itself. The rule table consists of entries of the form.

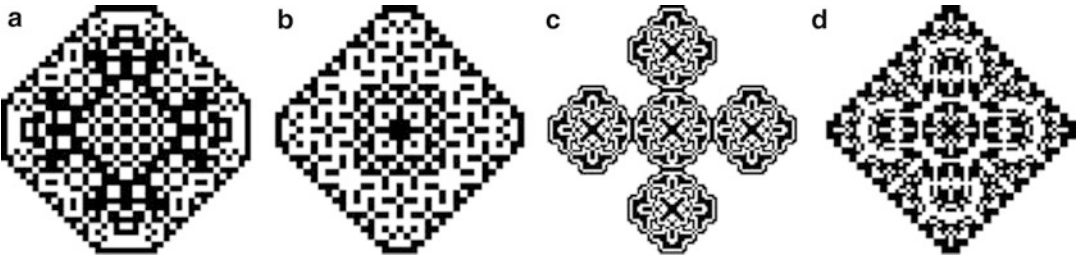


This means that if the current state of the cell is 1 and the states of the north, east, south, and west cells are 0, 0, 1, 1, respectively, then the state of the central cell at the next time step will be 1 (because three bits in the neighborhood are in state 1). The rule is completely specified by the rule table given in Table 1. Fig. 1 demonstrates patterns that are produced by the parity CA.

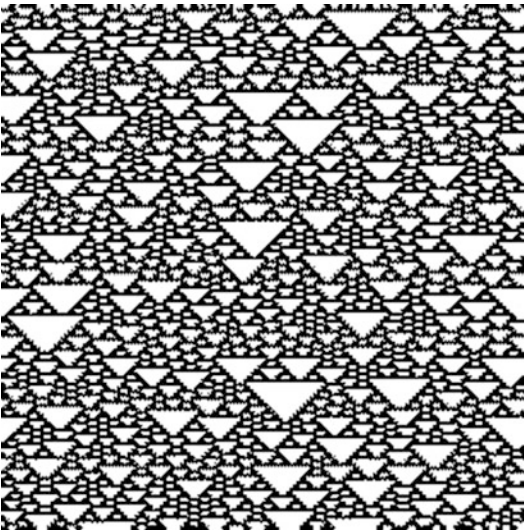
The simplest CA are one dimensional with only two possible states per cell and a neighborhood constituted of the cell itself and its immediate right and left neighboring cells. Fig. 2 shows an example of the time evolution of an elementary CA.

Cellular Automata, Table 1 Parity rule table. CNESW denotes the current states of the center, north, east, south, and west cells, respectively. S_{next} is the state of the central cell state at the next time step

CNESW	S_{next}	CNESW	S_{next}	CNESW	S_{next}	CNESW	S_{next}
00000	0	01000	1	10000	1	11000	0
00001	1	01001	0	10001	0	11001	1
00010	1	01010	0	10010	0	11010	1
00011	0	01011	1	10011	1	11011	0
00100	1	01100	0	10100	0	11100	1
00101	0	01101	1	10101	1	11101	0
00110	0	01110	1	10110	1	11110	0
00111	1	01111	0	10111	0	11111	1



Cellular Automata, Fig. 1 Patterns produced by the parity rule, starting from a 20×20 rectangular pattern. White squares represent cells in state 0, and black squares represent cells in state 1. **a** After 30 time steps ($t = 30$), **b** $t = 60$, **c** $t = 90$, **d** $t = 120$



Cellular Automata, Fig. 2 A one-dimensional elementary CA is shown, where the horizontal axis depicts the configuration at a certain time t and the vertical axis depicts successive time steps (increasing down the page). The system starts in a randomly generated configuration of zeroes and ones

More formally, a cellular automaton A is a quadruplet:

$$A = (S, G, d, f)$$

where S is a finite set of states, G is the cellular neighborhood, $d \in \mathbb{Z}^+$ is the dimension of A , and f is the local cellular interaction rule, also referred to as the transition function.

Given the position of a cell $\mathbf{i}$, $\mathbf{i} \in \mathbb{Z}^d$, in a regular d -dimensional uniform lattice, or *grid* (i.e., $\mathbf{i}$ is an integer vector in a d -dimensional space), its *neighborhood* G is defined by

$$G_i = \{\mathbf{i}, \mathbf{i} + \mathbf{r}_1, \mathbf{i} + \mathbf{r}_2, \dots, \mathbf{i} + \mathbf{r}_n\},$$

where n is a fixed parameter that determines the neighborhood size and $\mathbf{r}_j$ is a fixed vector in the d -dimensional space.

The *local transition rule* f

$$f : S^n \rightarrow S$$

maps the state $s_i \in S$ of a given cell i into another state from the set S , as a function of the states of the cells in the neighborhood G_i .

Consider a one-dimensional CA with only two states $S = \{0, 1\}$. In this case, f is a function $f: \{0, 1\}^n \rightarrow \{0, 1\}$ and the neighborhood size n is usually taken to be $n = 2r + 1$ such that

$$s_i(t+1) = f(s_{i-r}(t), \dots, s_i(t), \dots, s_{i+r}(t)),$$

where $r \in \mathbb{Z}^+$ is a parameter, known as the *radius*, representing the standard one-dimensional cellular neighborhood. Considering the $r = 1$ case, one obtains the so-called *elementary* CA, for which the neighborhood size is $n = 3$:

$$\begin{aligned} f: \{0, 1\}^3 &\rightarrow \{0, 1\}, s_i(t+1) \\ &= f(s_{i-1}(t), s_i(t), s_{i+1}(t)). \end{aligned}$$

In this case, the domain of f is the set of all 2^3 triplets, which gives rise to $2^8 = 256$ distinct elementary rules (Wolfram 1994). For finite-size grids, spatially periodic boundary conditions are frequently assumed, resulting in a circular grid. An example of an elementary rule has been shown in Fig. 2.

For a CA of size N , a *configuration* of the grid at time t is defined as

$$C(t) = (s_0(t), s_1(t), \dots, s_{N-1}(t)),$$

where $s_i(t) \in S$ is the state of cell i at time t . The progression of the CA in time is then given by the iteration of the *global mapping* F :

$$F: C(t) \rightarrow C(t+1), t = 0, 1, \dots$$

through the simultaneous application in each cell of the local transition rule f . The global dynamics of the CA can be described as a directed graph, referred to as the CA's *phase space* (Wolfram 1994).

Key Research Findings

Cellular automata have been proved to be universal computing devices and, as such, they can compute any computable function (Wolfram

1994). The question of whether cellular automata can model not only general phenomenological aspects of our world but also directly model the laws of physics themselves was raised by Fredkin and Toffoli (1982). A primary theme of this research is the formulation of computational models of physics that are *information preserving* and thus retain one of the most fundamental features of microscopic physics, namely, reversibility (Fredkin and Toffoli 1982; Margolus 1984; Toffoli 1980). This approach has been used to provide extremely simple models of common differential equations of physics, such as the heat and wave equations (Toffoli 1984) and the Navier-Stokes equation (Frisch et al. 1986). CA also provide a useful model for a branch of dynamical systems theory which studies the emergence of well-characterized collective phenomena, such as order, turbulence, chaos, symmetry breaking, and fractality, in discrete systems (Chopard and Droz 1998; Vichniac 1984).

Applications

For engineers and scientists, cellular automata are a particularly useful modeling device when the phenomenon to be studied does not lend itself to a clear mathematical model such as those represented by differential equations. In this case, simple local rules that are motivated by the phenomenon at hand may give rise to a global behavior that approaches that of the original system. Examples of this range from ► [chemotaxis](#), to snow transport by the wind, and to car traffic, just to name a few (Chopard and Droz 1998). Of course, how to choose the local cellular automata rules in order to produce the desired global behavior is a hard problem. It can be approached by trial and error or by heuristics such as evolutionary algorithms (Sipper 1997; Crutchfield et al. 2003) in which good rules evolve out of a population of possible candidate rules by the Darwinian principles of variation and selection. CA have thus been used as a simple and easy to implement model for studying phenomena of interest in several scientific fields, including physics, biology, engineering, and computer science.

Future Directions

In summary, CA suggest a new approach in which complex behavior arises in a bottom-up manner from nonlinear, spatially extended, local interactions and provide a simple and useful model for many complex systems arising in the sciences and in engineering.

CA exhibit massive parallelism, locality of cellular interactions, and simplicity of basic hardware components. As a consequence, in recent years, there has been a growing interest in the utilization of CA as actual embedded computing devices, e.g., in low-level vision, pseudorandom number generation, and cryptography (Chaudhuri et al. 1997). A trend that could become important in the future is the search for practical quantum computing CA devices, a concept that is potentially capable of revolutionizing computation and its applications; quantum cellular automata belong to this class (Pérez-Delgado and Cheung 2007).

Cross-References

- [Autopoiesis](#)
- [Biological Networks](#)
- [Chaotic Region](#)
- [Self-Replication](#)

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Cellular Theory, History of

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Keywords

Chromosomes · Globules

History

The cellular theory was formulated after more than one and a half century of microscopic observations. Indeed, the invention of microscope during the seventeenth century offered new investigations to naturalists. For example, Robert Hooke (1635–1703) in his *Micrographia* (1665), Antoni van Leeuwenhoek (1632–1723), and Jan Swammerdam (1737–1780) observed microscopic objects: individual entities, often named animalcules, and parts of organisms. However, they did not have concepts to consider all these new observations. For example, it is important to notice that when Hooke used the word cell to name some little spaces that he had observed in vegetable organism, he did not expect to conceptualize anything, and his intention was only descriptive.

During all the eighteenth century, microscopic observations were more and more accurate. They showed a broad diversity of animalcules and microscopic structures in living beings. At the beginning of the nineteenth century, some theories claimed that there could be a unity in the microscopic structure. The French botanist Charles-François Brisseau de Mirbel (1776–1854) suggested that plants were constituted by a set of membranes with a lot of pores. A few years later, René Joachim Henri Dutrochet (1776–1847), who had discovered the osmotic phenomenon, claimed that cells constituted plants. However, in the wall of these cells, there could be some little globules that could be the fundamental entities. Then, François-Vincent Raspail (1794–1878) (one of the inventors of the microscopic colorations) considered that living beings were made of globules that were to be formed in the wall of other globules which would fit into each other. In that period, Lorenz Okenfuss (Oken) (1779–1851) claimed that living beings were a synthesis of infusorians. All these proposals have in common the fact that they are conceptions about the possibility of a microscopic and universal structure.

In 1838, the German botanist Matthias Schleiden (1804–1881) claimed that vegetable organisms were composed of cells in which there was a systematic structure, the cytoblast (which will be later named nucleus). Besides, Schleiden suggested that cells were the result of the accumulation of a liquid, the cytoblastem, between the cytoblast and the membrane. His colleague, Theodor Schwann (1810–1882), a specialist of animal physiology, generalized this theory to animals and indicated that the cytoblastem came from the interstitial fluid.

During the 1850s, Robert Remak (1815–1865) and Rudolph Virchow (1821–1902) independently (Remak in 1855 and Virchow in 1855–1858) asserted that every cell was the result of the division of a previous cell. From this time forth, the concept of cell has become central in biology.

During the end of the nineteenth century, the progress of microscopy led to observations of chromosomes and to the description of mitosis

(Fleming 1882) and meiosis (Boveri, Hertwig 1887–1892).

Cross-References

- [Animalcules](#)
- [Cell](#)
- [Protoplasmic Theory of Life](#)
- [Spontaneous Generation, History of](#)

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Cenancestor

Luis Delaye
Departamento de Ingeniería Genética,
CINVESTAV-Irapuato, Irapuato, Gto, Mexico

Synonyms

[Last universal common ancestor](#)

Definition

The cenancestor is the most recent ancestral species from which all extant living species have evolved. The idea that all present-day life is related by common ancestry was already suggested by Charles Darwin in *The Origin of Species* (1872). Nowadays, this hypothesis is strongly supported by the similarities at the biochemical and molecular levels of all organisms belonging to the three domains of life, i.e., Archaea, Bacteria, and Eukarya. The nature of this ancestral entity continues to be a matter of debate. Its level of complexity (in number of genes), the chemical nature of its genome (whether DNA or RNA), or its prokaryotic-like nature have been discussed along other aspects of its biology.

Cross-References

- [Common Ancestor](#)
- [Darwin's Conception of the Origins of Life](#)
- [Domain \(Taxonomy\)](#)
- [Homology](#)
- [Last Universal Common Ancestor](#)
- [Phylogeny](#)

Centaurs (Asteroids)

Therese Encrenaz¹ and Hervé Cottin²

¹LESIA, Observatoire de Paris, PSL Université, CNRS, Sorbonne Université, Université de Paris, Meudon, France

²Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, F-94010 Créteil, France

Definition

The Centaurs are outer ► [asteroids](#) whose orbits are mostly confined between those of Jupiter and Neptune. Due to giant planets' perturbations, these objects have transient orbits with typical lifetimes of a few million years. There are a few hundreds of Centaurs presently known, among them (2060) Chiron (also named 95P/Chiron), (5145) Pholus, and (10199) Chariklo, the biggest Centaur found to date with a diameter of 260 km. Saturn's satellite Phoebe is believed to be a captured Centaur. This population appears to be intermediate between asteroids and ► [comets](#), as any Centaur coming close enough to the Sun is expected to show cometary activity. The total number of Centaurs of size above 1 km in diameter is estimated to be above 40,000 objects.

Cross-References

- [Asteroid](#)
- [Comet](#)
- [Kuiper Belt](#)
- [Trans-neptunian Object](#)

Center of Mass

- [Barycenter](#)

Center of Mass Velocity

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Synonyms

[Barycenter velocity](#)

Definition

The center of mass velocity of a system of massive points or objects is the velocity of the point where the resultant force of gravitational attraction acts. The system's whole mass can be considered to be concentrated at this point, for the purpose of calculations. The motion of the center of mass of an object in free fall is the same as the motion of a point object located there.

Centre for Advanced Studies in Astrobiology and Related Topics (CASA*)

- [CASA*, Poland](#)

Ceres

Ralf Jaumann

Institute of Geological Sciences, Planetary Sciences and Remote Sensing, Freie Universität Berlin, Berlin, Germany

Keywords

Asteroid · Dwarf planet

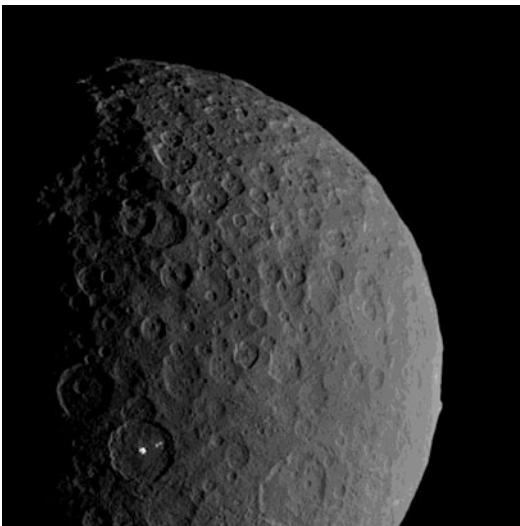
Definition

Discovered in 1801 by Giuseppe Piazzi, 1 Ceres is the largest and one of the oldest and most intact objects in the asteroid belt, cataloged by the IAU as a ► [dwarf planet](#) in 2006. Ceres orbits the ► [Sun](#) at a distance of 2.76 AU and differs from any other ► [asteroid](#) visited so far. Its surface is covered with ► [clay](#), a hydrated ► [rock](#) alteration product, and also shows water ice frost in the regolith. This is consistent with thermal models making Ceres an icy object that has been subject to differentiation and hydrothermal activity and that hosts a liquid brine-like subsurface layer even today with evidence for cryovolcanism. The NASAs Dawn spacecraft orbited Ceres for 3.5 years from 2015 to 2018.

Overview

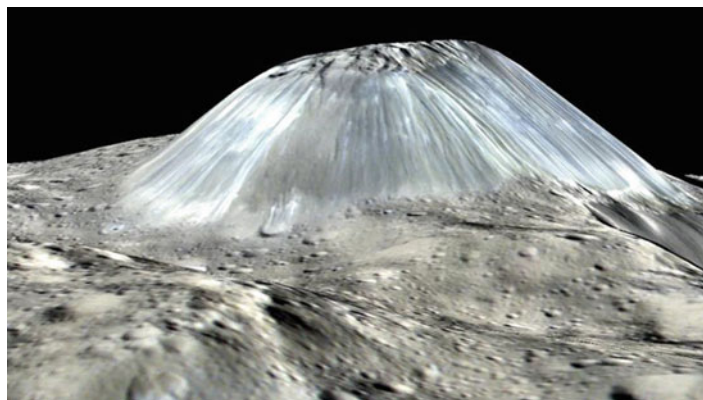
1Ceres (Fig. 1) is an oblate spheroid with a best-fitting ellipsoidal shape of $483.1 \times 481.0 \times 445.9 \pm 0.2$ km, a mass of $(938.416 \pm 0.013) \times 10^{18}$ kg, a density of

$2162 \pm 0.0008 \text{ kg/m}^{-3}$ (Park et al. 2016), a rotation period of 9.074170 ± 0.000001 h, and an orbital period of 4.6 years (Thomas et al. 2005; Russell et al. 2016; Konopliv et al. 2018). Ceres is classified as a C- or G-type asteroid, sharing similarities with carbonaceous chondrites. The physical properties of Ceres are consistent with a differentiated structure of a rocky core, a thick wet outer ► [mantle](#) containing ► [water](#) ice and brines and a desiccated surface (Russell et al. 2016). Its surface temperatures vary with latitude from 130 K at the poles to 180 K at the equator, reaching a maximum of 235 ± 4 K (Li et al. 2006; Tosi et al. 2015). The surface single scattering ► [albedo](#) varies from 0.094 to ~ 0.11 with the bright spot in Occator crater reaching 0.67 to 0.80 (Li et al. 2016). Ceres' surface is heavily cratered, but due to the weak interior, larger craters are morphologically relaxed. Ceres has a mechanically strong lithosphere with a weaker deep interior implying Ceres' icy shell to be in ► [hydrostatic equilibrium](#) (Russell et al. 2016; Buczkowski et al. 2016). The gravity field is consistent with a rigid crust floating on a more liquid substratum-balancing deficiency, so-called Airy isostatic compensation, limiting Ceres' crustal density to be between 1200 and 1600 kg/m^3 with mean crustal thickness between 27 and 43 km (Konopliv et al. 2018). Ceres' dry surface displays hydroxylated silicates, including ammoniated clays (Russell et al. 2016). The spectral analysis yields a composition of the surface of a dark component (carbon, magnetite?), Mg-phyllosilicates, ammoniated clays, carbonates, and salts indicating extensive water-related processes, chemical differentiation, and endogenous, global-scale aqueous alteration (De Sanctis et al. 2018). Sodium carbonates have been identified in several areas on the surface, notably in Occator bright faculae (De Sanctis et al. 2018). Organic matter has also been discovered in several places, most conspicuously in a large area close to the Ernutet crater (De Sanctis et al. 2018). The presence of abundant volatiles at depth is supported by geomorphologic features such as flat crater floors with pits, lobate flows of materials, and a singular mountain that appears to be an extrusive cryovolcanic dome (Buczkowski et al. 2016; Ruesch et al. 2016). Ahuna Mons (Fig. 2) is a



Ceres, Fig. 1 Dawn took this image during its third extended-mission science orbit (XMO3) in February 2017, from about 7500 kilometers above the surface of Ceres. Occator crater with the central white dot is 92 km in diameter. Ahuna Mons appears at the limb lower right as small mountain against the dark sky (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA). https://photojournal.jpl.nasa.gov/jpegMod/PIA11240_modest.jpg

Ceres, Fig. 2 Ceres' cryovolcano, Ahuna Mons, in perspective view. The spacecraft's framing camera took the images from Dawn's low-altitude mapping orbit, from an altitude of 385 km in August 2016. The mountain is 4 km high (NASA/JPL-Caltech/UCLA/MPS/DLR/IDA). <https://photojournal.jpl.nasa.gov/catalog/PIA20915>



~17-km-wide and 4-km-high mountain. Its summit topography is concave downward, and its flanks are at the angle of repose. The morphology is characterized by troughs, ridges, and hummocky areas at the summit, indicating multiple phases of activity, such as down-slope lineations on the flanks, due to rock-falls and accumulation of slope debris (Ruesch et al. 2016). Ahuna Mons is a volcanic dome of extruded material of high viscosity with recent activity within the past 210 ± 30 million years (Ruesch et al. 2016). Similar cryovolcanic activity occurs in the Occator impact crater. Cryovolcanism on Ceres is due to hydrated salts with low eutectic temperatures and low thermal conductivities enabling the presence of cryomagmatic hydrothermal brine-related liquids (Russell et al. 2016; De Sanctis et al. 2018).

- Differentiation, Planetary
- Dwarf Planet
- Heat Flow, Planetary
- Heat Transfer, Planetary
- Hydrosphere
- Hydrostatic Equilibrium
- Hydrothermal Environments
- Interior Structure, Planetary
- Mantle
- Minor Planet
- Phyllosilicates, Extraterrestrial
- Primordial Heat
- Regolith, Planetary
- Rock
- Rotation Planet
- Silicate Minerals
- Space Weathering
- Sun (and Young Sun)
- Water
- Water Activity

Cross-References

- Albedo
- Albedo Feature
- Ammonia
- Asteroid
- Asteroid Belt, Main
- Carbonaceous Chondrite
- Carbonate, Extraterrestrial
- C-Asteroid
- Clay
- Core, Planetary
- Crater, Impact
- Crust
- Cryovolcanism

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Cerium, Anomalies of

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

Cerium (Ce) is the second rare-earth element (REE) in the periodic table, most of which are trivalent at the conditions prevalent in the mantle, the crust, and planetary surfaces. In the modern ocean, the redox boundary between trivalent and tetravalent Ce is close enough to the O_2 – H_2O equilibrium that a substantial fraction of this element is oxidized and rapidly scavenged by Fe and Mn oxides. Excess Ce with respect to adjacent REE La and Pr is common in Mn nodules and encrustations, which leaves seawater, phosphates, and carbonates with a deficit. Cerium anomalies in sediments and sedimentary rocks are useful proxies for the state of oxidation in the ocean and the atmosphere in the past.

Cross-References

- [Chert](#)
- [Great Oxidation Event](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygenation of the Earth's Atmosphere](#)

CH

- [Methyldidyne \(CH\)](#)

CH⁺

- [Methyldidyne Cation \(CH⁺\)](#)

CH₂

- [Methylene \(CH₂\)](#)

CH₂CHCN

- [Vinyl Cyanide \(CH₂CHCN\)](#)

(CH₂OH)₂

- [Ethylene Glycol \(HOCH₂CH₂OH\)](#)

CH₃

- [Methyl Radical \(CH₃\)](#)

CH₃CH₂CHO

- [Propionaldehyde](#)

CH₃CH₂CN

- [Ethyl Cyanide \(CH₃CH₂CN\)](#)

CH₃CHCH₂

- [Propylene \(CH₃CHCH₂\)](#)

CH₃CHNH

- [Ethanimine](#)

CH₃Cl

- [Chloromethane \(CH₃Cl\)](#)

CH₃CN

- [Acetonitrile](#)

CH₃COOCH₃

- [Methyl Acetate \(CH₃COOCH₃\)](#)

CH₃O

- [Methoxy Radical \(CH₃O\)](#)

CH₃OCH₃

- [Dimethyl Ether \(CH₃OCH₃\)](#)

CH₃SH

- [Methanethiol \(CH₃SH\)](#)

CH₄

- [Methane](#)

Chain of Being

- [Great Chain of Being](#)

Chalcedony

- [Chert](#)

Chalcophile Elements

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

In the Berzelius-Goldschmidt classification, *chalcophile elements* are elements with a low affinity for oxygen and which preferentially bond with sulfur to form sulfides. Their name derives not from sulfur but from copper, which also forms sulfides. This group comprises transition elements (Cu, Zn, Cd, Ag, Hg), heavy metals (Ga, In, Sn, Pb, Po, Bi, Tl), and metalloids (Ge, S, Sb, Se, Te, As). As a consequence of their relatively low condensation temperatures (500–1,100 K), most of these elements are depleted in terrestrial planets with respect to chondrites.

Cross-References

- [Lithophile Elements](#)
- [Siderophile Elements](#)

Chance and Randomness

Francesca Merlin

CNRS UMR 8690 IHPST & Université Paris 1, Paris, France

Keywords

Chance · Determinism · Indeterminism · Probability · Randomness · Unpredictability

Synonyms

[Haphazardness](#); [Indeterminacy](#); [Stochasticity](#); [Uncertainty](#)

Definition

Chance and randomness are usually considered as synonymous; however, they can have different meanings, in several scientific fields as in everyday contexts. In particular, chance has a broader scope than randomness, the latter being often interpreted according to more specific mathematical connotations. Broadly speaking, both are used to qualify events that are unpredictable in the sense that they have no particular aim or direction (unbiased events) and that they occur in an irregular and disordered (haphazard) way which makes it difficult to make money betting.

Overview

Chance is a double-faced notion including subjective chance, which concerns our knowledge of real events, and objective chance, which refers to an inherent property of the structure of the world, independently of our knowledge. Chance and randomness are often used as counterparts to determinism: a random process is said to be nondeterministic in the sense that, from a set of starting conditions, it can produce different outcomes according to some law of probability. However, neither notion is necessarily incompatible with the assumption of determinism. Subjective chance, when defined as ignorance of the real underlying causes, implies that there is no chance in the real world, but for human knowledge: for instance, we might assign a 50% chance to both possible outcomes of the flip of a fair coin (“heads” and “tails”) because we ignore the underlying causes (e.g., the way the coin is flipped). This recalls the Laplacian notion of chance, which is a deterministic notion; nevertheless, subjective chance is also compatible with indeterminism in so far as the underlying causes that we do not know about might still be the result of an indeterministic process. Objective chance can refer to an event that is not planned (or by design), as in Aristotle’s accidental meeting with the person who owed him money. This notion implies the confluence of two or more independent causal chains: in this sense, Cournot claimed that the fact that two brothers

serving in different armies died the same day is a matter of chance. Chaotic processes provide an example of chance as sensitivity to initial conditions in the sense that small differences in initial conditions may yield radically different outcomes. Whereas all notions of chance mentioned above are noncommittal to determinism nor indeterminism, this is not the case for chance according to the Copenhagen interpretation of quantum mechanics, according to which indeterminism is considered a true description of the microlevel world. Randomness mostly has a mathematical connotation, like in algorithmic information theory where a binary sequence is said to be Kolmogorov random if and only if it is incompressible, i.e., it is shorter than any computer program that can produce it. Other formal definitions of a random sequence (e.g., Martin-Löf’s) have been recently formulated, each of which tries to capture our intuitive notion of randomness.

Cross-References

- [Materialism](#)
- [Physicalism](#)
- [Reductionism](#)
- [Vitalism](#)

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Chandrasekhar's Limit

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Chandrasekhar's limit, named after the Indian astrophysicist Subrahmanyan Chandrasekhar, is a critical mass of about 1.4 solar masses that the core of a ► [star](#) can attain, before collapsing to become a neutron star or a black hole. This core is built from the heavy elements that the star synthesizes during its lifetime through nuclear fusion. This limit is thus the maximum mass of a stable ► [white dwarf](#) star. Beyond this critical mass, the relativistic electron degeneracy pressure is unable to counteract the gravitational forces. Stars with mass higher than eight solar masses develop a degenerate core, whose mass will grow until it exceeds this limit, leading to a ► [supernova](#) explosion.

Cross-References

- [Supernova](#)
- [White Dwarf](#)

Channels

- [Valley Networks](#)

Chaotic Region

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Chaotic terrains](#)

Definition

A chaotic region is a distinctive area of fractured and disintegrated terrain. It is characterized by a textured matrix featuring randomly orientated flat-topped mesas, knobs of various sizes, and deep depressions. Chaoses are primarily found on ► [Mars](#) in regions unofficially called “chaotic terrains.” The latter is located east of ► [Valles Marineris](#) and involves parts of the huge ► [outflow channel](#) floors. Various processes are suggested to have formed the Martian chaoses, including disruption and collapse of an icy ► [permafrost](#) layer initiated by pressurized groundwater, the action of aqueous processes, and multiple episodes of nested surface collapses caused by the removal of subsurface material, either ground ice or magma. Chaos regions can also be found on ► [Jupiter's moon Europa](#), which is suggested to be sites of melt-through from the subsurface.

Cross-References

- [Europa](#)
- [Jupiter](#)
- [Mars](#)
- [Outflow Channels](#)
- [Permafrost](#)
- [Valles Marineris](#)

Chaotic Terrains

- [Chaotic Region](#)

Chaotropy

Ricardo Amils^{1,2} and José Manuel Martínez²

¹Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

²Centro de Biología Molecular Severo Ochoa,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Water stress · Mg_2Cl · LiCl , Ethanol · Urea ·
Phenol · Hydrogen bonds

Definition

Chaotropy is the disorder exerted by chaotropic agents on cellular macromolecular interactions.

Overview

Chaotropes are compounds that destabilize the secondary structure and the folding of biomolecules by replacing the water in the hydration shells, affecting the hydrogen bonds or penetrating in the hydrophobic areas. These compounds entropically disorder cellular macromolecules, via a chaotropy-mediated mode of action, inducing cellular water stress. Whereas this stress is independent of osmotic stress, it can occur concomitantly with osmotic stress. On the contrary, kosmotropes are compounds that favor the formation of stronger intermolecular hydrogen bonds than those formed between water molecules themselves. As a result, biomolecules become more rigid and their interactions more stable. Recent studies elaborate the reasons why chaotropy and kosmotropy refer to the entropic effects of substances on the biomolecules system rather than the solvent per se. Whereas parameters such as temperature, pressure, pH, hydrophobicity, and water activity can be quantified via standard scales of measurement, the chaotropic/kosmotropic activities of environmentally ubiquitous substances have no widely accepted, universal scale. Hallsworth and collaborators developed a method to compare the chaotropy and kosmotropy of different compounds using an agar-gelation assay. Ethanol, urea, MgCl_2 , LiCl , and phenol are well-known chaotropic agents, while NaCl , KCl , and NH_4SO_4 exhibit a potent kosmotropic activity. Knowing the natural existence of chaotropic and kosmotropic agents in the environment, it is considered of interest to know how their presence affects the development of microorganisms, regulating the interaction between macromolecules. Some natural environments, like the hypersaline anoxic lakes of the Mediterranean Ridge and Don Juan Pond (Antarctica) or Salar de Uyuni (Bolivia),

are well-known chaotropic model systems due to the detection of high concentrations of MgCl_2 and LiCl . Considering that (i) chaotropy is an important factor searching for the limits of life, (ii) that kosmotropic agents could buffer the negative effect of chaotropy, and (iii) the high concentration of chaotropic salts is detected on Mars and other bodies of the Solar System, it is considered a subject of interest in astrobiology.

Cross-References

- [Hydrophobicity](#)
- [pH](#)
- [Water Activity](#)

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Charge Exchange

► Charge Transfer

Charge Transfer

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Keywords

Chemical reactions · Interstellar medium

Synonyms

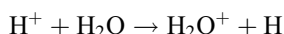
[Charge exchange](#)

Definition

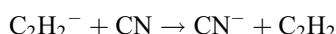
Charge transfer is a chemical process whereby electric charge is transferred from a positive or negative ion (cation or ► [anion](#)) to a neutral atom or molecule.

Overview

Simple charge transfer reactions between atomic or molecular ions and neutral atoms and molecules are important in many astronomical environments, ranging from ► [planetary nebulae](#) to ► [comets](#), to dark ► [molecular clouds](#). Reactions of the type

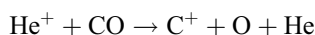


and

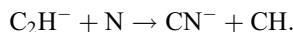


are ► [exothermic](#), rapid, and proceed with no molecular rearrangement. On the other hand,

dissociative charge transfer reactions involve the breaking of chemical bonds, examples of which are:



and



Cross-References

- [Anion](#)
- [Comet](#)
- [Exothermic](#)
- [Interstellar Chemical Processes](#)
- [Molecular Cloud](#)
- [Planetary Nebula](#)

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Charge-Coupled Device

- [CCD](#)

Charon

Tanguy Bertrand and Emmanuel Lellouch
Laboratoire d'Etudes Spatiales et
d'Instrumentation en Astrophysique (LESIA),
Observatoire de Paris, CNRS, Meudon, France

Keywords

Pluto system · Dwarf planet · Trans-neptunian object

Definition

Charon is the largest moon of Pluto and a massive Kuiper Belt object (currently the sixth largest

known trans-neptunian object). It was visited for the first time by the New Horizons spacecraft during its flyby of the Pluto system on July 14, 2015, which allowed for detailed observation of its surface. The name *Charon* refers to the Greek mythological figure who guided souls across the River Styx in the kingdom of Hades, which in Roman mythology corresponds to Pluto. James W. Christy, who discovered Charon, also suggested this name as a scientific-sounding version of his wife Charlene's nickname, "Char."

Overview

Discovery and Early Characterization

Charon was discovered on June 22, 1978, by Christy, who noticed that the available (astrometric-aimed) images of Pluto presented a slightly elongated shape with variable orientation that could be explained if there was another object periodically orbiting Pluto but not distant enough to be fully resolved. Charon's existence was indisputably proven when the Pluto-Charon system entered a period of mutual eclipses and transits in 1985–1990. In the 1990s, the Hubble Space Telescope imaged both Pluto and Charon as separate disks (their maximum separation is ~ 0.9 arcseconds, and Charon's apparent size is ~ 0.05 arcseconds).

Mass, Size, and Internal Structure

Charon's diameter is 1212 ± 6 km, just over half that of Pluto's, and larger than the dwarf planet Ceres. Its mass is 12.2% that of Pluto's, and its density is 1.702 ± 0.021 g/cm³, slightly lower than that of Pluto (1.860 ± 13 g/cm³). This suggests that Charon is made of 55% rock and 45% water ice whereas Pluto is about 70% rock, and supports the idea that Charon was created from Pluto's icy mantle material by a giant impact (see "[Formation](#)" below).

Orbital and Spin Parameters

Charon orbits Pluto at a distance of 19,590 km or ~ 17 Pluto radii, making it 20 times closer to it than Earth's Moon is to Earth. With a mass ratio of

about 8, the system barycenter is outside of Pluto, and consequently the Pluto–Charon system can be thought of as a dwarf double planet system, as both bodies rotate around the system's center of mass.

As the result of full tidal evolution, the two objects are gravitationally locked, and therefore always show the same face to each other, with a mutual rotational period of 6.387 days.

Surface Appearance and Geology

Charon is geologically simpler than Pluto, and appears more similar to some of the icy moons of Saturn and Uranus, having a water-ice-dominated, ancient cratered surface that preserves an early history of tectonism and resurfacing, likely completed within the first billion years of Solar System history.

Charon's main geological features are (1) extensive smooth plains with few craters, providing evidence of effusive cryovolcanism (resurfacing flows), and (2) aligned tectonic features including up to 12 km-deep faulting systems and canyons at the equator (most prominently Serenity Chasma that extends over ~ 1000 km). These are indicative of an early internal liquid water ocean (~ 40 km thick according to models), whose freezing would have produced global expansion of the crust as ice replaced higher-density liquid water and formation of the faulting systems. The absence of compressional features provides strong evidence that Charon is differentiated. Some regions of Charon, e.g., Vulcan Planitia and Oz Terra, are relatively heavily cratered (comparable to the most cratered regions on Pluto), indicating ages older than 4 Ga.

Surface Color, Composition, and Temperature

Charon's surface has a mean geometric albedo of 0.38, and presents a latitudinal albedo trend with a bright equator band and darker poles, with a factor of ~ 2 contrast on global scale. In relation to its darker mean albedo and smaller thermal inertia than Pluto, Charon's dayside mean surface temperature (~ 55 K) is higher than Pluto's.

Unlike Pluto, Charon's surface lacks volatile ices and appears to be dominated by water ice,

with the presence of ammonia-bearing species near specific impact craters only, suggesting that the bulk of the resurfacing flows are water ice rich.

The north polar region, called Mordor Macula, is distinctly red, likely due to solid hydrocarbons formed by condensation of methane gas that escaped from Pluto's atmosphere and subsequent processing by UV photolysis and energetic radiation. This scenario requires Charon's poles to reach temperatures <25 K during polar night, for methane to be stably cold-trapped.

As expected in relation to the lack of surface volatiles, Charon appears to have little, if any, atmosphere, with upper limits of at most 0.3 nanobar for a variety of compounds and as low as 4 picobar for N_2 .

Formation

As has long been recognized, the angular momentum of the Pluto-Charon binary system is best explained by a giant impact between comparably sized bodies that occurred during the early history of the Solar System. This scenario, similar to that explaining the origin of Earth's Moon, is now supported by hydrodynamic simulations, in which Charon forms either "intact" or through accumulation from a disk produced by the collision, which can also account for the formation of Pluto's other small moons. Favored cases include oblique, low-velocity impacts, but there are a range of solutions in terms of the possible internal structures (differentiated or not) of the pre-impact bodies.

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Arrokoth](#)
- [Pluto](#)
- [Trans-Neptunian Object](#)

Further Reading

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Chasma, Chasmata

Roland J. Wagner

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Synonyms

[Canyon](#)

Definition

A chasma (plural: chasmata) is a broad, deep, elongated trough or depression. Chasmata are bounded by steep scarps that can form a series of terraces. A chasma is preferentially created by extensional tectonic forces. The ► [terrestrial planets](#), ► [Venus](#) and ► [Mars](#), have a large number of chasmata on their surface. In the outer ► [Solar System](#), chasmata are major surface features on the icy satellites of ► [Saturn](#) and ► [Uranus](#).

Cross-References

- [Fossa, Fossae](#)
- [Mars](#)
- [Rima, Rimae](#)
- [Rupes, Rupēs](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Sulcus, Sulci](#)
- [Terrestrial Planet](#)
- [Uranus](#)
- [Venus](#)

Chassignites

Ana-Catalina Plesa

Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Keywords

SNC meteorites · Isotopic ratio · Cosmic-ray
exposure age · Noachian · Amazonian

Definition

Chassignites are a subgroup of the SNC meteorites named after the first sample found, the Chassigny meteorite. These dunitic samples (more than 90% olivine) are classified as olivine-chromite cumulate rocks.

Overview

This subgroup of the Martian meteorites contains three samples: Chassigny, NWA 2737 (field name “Diderot”), and NWA 8694 (Udry et al. 2020).

The crystallization ages of the samples have been determined to lie around 1.3 Ga, corresponding to middle Amazonian epoch (Bogard and Garrison 1999; Nakamura et al. 1982; Nyquist et al. 2001), similar to the nakhlites crystallization age. The similarity with the crystallization history of the nakhlites and a nearly identical initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio led first to the conclusion that both the chassignites and the nakhlites may sample different sites of the same or similar igneous complexes (Nakamura et al. 1982). Moreover, the similar cosmic-ray exposure age (11.1 ± 1.6 Ma) implies that they all have been ejected in one event (Nyquist et al. 2001). However, their rare earth elements (REE) abundances indicate that they have not crystallized from the same magma (Longhi 1991; Wadhwa and Crozaz 1994). Harvey and Hamilton (2005) proposed the northeast region of Syrtis Major volcanic complex to be a possible site for the ejection of chassignites. Although some sites, for example, Nili Fossae, that were proposed as

source terrains for chassignites are of Noachian age, the olivine-bearing regions within these terrains could be much younger.

Cross-References

- [Crater, Impact](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Meteorites](#)

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Chassigny

Ana-Catalina Plesa

Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Definition

Chassigny is a 4-kg Martian meteorite found in 1815 in Chassigny, France. It names the SNC subgroup containing also the NWA 2737

(Diderot) and the NWA 8694 samples. *Chassigny* is a dunitic sample (more than 90% olivine), classified as an olivine-chromite cumulate rock, for which a crystallization age has been determined to lie around 1.36 Ga, similar to the nakhlites age. Spectral signatures matching the mineralogy of *Chassigny* have been identified in Nili Fossae near Syrtis Major, southwestern region of Isidis rim, in the Ganges and Eos Chasmata, within craters southwest of the Ganges Chasma, and in the northeastern part of the Hellas basin rim. Although some candidate sites like Nili Fossae have an old Noachian age, the olivine-bearing materials located within could be much younger.

Cross-References

- [Crater, Impact](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Meteorites](#)

Chemical Adsorption

- [Chemisorption](#)

Chemical Bistability

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Chemical bistability in astrochemistry refers to the existence of multiple steady states known to occur in chemical models of molecular abundances in dense interstellar clouds. For certain combinations of model (control) parameters (cosmic ray ionization rate, elemental abundances, etc.), three steady states can appear, comprising two stable states connected by an unstable one, i.e., the solutions exhibit hysteresis.

History

Chemical bistability in astrochemical models was first positively identified by Le Boulrot et al. (1993).

Cross-References

- [Molecular Cloud](#)

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Le Boulrot J, Pineau des Forets G, Roueff E, Schilke P (1993) Bistability in dark cloud chemistry. *Astrophys J* 416:L87–L91

Chemical Evolution

- [Prebiotic Chemistry](#)

Chemical Fossil

- [Biomarkers](#)

Chemical Gardens

Raffaele Saladino
University of Tuscia, Viterbo, Italy

Synonyms

[Mineral self-assembling structures](#)

Acronyms

Chemobrionics

Definition

Chemical gardens are mineral biomorphic structures produced by self-organizing nonequilibrium

processes during which a metal-salt acts as a seed for the irreversible precipitation of a large panel of anions (silicate, phosphate, carbonate, and others). Generally, the process involves the following step: (a) formation of a semipermeable metal/anion hydrate membrane; (b) osmotic expansion and rupture of the initial membrane; and (c) growing of a bilayered biomorphic structure (composed by external anion-rich layer and internal metal oxide-rich layer) (Cartwright et al. 2002). Chemical gardens can fuel prebiotic chemistry transformations due to the generation of ionic and pH gradients across the membrane (Glaab et al. 2021). Representative examples are the syntheses of prebiotically relevant compounds, such as amino acids, nucleic acid bases, and carboxylic acids, from formamide and metal salts in the presence of alkaline (pH 12) sodium silicate solutions (Saladino et al. 2016; Bizzarri et al. 2018). In these reactions, a different selectivity was observed in association with the occurrence of the compartmentalization process, nucleic acid components being mainly confined inside the membrane (Saladino et al. 2019). In addition, amino acids affect chemical garden growth and morphology by their preferential accumulation outside the membrane (Hooks et al. 2020). These results provide an example of how an inorganic process can favor the synthesis and compartmentalization of biologically relevant molecules playing a different role in the emergence of life.

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Chemical Reaction Network

Raphaël Plasson

Department of Earth and Planetary Science,
Harvard University, Cambridge, MA, USA

Keywords

Metabolism · Stoichiometric matrix

Synonyms

Automaton, Chemical; Chemical system;
Reaction network

Definition

A chemical reaction network is a set of chemical compounds (being the network nodes) connected by a set of chemical reactions (being the network vertices).

Overview

A chemical system is a set of chemical compounds that are involved in a set of chemical reactions. Formally, this can be described as a network, where each compound is connected with each other by the corresponding chemical transformations; each chemical compound is then a node of the network, while each chemical reaction is a directed vertex of the network, connecting the involved chemical compounds, from the reactants towards the products. The purpose is to study this system as a whole, rather than solely considering it as the sum of its different elements.

A reaction network is typically described by its stoichiometric matrix v . The $v_{i,j}$ element is the stoichiometric coefficient of the compound i in

the reaction j , i.e., the number of molecule of i that is involved in the reaction j . This number is by convention negative for the reactants (that are disappearing) and positive for the products (that are formed). The mathematical analysis of this matrix gives information about the structure of the reaction network (Schilling et al. 2000). The identification of matter fluxes and of patterns of mass conservation leads to the description of the reaction network in terms of transformation pathways (Papin et al. 2004) and of conserved moieties (Schuster and Hilgetag 1995). This mathematical analysis only gives static information about the reaction network. Adding the kinetic data relative to each chemical reaction allows establishment of the set of ordinary differential equations (ODE) describing the reaction network. Its numerical integration gives the dynamical behavior of the system (Alves et al. 2006).

The description of chemical reaction networks is used in very different fields, dealing with chemical complexity. This is typically the case of biosystems, especially for the description of ► **metabolism** (Schuster and Hilgetag 1995; Schilling et al. 2000; Papin et al. 2004; Metabolism databases), but also in abiotic systems as in astrochemistry (Woodall et al. 2007), combustion modeling (Manion et al. 2008), etc. The precise description of these complex chemical systems generally relies on the existence of extensive databases, summing up thermodynamic and kinetic data.

In the field of astrobiology, ► **prebiotic chemistry** can be seen as a bridge between ► **abiotic** and biotic chemical reaction networks. The purpose is to understand how a reaction network consisting of very simple compounds can spontaneously evolve into a more complex and structured network, and how complex behaviors can emerge from the association of several simple reactions (e.g., network ► **autocatalysis**, energy coupling, self-replication, etc.) (Wagner and Ashkenasy 2009).

Cross-References

- **Automaton, Chemical**
- **Chemical Evolution**

- **Cosmochemistry**
- **Interstellar Chemical Processes**
- **Metabolism**
- **Prebiotic Chemistry**

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Chemical System

- **Chemical Reaction Network**

Chemical Zone

- **Redox Zonation**

Chemiosmotic Potential

- **Proton Motive Force**

Chemisorption

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Chemical adsorption](#)

Definition

Chemisorption involves the formation of covalent chemical bonds between an adsorbed atom or molecule (or its dissociation products) and the molecules present in a solid surface, such as that of an interstellar dust grain. This strong bonding contrasts with the weaker bonding during [physisorption](#).

Cross-References

- ▶ [Adsorption](#)
- ▶ [Interstellar Dust](#)
- ▶ [Physisorption](#)

Chemoautotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Chemoautotrophs are organisms that obtain their energy from a chemical reaction (chemotrophs) but their source of carbon is the most oxidized form of carbon, carbon dioxide (CO₂). The best known chemoautotrophs are the chemolithoautotrophs that use inorganic [energy sources](#), such as ferrous iron, hydrogen, hydrogen sulfide, elemental sulfur or ammonia, and CO₂ as their

▶ [carbon source](#). All known chemoautotrophs are prokaryotes, belonging to the ▶ [Archaea](#) or ▶ [Bacteria](#) domains. They have been isolated in different extreme habitats, associated to deep-sea vents, the deep biosphere, or acidic environments. This form of ▶ [energy conservation](#) is considered one of the oldest on Earth. These microorganisms are of astrobiological interest because they could develop in the extreme conditions existing in different extraterrestrial planetary bodies, like Mars or Europa.

Cross-References

- ▶ [Acidophile](#)
- ▶ [Autotroph](#)
- ▶ [Autotrophy](#)
- ▶ [Bacteria](#)
- ▶ [Bioenergetics](#)
- ▶ [Carbon Source](#)
- ▶ [Chemolithoautotroph](#)
- ▶ [Chemotroph](#)
- ▶ [Deep-Sea Microbiology](#)
- ▶ [Deep Subsurface Microbiology](#)
- ▶ [Energy Conservation](#)
- ▶ [Energy Sources](#)
- ▶ [Extreme Environment](#)
- ▶ [Extremophiles](#)
- ▶ [Hot Vent Microbiology](#)
- ▶ [Iron Cycle](#)
- ▶ [Lithotroph](#)
- ▶ [Prokaryote](#)
- ▶ [Respiration](#)

Chemocline

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the
Earth System, Université du Québec à Montréal,
Montréal, QC, Canada

Definition

The chemocline is the vertical chemical gradient or cline, which is produced in a mass of water

having restricted circulation (e.g., meromictic lakes where water layers do not intermix). Local conditions of circulation provoke the formation of bottom anoxic waters – where only anaerobic organisms exist – overlain by oxygenated waters, where aerobic photosynthetic life flourishes. At the contact between these two zones, photosynthetic communities of anaerobic purple sulfur bacteria develop, taking advantage of both the sunlight from above and the hydrogen sulfide (H_2S) produced below. In astrobiology, this zone of the chemocline is studied because it could be an analogue of Archean niches of life where limited oxygenated waters developed over an anoxic Archean ocean.

Cross-References

- ▶ [Photosynthesis](#)
- ▶ [Redox Zone](#)

Chemolithoautotroph

Ricardo Amils
Centro de Biología Molecular, Universidad
Autónoma de Madrid, Madrid, Spain

Keywords

Hydrogen oxidizers · Iron oxidizers ·
Nitrifying bacteria · Sulfur oxidizers

Definition

A chemolithoautotroph is an autotrophic microorganism that obtains energy by oxidizing inorganic compounds. Most ▶ [chemolithotrophs](#) are ▶ [autotrophs](#). Examples of relevant inorganic electron donors include hydrogen, hydrogen sulfide, ferrous iron, and ammonia. Winogradsky described the concept of chemolithoautotrophy for the first time while studying the ammonia-oxidizing bacteria. Chemolithoautotrophic organisms have ▶ [electron transport](#) complexes, similar to those of chemoorganotrophs, which are used to generate a ▶ [protein motive force](#). The proton

motive force drives the synthesis of ATP. In this case, the reduction of CO_2 requires the use of ATP and reducing power, which is, most often, obtained through the use of the electron transport chain in reverse mode, consuming energy. Sulfur, iron, and ammonia oxidizers are fundamental elements in the biogeochemical cycles of these elements. Chemolithoautotrophic organisms are of special interest to astrobiology due to their minimal requirements for development and their ability to readily adapt to extreme conditions.

Cross-References

- ▶ [ATP Synthase](#)
- ▶ [Bioenergetics](#)
- ▶ [Carbon Dioxide](#)
- ▶ [Chemotroph](#)
- ▶ [Electron Transport](#)
- ▶ [Nitrification](#)
- ▶ [Proton Motive Force](#)

Chemolithotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Chemolithotrophy

Definition

A chemolithotroph is an organism that is able to use inorganic reduced compounds as a source of energy. This mode of metabolism is known as chemolithotrophy.

History

Chemolithotrophy was discovered by Winogradsky while studying the microorganisms involved in the oxidation of sulfur compounds.

Overview

Chemolithotrophy is found only in prokaryotes and is widely distributed among Bacteria and Archaea. The spectrum of inorganic compounds that can be used as electron donors by chemolithotrophs is rather broad (H_2S , S^0 , $\text{S}_2\text{O}_3^{2-}$, H_2 , Fe^{2+} , NO_2^- , or NH_3). Some microorganisms are rather specific regarding the inorganic substrates they can use to generate energy, while others are able to use different compounds (versatile). The best characterized chemolithotrophs are aerobic respirers, which use oxygen as the ► [electron acceptor](#), although the list of chemolithotrophs capable of employing ► [anaerobic respiration](#) is increasing rapidly. Chemolithotrophs have ► [electron transport](#) systems similar to those of chemoorganotrophs, which are used for the generation of a ► [proton motive force](#). The only difference is that chemolithotrophs donate electrons directly to the electron transport chain, while chemoorganotrophs must generate cellular reducing power (NADH) from the ► [oxidation](#) of reduced organic compounds, which is then used to donate electrons to the electron transport system. This proton motive force is used to generate ATP or any cellular functions that might require this type of energy (active transport, movement, etc.). An important distinction between chemolithotrophs and chemoorganotrophs is their source of carbon. Chemoorganotrophs use organic compounds as both energy and carbon sources, while chemolithotrophs are generally autotrophs (with few exceptions, known as mixotrophs, that use reduced organic compounds as a source of carbon). Chemolithotrophs can obtain the reducing power needed to assimilate CO_2 directly from the inorganic substrate (only H_2 oxidizers) or by the reverse electron transport reaction (the rest of chemolithotrophs), in this case using proton motive force as a source of energy.

Hydrogen is a common product of geochemical reactions and microbial metabolism, and a number of chemolithotrophs are able to use it as an electron donor in energy metabolism. A wide variety of anaerobic H_2 -oxidizing Bacteria and

Archaea are known, differing in the electron acceptor they use (nitrate, sulfate, ferric iron, etc.).

The most common sulfur compounds used as electron donors are hydrogen sulfide (H_2S), elemental sulfur (S^0), and thiosulfate ($\text{S}_2\text{O}_3^{2-}$). The final product of sulfur oxidation is sulfate (SO_4^{2-}), although an intermediate step is the formation of elemental sulfur, which in some cases is stored as an alternative source of energy. One of the products of sulfur oxidation reaction is the generation of protons (H^+); consequently, one result of the oxidation of reduced sulfur compounds is the acidification of the environment by the production of sulfuric acid.

The aerobic oxidation of ferrous iron (Fe^{2+}) to ferric ► [iron](#) (Fe^{3+}) is an energy-yielding reaction, used by some prokaryotes to conserve energy. Only a small amount of energy is generated by this reaction; thus, iron-oxidizing microorganisms must oxidize large amounts of reduced iron to grow. Ferrous iron is oxidized very rapidly in the presence of oxygen, while it is very stable at acidic conditions. This is probably the reason why many iron-oxidizing microorganisms are acidophilic. Despite the instability of ferrous iron at neutral pH, there are a number of iron-oxidizing bacteria that can thrive at circumneutral pH. Some anoxygenic phototrophic bacteria can use ferrous iron as a source of environmental reducing power. Recently, it has been shown that some denitrifying bacteria can anaerobically respire (oxidize) reduced iron. The use of ferrous iron to obtain energy is widely distributed in nature, a property that was ignored until recently, due to thermodynamic considerations.

The most common nitrogen compounds used as electron donors for energy conservation are ammonia (NH_3) and nitrite (NO_2^-). Both compounds can be oxidized aerobically by chemolithotrophic nitrifying bacteria. Some nitrifying microorganisms oxidize ammonia to nitrite, while another group oxidizes nitrite to nitrate. For many years, the complete oxidation of ammonia required the concerted activity of these two types of microorganisms, but recently it has been shown that bacteria from the *Nitrospira* genus can oxidize ammonia to nitrate (Comammox). A special case of nitrogen-oxidizing microorganisms

corresponds to those capable of carrying out the anoxic oxidation of ammonia, a process known as Anammox. In this case, the electron acceptor is nitrite, and the product of the metabolic reaction in addition to proton motive force is the generation of N_2 . This metabolic reaction is carried out by a special type of microorganisms belonging to the Planctomycetes phylum of Bacteria.

Due to their metabolic properties, chemolithotrophs are of astrobiological interest and also critical elements of the ► [biogeochemical cycles](#).

Cross-References

- [Acidophile](#)
- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [ATP Synthase](#)
- [Autotrophy](#)
- [Bioenergetics](#)
- [Biogeochemical Cycles](#)
- [Chemoautotroph](#)
- [Chemolithoautotroph](#)
- [Chemoorganotroph](#)
- [Electrochemical Potential](#)
- [Electron Acceptor](#)
- [Electron Carrier](#)
- [Electron Donor](#)
- [Electron Transport](#)
- [Energy Conservation](#)
- [Energy Sources](#)
- [Iron](#)
- [Iron Cycle](#)
- [NADH, NADPH](#)
- [Nitrogen Cycle, Biological](#)
- [Oxidation](#)
- [Proton Motive Force](#)
- [Sulfur Cycle](#)

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Chemoorganotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Fermentation · Heterotrophs · Respiration

Definition

A chemoorganotroph is an organism that obtains energy from the oxidation of reduced organic compounds. The list of compounds from which chemoorganotrophic organisms can generate energy and their sources of carbon is very long, making these microorganisms extremely versatile. Two mechanisms for energy conservation are known for chemoorganotrophs: ► [fermentation](#) and ► [respiration](#). In the case of fermentation,

cellular energy in the form of ATP is obtained by cytoplasmatic soluble catalytic reactions involved in substrate-level phosphorylation. In the case of respiration, ATP is produced at the expense of the ► [proton motive force](#) resulting from coupling the substrate oxidation reactions via the generation of reducing power to the electron transport chain. Due to their type of metabolism, chemoorganotrophs are fundamental elements of the carbon cycle.

Cross-References

- [Aerobic Respiration](#)
- [ATP Synthase](#)
- [Catabolism](#)
- [Chemotroph](#)
- [Energy Sources](#)
- [Proton Motive Force](#)

Chemotaxis

Irma Marín
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Ciudad
Universitaria de Cantoblanco, Madrid, Spain

Keywords

Motility · Two-component system

Definition

Chemotaxis is the process by which motile bacteria sense changes in their chemical environment and move to more favorable conditions.

Overview

Bacteria, Archaea, and some eukaryotes use two-component signaling pathways to detect environmental conditions and bring about appropriate changes in cellular behavior. This process has been studied in *Escherichia coli* over the past 40 years.

E. coli has several flagella per cell (4–19) that can rotate in two ways: counterclockwise (CCW) that aligns the flagella causing the bacterium to swim in a straight line and clockwise (CW) that causes the bacterium to tumble since each flagellum rotates independently.

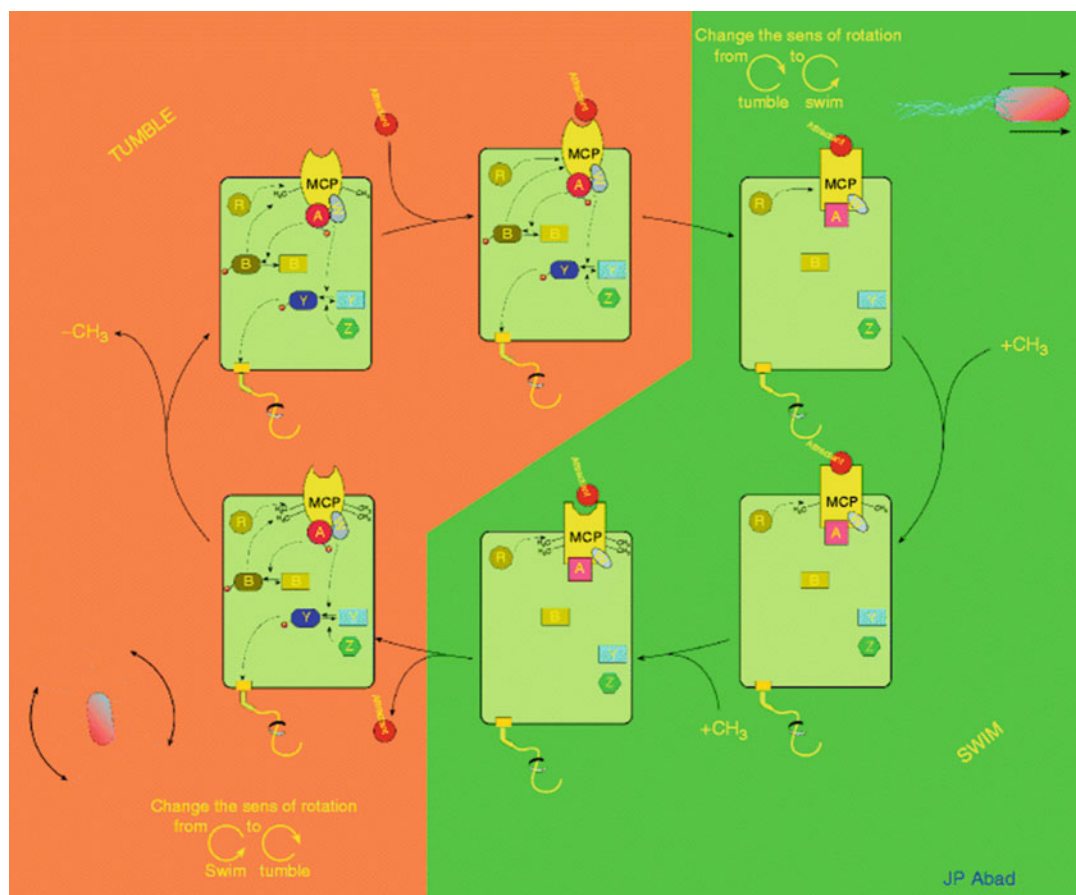
Bacteria monitor chemical concentrations using multiple transmembrane receptors, named methyl-accepting chemotaxis proteins (MCPs). Five MCP-mediating responses to specific attractant and repellent stimuli have been reported in *E. coli*: Tar, Tsr, Trg, Aer, and Tap. The signals from these receptors are transmitted across the cell membrane into the cytoplasm, where Che proteins (CheA, CheB, CheW, CheY, CheR, and CheZ) are activated.

Signals from the receptors are received by the CheA histidine kinase. CheA is coupled to transmembrane receptors (MCP) by the adaptor protein CheW. The activation of the receptor causes autophosphorylation of CheA that also phosphorylates CheB and CheY. CheY~P binds then to the flagellar motor protein FliM, inducing a change from CCW to CW rotation of flagella, thus increasing the frequency of tumbles of the bacterium (Fig. 1).

A feedback mechanism that modulates the methylation level of the MCP receptors controls adaptation. Two enzymes, CheB and CheR, are involved in this mechanism by interacting with the receptor and chemically modifying them.

CheB, activated by CheA, acts as a methylesterase that removes methyls from the cytoplasmic part of the receptor. It works antagonistically with CheR, which is a methyltransferase. The higher the amount of methylated residues of the receptor, the lower the sensitivity to stimuli. The result is an enhancement of CheA autophosphorylation and, thereby, transmission of a CW signal. When an attractant generates a signal, demethylation of the receptor is induced, closing the feedback loop.

The system is continuously adjusted to environmental chemical levels, remaining sensitive to small changes even under extreme chemical concentrations, since the system compares concentrations along the movement path. When necessary this is switched to go closer to or further away



Chemotaxis, Fig. 1 Model of chemotaxis mechanism as described in the text. A, B, R, W, Y, and Z are CheA, CheB, CheR, CheW, CheY, and CheZ proteins, respectively

from a higher concentration of attractant or a repellent, respectively. Other mechanisms are involved in increasing the absolute value of the sensitivity on a given background. *E. coli*, but not *B. subtilis*, possesses the protein CheZ that enhances the rate of CheY dephosphorylation.

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Chemotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Cross-References

► Motility

References and Further Reading

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Definition

Chemotrophs are organisms that obtain energy by the oxidation of reduced compounds. The

substrates used by chemotrophs can be organic (organotrophs) or inorganic compounds (lithotrophs). According to the carbon source, chemotrophs can be either chemoautotrophs or chemoheterotrophs. Because chemoheterotrophs use reduced organic compounds as a source of energy and a source of carbon, they are usually called heterotrophs, although the term is misleading because, strictly, it only refers to the carbon source. Chemoautotrophs use inorganic energy sources and are known as chemolithoautotrophs or lithoautotrophs. Chemolithoheterotrophs are a special kind of chemotroph that use inorganic compounds as an energy source and reduced organic compounds as a carbon source. They are known as mixotrophs. Chemotrophs use ► [fermentation](#) and ► [respiration](#) to obtain energy. Fermentation is restricted to organotrophs.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Autotrophy](#)
- [Bioenergetics](#)
- [Carbon Dioxide](#)
- [Chemoautotroph](#)
- [Chemolithoautotroph](#)
- [Chemolithotroph](#)
- [Chemoorganotroph](#)
- [Energy Conservation](#)
- [Fermentation](#)
- [Respiration](#)

CHEOPS

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Exoplanet · Transit

Definition

The CHaracterizing ExOPlanet Satellite (CHEOPS) is a small mission selected by the

European Space Agency (ESA) in October 2012 and then adopted in February 2014. It is the first mission dedicated to analyze exoplanet ► [transits](#) by means of ultrahigh precision photometry on bright stars already known to host planets. It provides the unique capability of determining accurate radii for a subset of planets with a size ranging from Earth to Saturn which orbit bright stars and for which the mass has already been estimated from ground-based spectroscopic surveys. The knowledge of mass and diameter allows to derive the precise density and then to draw hypotheses about the composition of these planets. The 250 kg satellite is equipped with a 32 cm telescope. The payload is developed under the responsibility of the University of Bern (Switzerland). Cheops was launched December 18, 2018, in a sun-synchronous orbit at about 700 km. Its lifetime is set at 3.5 years. Recently Cheops has revealed that an exoplanet orbiting its host star within a day has an ovoid shape more like that of a rugby ball than a sphere. The detection, for the first time, of such a deformation offers new insights into the internal structure of this kind of planets.

Mission site: <https://cheops.unibe.ch/fr/>

Chert

Tanja Elsa Zegers
Paleomagnetic Laboratory, Institute of Earth Sciences, Utrecht University, Utrecht, The Netherlands

Keywords

Archean · Microfossils · Alteration (hydrothermal) · Sediments

Synonyms

[Chalcedony](#); [Flint](#); [Jasper](#)

Definition

Chert is a microcrystalline rock consisting almost exclusively of silica. Chert may occur as

stratiform units, occasionally with laminar alteration of colors (red, white, black, green), in dikes crosscutting the stratigraphy, or as nodules in carbonates. Some stratiform cherts in Archean ► [greenstone belts](#) are among the earliest sedimentary rocks and preserve the oldest evidence for life (► [Apex Chert](#), ► [Pilbara Craton](#), Western Australia).

History

The oldest preserved chert units occur in the highly metamorphic and deformed 3.6–3.7 Ga supracrustal units of the ► [Isua Supracrustal Belt](#) in West Greenland (Nutman et al. 1984). The Isua cherts may have had a sedimentary origin or may represent volcanic rocks that were hydrothermally altered and layered as a consequence of intense plastic deformation (Nutman and Friend 2009; Polat and Frei 2005). Trace elements indicate that the chert/► [banded iron formation](#) units have seawater-like signatures suggesting at least a component of sedimentary origin as a marine chemical precipitate.

In both the ► [Pilbara](#) (Australia) and the Barberton (South Africa) Greenstone Belts, the oldest well-preserved volcanic sequences which contain stratiform chert units (Byerly et al. 1996; Van Kranendonk et al. 2002) formed between ~3.57 and ~3.30 Ga. Despite the good preservation of the greenstone sequence, the origin of the stratiform chert units is still controversial. van den Boorn et al. (2007) distinguished three different end members of silica derivation on the basis of Si isotopic signatures: direct precipitation of silica from seawater on the seafloor, alteration of a precursor rock (volcanic, carbonate, siliciclastic) by addition of silica from seawater, and silica precipitation from hydrothermal vents. Only in the first case does the chemical and isotopic composition of chert reflect the chemistry and temperature of Archean seawater.

Chert is very resistant to surface weathering and associated chemical alteration. Therefore, chert is often considered to be the ideal agent for the preservation of very ancient and potentially extraterrestrial biosignatures (Westall 2008).

Overview

Cherts, both sedimentary (authigenic) and as a secondary alteration product, form by precipitation from aqueous fluids. The solubility of silica (Dove and Rimstidt 1994; Fleming and Crerar 1982) in water is largely independent of its pH for pH lower than 9 but increases exponentially for pH >9. Solubility of silica also increases with increasing temperature and with increasing salinity. During the Archean, precipitation of silica was most likely abiogenic and either derived originally from ocean-floor hydrothermal vents or from regional precipitation from normal but silica-supersaturated seawater. From ~1.8 Ga ago (Maliva et al. 2005), the silica cycle in the oceans began to be governed, as it still is, by silica-secreting organisms. Radiolaria are thought to have appeared in the late Cambrian diatoms in the Jurassic. Since then, most silica derived from continental weathering and delivered by rivers to the oceans is biologically consumed (Laruelle et al. 2009).

For our understanding of the evolution and conditions of early life, the chert units found in early and mid-Archean stratigraphic sequences such as in the Pilbara Craton (Australia) and Barberton Greenstone Belt (South Africa) are most important. Both sequences, the Warrawoona Group in the Pilbara Craton and the Onverwacht Group in the Barberton Greenstone Belt, consist predominantly of mafic to ultramafic volcanic units, with minor felsic volcanic and associated volcanoclastic units (3.47–3.3 Ga). Both sequences are so similar that they may have been part of a single terrain at the time of deposition (Zegers et al. 1998). Chert units (typically less than 20 m thick) cap volcanic sequences and can commonly be traced over large (>50 km) distances (Kato and Nakamura 2003). A few thicker chert units occur in both the Pilbara Craton and Barberton Greenstone Belt: the Strelley Pool Chert and the Buck Reef Chert (350 m, Hofmann and Harris 2008), respectively. The detailed study of the Strelley Pool Chert (~3.43 Ga) by Allwood et al. (2006) showed that the chert consists of at least four members with different characteristics and compositions, some of which show excellently preserved ► [stromatolites](#). The unit

was most likely deposited as a dolomite/carbonate reef on a shallow platform consisting of felsic volcanoclastic sediments. Tice and Lowe (2004) studied in detail the Buck Reef Chert, and sedimentary structures were interpreted to represent deposition in a shallow- to deep-marine environment, with organic matter in the shallow-water facies resulting from photosynthetic microbial mats.

Other chert units in the earliest greenstone sequences show no strong evidence of carbonaceous and clastic sedimentary deposition but are more likely to represent deposition of silica directly from oversaturated seawater. Silica is thought to have been released from nearby ocean-floor hydrothermal vents even though these can only rarely be documented. These cherts show no macroscopic biogenic textures, but have been studied extensively for microtextures that might be indicative of fossilized microorganisms and microbial mats (Schopf et al. 2002; Westall et al. 2006; Westall 2008; Sugitani et al. 2013). Some of the most famous putative microtextures were found in the ► [Apex Chert](#) (Schopf et al. 2002). The claim that those filamentous textures represented evidence for life at 3.45 Ga was countered by studies showing that similar textures could be generated in hydrothermal systems by Fischer-Tropsch-type abiotic processes (Brasier et al. 2002).

Because chert is so resistant to erosion, it provides a good record for any study of ► [early Earth conditions](#). Samples from the Marble Bar Chert (► [Pilbara](#), Australia) have been used for paleomagnetic studies (Suganuma et al. 2006). Oxygen and Si isotopic compositions in chert have been used to infer the temperature of the Archean ocean (Knauth and Lowe 2003; Robert and Chaussidon 2006) of up to 70 °C. However, van den Boorn et al. (2010) showed that the samples used in those studies were most likely deposited from hot hydrothermal water rather than from ambient seawater. They suggest a maximum temperature of ambient seawater of 55 °C.

Because of its formation by precipitation from water and the potential to preserve textural and geochemical proxies for fossil life, chert is one of the targets to detect former life

on Mars (Westall 2008). The ► [Mars Exploration Rover Spirit](#) recently found amorphous silica (a precursor to chert) in the Gusev Crater (Rice et al. 2010).

Key Research Findings

Chert units in Archean greenstone belts represent the oldest sedimentary units in otherwise entirely volcanic sequences. Stratiform chert units may be the result of direct precipitation from oversaturated seawater or may represent hydrothermal deposits. In some cases, units that originally contain largely carbonate (dolomite, siderite) have been pervasively silicified. Some of those units contain stromatolites and other micromorphological indications of biological activity.

Applications

Chert is very resistant to weathering and chemical alteration under surface conditions. This makes chert units, if they can be shown to have formed in the Archean, ideal recorders of Archean conditions, to be probed by a variety of techniques.

Future Directions

Chert units will continue to be studied as some of the best recorders of the conditions of early life. To correctly interpret micromorphological and geochemical signatures, the context of chert units and their surroundings must be considered closely. To obtain a continuous stratigraphic sequence, unaltered by surface conditions and unaffected by lightning strikes (for paleomagnetic studies), it will be important to drill cores through chert units. Such core samples should be studied collaboratively using different techniques and methods to obtain a more accurate insight into the conditions of life in the Archean. Amorphous silica deposits on Mars deserve full attention in preparation for future missions such as ExoMars and Mars Sample Return.

Cross-References

- [Alteration](#)
- [Apex Basalt, Australia](#)
- [Apex Chert](#)
- [Apex Chert, Microfossils](#)
- [Archean Drilling Projects](#)
- [Archean Environmental Conditions](#)
- [Banded Iron Formation](#)
- [Barberton Greenstone Belt](#)
- [Barberton Greenstone Belt, Sedimentology](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Biomarkers](#)
- [Biomarkers, Morphological](#)
- [Hydrothermal Environments](#)
- [Microfossils](#)
- [Pilbara Craton](#)
- [Precambrian Oceans, Temperature of](#)

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- [Origin of Life](#)
- [Protein](#)
- [RNA World](#)

Chicken or Egg Problem

Henderson James CleavesII
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

Chicken or egg problems are apparent causality problems; for example, which came first, the chicken or the egg? This is paradoxical because chickens are required to lay eggs, and yet chickens hatch from eggs. An apparent paradox in modern biochemistry is the fact that nucleic acids (both DNA and RNA) are required to make coded proteins, and at the same time, coded proteins are required to make nucleic acids. In the origin and early evolution of life then, it is not apparent which of these two must have come first. One possible solution to this problem is offered by the discovery of ribozymes, RNA molecules which could potentially code for their own replication and serve as catalysts for their replication as well.

Cross-References

- [Genetic Code](#)
- [Nucleic Acids](#)

Chicxulub Crater

Philippe Claeys
 Analytical-Environmental & Geo-Chemistry,
 Vrije Universiteit Brussel, Brussels, Belgium

Keywords

Carbonaceous chondrites · Dinosaurs · Crater (impact) · Mass extinctions · Meteorites

Definition

The Chicxulub structure is a large impact crater formed 66 Ma ago at the tip of the Yucatan Peninsula (Mexico). With a diameter between 180 and 220 km, it is the second largest impact crater known on Earth after Vredefort (South Africa) and the only one with a well-preserved peak-ring. The Chicxulub impact is considered the cause of the last major mass extinction, at the Cretaceous-Paleogene (KPg) boundary (or previously ► [KT boundary](#)). This mass extinction led to the disappearance of 75% of the fauna and flora on the continent and in the oceans, including emblematic organisms such as ammonites and all the nonavian dinosaurs.

Overview

The Chicxulub structure formed by the collision of a projectile, most likely a ~10–12 km in size ► [carbonaceous chondrite](#) meteorite (Goderis et al. 2013), with the Earth crust. In the end Cretaceous, the Yucatan region consisted of a shallow to deep water carbonate and evaporite platform overlying a gneiss-granitic basement. Buried under ~1 km of Cenozoic sediments, geophysical methods were used to image the morphology and characteristics of the structure. Seismic data showed the cavity concave morphology, its multi-ring structure as well as the excellent preservation

of its central peak-ring (Morgan and Warner 1999), in analogy with large craters observed on other planets (Moon, Mars...). Gravity measurements also clearly outlined the central-peak ring surrounded by a region of lower density forming the trough zone. A magnetic anomaly, likely caused by the presence of iron-rich rocks, corresponds to the uplifted central peak area. The crater was drilled first for oil exploration purposes (unsuccessful) in the 1970s, and again onshore in 2002 by the International Continental Scientific Drilling Program (ICDP, see Urrutia-Fucugauchi et al. 2004 for a summary), revealing the stratigraphy and proportion of carbonate and evaporite within the target rock and sampling the impactites. Based on ^{40}Ar – ^{39}Ar dating of the latter, the crater formed exactly 66 million years ago (Swisher et al. 1992; Renne et al. 2013), which stratigraphically correspond to the KPg boundary.

In 2016, Expedition 364 of the International Ocean Discovery Program (IODP) together with the ICDP drilled the offshore part of the peak-ring structure down to ~1335 m. The recovered cores contain below Cenozoic sediments: a KPg transition zone, ► [suevite](#) of various grain sizes, different types of impact melt rocks, as well as fractured, sheared, and shocked uplifted granitic basement, cut by numerous dikes, characterized by low density and low seismic velocity. These characteristics and the omnipresence of shock metamorphism (~25 GPa) within the granite support the dynamic collapse model of peak-ring formation process (Morgan et al. 2016); a key element to better understand cratering on rocky planets. The transition zone from impactite to Paleogene sediments shows that life reappeared in the crater shortly (30 kyr) after the impact (Lowry et al. 2018), implying that proximity to Chicxulub did not affect recovery. The famous worldwide Ir positive anomaly occurs at the top of this transition sequence confirming without a doubt the link between the crater formation and the KPg boundary (Goderis et al. 2021). Gulick et al. (2019) provide an account of the processes that occurred within a time frame of minutes to days directly after the impact: from peak ring formation and collapse, followed by rapid ocean resurge within the cavity, to the arrival of tsunami

and the complex deposition of reworked sediments and suevite. The crater impactites are described by Feignon et al. (2021), De Graaff et al. (2022), and Kaskes et al. (2022). Geochemically, these impactites are clearly connected to the proximal ► [ejecta](#) material spread all over the Gulf of Mexico, while the more distal ejecta, transported through the atmosphere, covers the entire planet (Schulte et al. 2010).

The release and injection at high altitudes (25 km) in the atmosphere of climate active gases (CO_2 ; SO_x , H_2Ov), released by shock vaporization of the carbonate and evaporite from the target rock, and fine dust are responsible for the global consequences of the impact at Chicxulub. Using 3D hydrodynamic code SOVA and taking into consideration the following: impact angle (45° to 60° according to Collins et al. 2020), sediment properties, average shock pressure, and water depth, Artemieva et al. (2017) estimate that 325 ± 130 Gt of sulfur and 425 ± 160 Gt CO_2 were ejected, more than enough to induce severe changes to the global climate. Together with the pulverized fine dust, these gases likely led to yearlong darkness and brutal cooling all over the Earth, strongly reducing photosynthesis and triggering the biosphere collapse. Using a lower volume of gases produced, Brugger et al. (2017) estimate that sulfate aerosols caused a 25°C cooling of the average temperature, lasting between 10 and 30 years after the collision. In the ocean, carbonate productivity (mainly CaCO_3 plankton) significantly decreased, perhaps related to a brutal postimpact drop in pH of the surface-ocean, supporting ocean acidification as a key mechanism for the ecological collapse in the marine realm, followed by major perturbation of global carbon cycle (Henahan et al. 2019).

Cross-References

- [Crater, Impact](#)
- [Deccan Trapps](#)
- [Ejecta](#)
- [Impact Melt Rock](#)
- [Impactite](#)

- [KT Boundary](#)
- [Mass Extinctions](#)
- [Shocked Quartz](#)
- [Suevite](#)

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Chiral Excess

- [Enantiomeric Excess](#)

Chirality

Donna Blackmond
The Scripps Research Institute, La Jolla,
CA, USA

Keywords

Enantiomers · Enantiomorphs ·
Diastereomers · Stereochemistry ·
Conglomerates · Racemic compounds ·
Symmetry breaking · Chiral bias · Chiral
amplification · Biological homochirality

Synonyms

[Handedness](#); [Non-superimposable mirror image object](#)

Definition

The term chirality, from the Greek word *cheir* for “hand,” refers to the property of “handedness” possessed by some molecules and macroscopic objects. A molecule or object is chiral if it is not superimposable on its mirror image, as is the case for left and right hands. The word was introduced by Lord Kelvin (1904) and has been further quantified by Mislow (1965) and Cahn et al. (1966), who define an object as chiral when it contains no element of symmetry (excepting in some cases an axis of rotation). The two distinct mirror-image forms are called enantiomers in the case of chiral molecules and enantiomorphs in the case of chiral crystals.

Overview

The two enantiomers of a chiral molecule have identical physical and chemical properties, which was demonstrated by van't Hoff and Le Bel using arguments about the “exact mechanical symmetry” between enantiomers (van't Hoff 1887). It has since been proven, however, that because of parity violation, there is a minute – and, to date, experimentally immeasurable – energy difference between enantiomeric molecules, which by current predictions lie in the range of femto- to picojoules/mol (Quack 2002).

Each of the two enantiomeric forms of a molecule interacts differently with other chiral molecules, chiral objects, or chiral forces such as plane-polarized light. Such chiral interactions form the basis for the molecular recognition that enables the specificity of reactions observed in biological systems.

A collection of enantiomers of a molecule may be comprised of equal amounts of each hand (a racemic mixture), all of a single hand (an enantiopure mixture), or any fraction of each enantiomer (a scalemic mixture). The standard definition of enantiomeric purity, known as the enantiomeric excess, arose from the observation that pure enantiomers rotate the plane of polarized light to the same degree but in opposite directions. Thus, an equal mixture of left- and right-handed molecules exhibits no rotation of plane-polarized light. The enantiomeric excess of a collection of enantiomeric molecules is defined by the degree and direction of rotation compared to the enantiopure case and is given by Eq. 1:

$$\% \text{enantiomeric excess} = \%ee = 100 \cdot \frac{R - S}{R + S}$$

where R and S are defined in the following paragraph.

The term homochirality typically refers to the fact that the two main building blocks of biological molecules, sugars and amino acids, each exist in only one of the two possible enantiomeric forms. Convention describes these as right-handed, R , or d-sugars and left-handed, S , or l-amino acids. The term homochirality was introduced by Lord

Kelvin, who wrote: “two equal and similar right hands are homochirally similar” (Lord Kelvin 1904). This description could apply, for example, to a series of different amino acids with all in the same enantiopure form or to an enantiopure collection of molecules of a single amino acid. Biopolymers formed from d-sugars, such as RNA and DNA, and from l-amino acids, such as polypeptides and proteins, are homochiral.

In the modern literature concerning origin of life, the term homochirality has become synonymous with the single-handedness of the molecular building blocks and biopolymers of living systems. Homochirality has been suggested as a possible biosignature, an idea that has been expressed even more strongly as “the homochiral imperative of molecular evolution” (Siegel 1998) or by the tenet of “No homochirality, no life!” (Bonner 1998). More recent experiments demonstrating that a d-polymerase ribozyme could evolve to catalyze the cross-chiral replication of its mirror image suggest the possibility that replicating d- and l-RNA molecules may have emerged together (Szczepanski and Joyce 2014). In such a scenario, the homochiral path of modern life might have arisen from later evolutionary pressures on early forms of life.

Emergence of Homochirality

The abiotic synthesis of chiral molecules results in a racemic mixture of products in the absence of a chiral bias that helps to direct the reaction preferentially toward one hand. In modern organic synthesis, such a chiral bias may be obtained from the pool of enantioenriched molecules produced by living systems. In a prebiotic world, however, prior to the presence of a chiral pool, racemic mixtures of chiral molecules would be expected from such reactions. How a racemic prebiotic world came to develop life based on single chirality is a central problem that has intrigued scientists for generations. It is in fact two questions (Blackmond 2009): First, how was an initial chiral bias induced, known as symmetry breaking? And second, how was such an imbalance sustained and propagated to high levels of enantiopurity?

Proposals for how an imbalance initially came about may be classified as either terrestrial or

extraterrestrial and then subdivided into either random or deterministic, sometimes called “*de facto*” and “*de lege*,” respectively (Quack 2002). Evidence of small enantiomeric excesses in amino acids found in chondritic meteor deposits has been suggested to support the extraterrestrial breaking of symmetry (Burton et al. 2012). The possible role of parity violation energy differences fits into a “*de lege*” model, although to date no chemical or physical difference between enantiomers has been confirmed in experiments.

Proponents on the “chance” side of this question suggest that symmetry breaking could occur stochastically due to transient fluctuations in the physical and chemical environment. However, any small imbalance created in this way should average out as the racemic state unless some process intervenes to sustain and amplify it. Thus whether or not the imbalance in enantiomers came about by chance, arising on Earth or elsewhere, an amplification mechanism remains the key to increasing enantiomeric excess.

Theoretical work from the 1950s (Frank 1953) and experimental studies from the 1990s to the present day have provided a number of proposals for the amplification of a small initial imbalance in enantiomers. Experimental models invoke both chemical reactions and physical phase behavior to rationalize enantioenrichment. Chemical models invoke autocatalytic reactions, chirality transfer, or kinetic resolutions, while physical models exploit aspects of the crystallization behavior of chiral molecules to provide enantioenrichment of either the solid or solution phases.

Chemical Models for Enantioenrichment

The Soai reaction provides the most robust experimental example of asymmetric autocatalytic amplification of enantiomeric excess (Soai et al. 1995). Although the chemistry is not itself prebiotically plausible, the reaction provides the first experimental proof of concept of the Frank model for the emergence of homochirality (Blackmond 2004). Catalysis of the formose reaction by amino acids (Breslow and Cheng 2010) or amino acid salts (Hein and Blackmond 2012) leads to enantioenrichment of the resulting

glyceraldehyde, the smallest chiral sugar. The transfer of chirality to amino acids via transamination reactions has been demonstrated (Levine et al. 2008). A kinetic resolution of sugars by amino acids – or, conversely, of amino acids by sugars – results in significant enantioenrichment (Hein et al. 2011) of precursors in a prebiotically plausible route to RNA (Powner et al. 2009).

Physical Models for Enantioenrichment

Ever since Pasteur used tweezers to separate the mirror-image crystals of the di-salt of tartaric acid, crystallization processes and the phase behavior of chiral molecules have intrigued scientists as a potential means for the emergence of homochirality. Kondepudi showed striking amplification of the enantiomeric excess of NaClO_3 crystals by rapidly stirring supersaturated solutions (Kondepudi 1990), and Viedma showed that racemic mixtures of these same crystals evolved to homochirality under the influence of attrition (Viedma 2005). The former case is noted as a “far from equilibrium” process, while the latter takes place close to equilibrium; both rely on the fact that while NaClO_3 is achiral in solution, it forms separate left- and right-handed crystals. It was recognized that such processes for chiral amplification might be extended to intrinsically chiral molecules that form separate crystals (called conglomerates) if the enantiomers could be made to exchange rapidly in solution. The first proof of concept of attrition-enhanced deracemization of intrinsically chiral molecules was demonstrated for amino acid derivatives (Noorduyn et al. 2008) and for a proteinogenic amino acid (proteinogenic refers to amino acids that are precursors to proteins) (Viedma et al. 2008).

The majority of chiral molecules – including 17 of the 19 proteinogenic amino acids that are chiral – do not crystallize as conglomerates or separate left- and right-handed crystals, but instead form heterochiral crystals usually comprised of a 1:1 ratio of enantiomers, called racemic compounds. Models for enantioenrichment based on the phase behavior of racemic compounds rely on the thermodynamic partitioning of the enantiomers between the solution and solid phases.

A system containing an unequal number of left- and right-handed molecules in an equilibrium mixture of crystals in saturated solution contains both the heterochiral solid and an enantiopure solid of the enantiomer present in excess. The composition of the solution phase – that is, the solution enantiomeric excess – is a constant value dictated by the Gibbs phase rule. Known as the eutectic composition, this is a characteristic property of each amino acid and is related to the relative solubilities of the heterochiral and homochiral solids. For example, serine and valine exhibit eutectic compositions of 99% ee and 47% ee, respectively. This property was first recognized as a possible route to enantioenrichment by Morowitz (1969) and was elaborated by Blackmond and coworkers (Klussmann et al. 2006a, b) and by Breslow and coworkers (Breslow and Cheng 2009). A similar approach to enantioenrichment via sublimation of amino acids has been reported (Fletcher et al. 2007; Perry et al. 2007).

The explosion of experimental reports on the subject of the emergence of biological homochirality in the first decade of the twenty-first century led *Chemistry World* to suggest that we are now “spoilt for choice” (Ball 2007) in proposals for answering the puzzle of the single chirality of life on Earth.

Cross-References

- [Enantiomeric Excess](#)
- [Enantiomers](#)
- [Homochirality](#)
- [Origin of Life](#)
- [Racemic Mixture](#)

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Chiron

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Chiron, discovered in 1977, was first identified as an ► [asteroid](#), labeled 2060 Chiron. In 1989, as the object was moving toward perihelion, a coma was discovered and it was also designated as a comet, 95 P/Chiron. Chiron is the first identified object among the class of the ► [Centaurs](#) which orbit between Jupiter and Neptune. Its period is 50 years and its perihelion distance is 8.4 AU. Its diameter is about 180 km and its albedo is about 0.05. Chiron is now considered to belong to the C-type class of asteroids. Like other Centaurs, Chiron is assumed to be originally a ► [trans-Neptunian object](#) which escaped from the ► [Kuiper Belt](#).

Cross-References

- [Centaurs \(Asteroids\)](#)
- [Kuiper Belt](#)
- [Trans-Neptunian Object](#)

Chlorine Hydrides in the Interstellar Medium

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Chloronium](#); [Chloroniumyl](#); H_2Cl^+ ; [HCl](#); HCl^+ ; [Hydrogen chloride](#)

Definition

Not only the familiar diatomic molecule containing hydrogen and chlorine, ► [hydrogen chloride](#) (HCl), but also the cations HCl^+ and H_2Cl^+ have been detected by astronomers in the ► [interstellar medium](#). In fact, both the ^{35}Cl and the ^{37}Cl ► [isotopologs](#) for all three molecular species have been identified in space.

History

Whereas HCl was detected using the Kuiper Airborne Observatory (KAO), HCl^+ and H_2Cl^+ were observed with the Herschel Space Observatory. For more information, see ► [Molecules in Space](#).

Cross-References

- [Diffuse Cloud](#)
- [Herschel Mission](#)
- [Hydrogen Chloride](#)
- [Interstellar Medium](#)
- [Isotopolog](#)
- [Molecules in Space](#)

Chloromethane (CH₃Cl)

Audrey Coutens
Laboratoire d'Astrophysique de Bordeaux,
Pessac, France

Synonyms

CH₃Cl; Freon-40; Methyl chloride; R40

Chemical Formula

CH₃Cl

Definition

Chloromethane is a colorless and poisonous gas. It is the most abundant of the organohalogens present in the Earth's atmosphere and is produced by both natural and synthetic pathways. Chloromethane was formerly used as a refrigerant. This use was, however, discontinued because of its toxicity and flammability. Chloromethane was identified in our ► [Solar System](#), both on Mars (Glavin et al. 2013) and in the coma of the comet ► [67P/Churyumov–Gerasimenko](#) (Fayolle et al. 2017). It was also detected in the ► [interstellar medium](#) towards the two components of the protostellar binary ► [IRAS 16293–2422](#) (Fayolle et al. 2017).

History

Chloromethane was detected for the first time in the ► [interstellar medium](#) in 2017 (Fayolle et al. 2017).

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Interstellar Medium](#)

- [IRAS16293-2422](#)
- [Solar System](#)

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Chloronium

- [Chlorine Hydrides in the Interstellar Medium](#)

Chloroniumyl

- [Chlorine Hydrides in the Interstellar Medium](#)

Chlorophylls

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Chlorophylls are a class of pigments derivative of protoporphyrin complexed with magnesium. Chlorophylls function in photosynthetic organisms both as light receptors and special photochemical devices in photosynthetic reaction centers.

Cross-References

- [Bacteriochlorophyll](#)
- [Photosynthesis](#)

Chloroplast

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Chloroplast is a ► [chlorophyll](#)-containing organelle of phototrophic eukaryotes responsible for the generation of energy from radiation. A major feature of eukaryotic cells, absent from prokaryotic cells, is the presence of membrane-enclosed structures called ► [organelles](#). These include mitochondria and chloroplasts, the latter only in photosynthetic cells. Like mitochondria, chloroplasts have a permeable outermost membrane, a much less permeable inner membrane, and an intermembrane space. The inner membrane surrounds the lumen of the chloroplast, called stroma. Chlorophyll and all other components needed for ► [photosynthesis](#) are located in a series of flattened membrane disks called thylakoids. The thylakoid membrane is highly impermeable to ions and other metabolites because its function is to establish the ► [proton motive force](#) necessary for ATP synthesis. In green ► [algae](#) and plants, thylakoids are typically stacked into discrete structural units called grana. The chloroplast stroma contains large amounts of the enzyme ribulose biphosphate carboxylase (RubisCO). RubisCO is a key catalyst of the Calvin cycle, the series of biosynthetic reactions by which most photosynthetic organisms convert CO₂ to organic compounds. RubisCO makes up over 50% of the total chloroplast protein and catalyzes the formation of phosphoglyceric acid, a key compound in the biosynthesis of glucose. The permeability of the outermost chloroplast membrane allows glucose and ATP produced during photosynthesis to diffuse into the cytoplasm where they can be used to build new cell material. On the basis of their relative autonomy, size, and morphological resemblance to prokaryotes, it was

suggested that chloroplasts were descendants of bacteria by ► [endosymbiosis](#). There is different structural, functional, and molecular evidence that supports the endosymbiotic origin of chloroplasts: existence of a small genome, presence of ribosomes, antibiotic specificity, and molecular phylogeny.

Cross-References

- [Algae](#)
- [Anoxygenic Photosynthesis](#)
- [ATP Synthase](#)
- [Autotrophy](#)
- [Calvin-Benson Cycle](#)
- [Carbon Dioxide](#)
- [Chlorophylls](#)
- [Endosymbiosis](#)
- [Organelle](#)
- [Photoautotroph](#)
- [Photosynthesis](#)
- [Photosynthetic Pigments](#)
- [Proton Motive Force](#)

Chondrite

Frank Sohl

DLR, Institute of Planetary Research, Berlin,
Germany

Definition

Chondrites are undifferentiated stony ► [meteorites](#) and represent the majority among stony meteorites. The term literally means “with ► [chondrules](#)” and therefore underlines the main difference to ► [achondrites](#). Chondrites consist of a fine-grained matrix of micrometer-sized dust particles, surrounding roughly millimeter-sized, round inclusions (► [chondrules](#)), refractory ► [CAIs](#) (*Ca-Al-rich inclusions*), particles enriched in metallic Fe-Ni and sulfides, and

other individual mineral grains. The matrix also contains presolar grains that formed elsewhere in the Galaxy before the Solar System came into being. The presence of ► [chondrules](#) indicates that chondrites were formed by accretion of thermally processed dust particles, whereas their primitive parent bodies never experienced partial melting and recrystallization. The class of chondrites has been divided into enstatite (EH and EL types), Rumuruti (R type), ordinary (H, L, and LL types), and ► [carbonaceous](#) (C types); the latter is subject to aqueous alteration and thought to be the most primitive meteorites. H, L, and LL indicate high-iron, low-iron, and low-iron/-metal contents, respectively.

Cross-References

- [Achondrite](#)
- [CAIs](#)
- [Carbonaceous Chondrite](#)
- [Chondrule](#)
- [Meteorites](#)

Chondrule

Frank Sohl¹ and Tilman Spohn²

¹Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

²International Space Science Institute, Bern, Switzerland

Definition

The term chondrule comes from the Greek word “chondros” for grain or seed. They are the major component of ► [chondrites](#) and can make up to 80% of the volume of a given ► [meteorite](#). In general, chondrules are rounded inclusions, roughly millimeter-sized silicates. Their formation is not fully understood, but they did go through a transient heating process which was followed by a

cooling period, so that molten or partly molten droplets came together before these pieces accreted to their parent body. Chondrules together with the ► [CAIs](#) (Ca-Al-rich inclusions) constitute the oldest material of our ► [Solar System](#).

Cross-References

- [CAIs](#)
- [Chondrite](#)
- [Meteorites](#)
- [Silicate](#)
- [System Solar Formation, Chronology of](#)

Chromatographic Coelution

Jason P. Dworkin

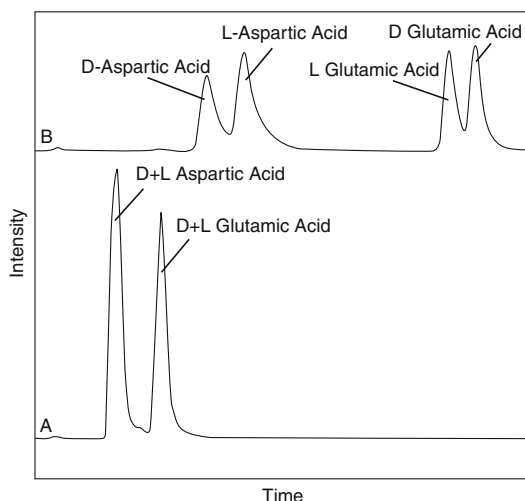
Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Co-elution](#)

Definition

Chromatographic coelution occurs when two (or more) compounds do not chromatographically separate due to the fact that both species have retention times that differ by less than the resolution of the method. This can be solved by increasing the selectivity and/or efficiency of the ► [chromatography](#) or by employing different detection techniques that can differentiate the coeluting compounds. Changing the chemistry of the mobile phase, stationary phase, temperature, and column or plane length are good methods to increase the separation. Techniques such as mass spectrometry and optical spectroscopy are common ways to distinguish between coeluting compounds that cannot be resolved (Fig. 1).



Chromatographic Coelution, Fig. 1 Chromatographic co-elution can be resolved by adjusting the chromatographic conditions. In these reverse phase HPLC traces, fluorescently labeled amino acids are resolved by decreasing the methanol concentration in the mobile phase from trace A to trace B

Cross-References

- [Chromatography](#)
- [Gas Chromatography](#)
- [GC/MS](#)
- [Ion-Exchange Chromatography](#)
- [Liquid Chromatography-Mass Spectrometry](#)
- [Pyrolysis GC/MS](#)

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Chromatography

Jason P. Dworkin
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Keywords

Column chromatography · GC · Hyphenated techniques · LC · Planar chromatography · Separation science · Solid phase extraction

Definition

Chromatography (either preparative or analytical) is a qualitative or quantitative experimental method based on the properties of all molecules to partition more or less selectively from one phase into another and therefore to migrate at different rates when they are carried across a solid or liquid stationary phase by a mobile phase, which can be a gas, liquid, or supercritical fluid.

Overview

Chromatography is a broad laboratory method for physically separating compounds from a mixture based on the preferential partitioning of different molecules across two different phases. The analyte is carried in the mobile phase (gas, liquid, or supercritical fluid) and then passes through a stationary phase (liquid or solid), and some analytes are retained more efficiently than others. Different types of chromatography are based on the geometry (through a stationary phase-filled tube or “column” or over a plate or “plane” with stationary phase), the type of mobile/stationary phase interaction (gas/liquid, gas/solid, liquid/liquid, liquid/solid, supercritical fluid/solid), and the nature of the analyte/stationary phase interaction (e.g., host/guest chemistry, hydrophobic interactions, ion exchange, hydrodynamic volume, volatility, etc.). ► [Electrophoresis](#), while not strictly chromatography, is closely related.

While planar chromatography (e.g., paper and thin layer (TLC)) is typically qualitative, column chromatography is well suited for real-time interrogation of the eluting compounds with detectors. Common types of gas-liquid chromatography (GC) detection techniques are flame ionization detection, thermal conductivity, and any number of mass spectrometric techniques (GC-MS). Common detectors in liquid/solid chromatography (LC or ► [HPLC](#)) are ultraviolet absorbance, fluorescence, refractive index, and various mass spectrometric methods (LC-MS). The addition of more elaborate detectors with a chromatographic or capillary

electrophoretic “front end” (or “inlet”) is collectively referred to as hyphenated or hybrid techniques. Combinations of chromatography with ► [mass spectrometry](#), nuclear magnetic resonance, and optical spectroscopy increase the ability of an analytical chemist to study small quantities of complex mixtures.

Conversely, preparative chromatography (either column or planar) is used to purify large quantities of a compound of interest. While GC or supercritical fluid chromatography is sometimes used, the most popular method is LC (or electrophoresis). One popular method is solid-phase extraction (SPE).

While the majority of chromatography is conducted in laboratories or industry, the process can be found elsewhere. Naturally occurring chromatography is typically fractional distillation or geochromatography, where, for example, compounds dissolved in water are roughly separated as they pass through rocks or sediment columns. Chromatography (GC-MS) has also been used in robotic planetary science missions to study Mars; Saturn’s moon, Titan; and comets.

Cross-References

- [Affinity Chromatography](#)
- [Electrophoresis](#)
- [ExoMars](#)
- [Gas Chromatography](#)
- [GC/MS](#)
- [Ion-Exchange Chromatography](#)
- [Liquid Chromatography-Mass Spectrometry](#)
- [Mars Science Laboratory](#)
- [Mass Spectrometry](#)
- [Pyrolysis GC/MS](#)
- [Viking](#)

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Chromium Isotopes

Sean A. Crowe, Kohen W. Bauer and
Ashley B. Davidson

Departments of Microbiology and Immunology,
and Earth, Ocean, and Atmospheric Sciences,
The University of British Columbia, Vancouver,
BC, Canada

Keywords

Stable isotopes · Transition metals ·
Chromium · Isotope fractionation · Redox
reactions · Meteorites · Contamination · Earth
history

Synonyms

[Isotopes of chromium](#)

Chemical Formula

^{50}Cr , ^{52}Cr , ^{53}Cr , and ^{54}Cr

Definition

The transition metal chromium (Cr) has four naturally occurring stable isotopes; ^{50}Cr (4.345%), ^{52}Cr (83.789%), ^{53}Cr (9.501%), and ^{54}Cr (2.365%) as well as 22 synthetic radioactive isotopes with ^{51}Cr being the most stable with a half-life of 27.7 days. Cr has an atomic number of 24, and a standard atomic weight of 51.9961. The stable isotopic composition of Cr is generally reported in delta notation as $\delta^{53}\text{Cr}_{(\text{NIST-979})} = [({}^{53}\text{Cr}/{}^{52}\text{Cr})_{\text{substance}} / ({}^{53}\text{Cr}/{}^{52}\text{Cr})_{\text{NIST-979}} - 1]$, where substance is a material of interest and NIST 979 is a certified Cr nitrate solution with the relative isotope abundances noted above.

History

Measurements of Cr stable isotope ratios were initially applied in astrophysics to study the origins of the Solar System (Birck and Allègre 1984,

1988). The relatively short-lived radionuclide ^{53}Mn decays to ^{53}Cr in 3.7 Ma. Variability in the relative abundance of ^{53}Cr , as measured, for example, through the ratio of ^{53}Cr to ^{52}Cr thus provides information on the abundance of the now extinct ^{53}Mn isotope during the formation of Solar System objects like meteorites (Birck and Allègre 1984, 1988). Combined with the decay rate of ^{53}Mn , Cr isotope ratios in Solar System objects provide information on their timing of formation and inform models of nucleosynthesis (Birck and Allègre 1984, 1988). Stable Cr isotope ratio measurements were subsequently adopted to track natural attenuation of hexavalent Cr (Cr(VI)) in Cr contaminated groundwater (Ellis et al. 2002). The utility of stable Cr isotope measurements in tracking Cr(VI) attenuation arises from the stable isotope fractionation that accompanies the reduction of Cr(VI) to trivalent Cr (Cr(III)), which is much less soluble and more particle reactive than Cr(VI) (Ellis et al. 2002). As Cr(VI) is progressively reduced to Cr(III), the isotopic composition of residual Cr(VI) becomes heavier (i.e., $\delta^{53}\text{Cr}_{(\text{NIST-979})}$), and thus isotope ratio measurements inform on the extent of Cr (VI) reduction (Ellis et al. 2002). Following application of Cr stable isotope ratio measurements to Cr (VI) natural attenuation, studies found that equilibrium fractionation was only expected during redox reactions of Cr (Schauble et al. 2004) and that the Cr stable isotope composition of igneous rocks all fell within a very narrow range (Schoenberg et al. 2008) ($\delta^{53}\text{Cr}_{(\text{NIST-979})} = -0.124 \pm 0.101\%$ (2 SD)). Application of Cr isotopes to reconstructing the evolution of Earth surface chemistry began with the finding that Cr isotope ratios in marine chemical sediments appeared to broadly track the oxygenation of the atmosphere between the Archean and Phanerozoic Eons (Frei et al. 2009). This finding prompted numerous studies that applied Cr isotope ratio measurements in geological materials as a paleo-oxygen proxy (Cole et al. 2016; Crowe et al. 2013). At the same time, efforts to determine the multiple physical-chemical-biological processes that redistribute Cr and fractionate its isotopes in relevant Cr reservoirs intensified (Basu and Johnson 2012; Berna et al. 2010; Døssing et al. 2011).

Overview

Cr stable isotope ratio measurements are used in astrophysics, environmental chemistry, oceanography, and geobiology. Cr stable isotope ratio measurements are commonly conducted using either Thermal Ionization Mass Spectrometry (TIMS) or Multicollector-Inductively Coupled Plasma-Mass Spectrometry (MC-ICP-MS) following Cr purification through ion exchange resins (Qin and Wang 2017). Application of Cr stable isotopes in astrophysics is generally restricted to analyses of meteorites to determine variability in ^{53}Cr abundance as a proxy for now extinct ^{53}Mn (Birck and Allègre 1984, 1988). Cr stable isotope variability in meteorites is small and thus very high precision isotope ratio measurements are required (Birck and Allègre 1984, 1988). Measurements of Cr isotope ratios in terrestrial igneous rocks also show limited variability ($\delta^{53}\text{Cr}_{(\text{NIST-979})} = -0.124 \pm 0.101\%$ (2 SD)) (Schoenberg et al. 2008). Larger Cr isotope fractionations (are known to accompany the reduction of Cr(VI) to Cr(III) at Earth's surface and this can give rise to large ($>1\%$) differences in the $\delta^{53}\text{Cr}_{(\text{NIST-979})}$ of redox cycled Earth surface materials. Cr(VI) is known to form on the Earth's surface due to reactions with strong oxidants like manganese oxides (Fendorf and Zasoski 1992), or hydrogen peroxide (Pettine and Millero 1990). The presence of Cr(VI) in Earth's surface environments is thus thought to require an atmosphere-ocean system oxygenated through biological photosynthesis (Frei et al. 2009; Crowe et al. 2013), though traces of strong oxidants can be generated through abiotic photochemical reactions (Availability of O_2 and H_2O_2 on Pre-Photosynthetic Earth 2011). It is also worth noting that Cr(VI) itself is a strong oxidant and a carcinogen (Norseth 1981)—Cr(VI) can accumulate to naturally high concentrations due to oxidative weathering of ultramafic rocks (Oze et al. 2007), and in cases, it has been released into the environment due to anthropogenic activities. Reduction of Cr(VI) is accompanied by a strong kinetic isotope fractionation effect, which can vary in magnitude depending on the specific reductant, and invariably leads to enrichment of

the light isotopes in the Cr(III) product (Ellis et al. 2002; Døssing et al. 2011; Kitchen et al. 2012; Basu et al. 2014). Groundwater models that apply known fractionation factors can thus be used to predict the extent of Cr(VI) reduction based on the isotopic composition of residual Cr(VI) (Berna et al. 2010). In contrast, experiments to date imply limited fractionation associated with oxidation of Cr(III) to Cr(VI) (Zink et al. 2010). Experiments, however, show that Cr(III) chelation by strong organic ligands can induce appreciable fractionation (Saad et al. 2017). Theory predicts that equilibrium fractionation between Cr(VI) and Cr(III) species leads to enrichment of the light isotopes in Cr(III) and also predicts negligible equilibrium isotope fractionation between inorganic Cr(III) species (Schauble et al. 2004). The extent to which equilibrium fractionations between Cr species are expressed in the environment depends on the kinetics through which isotope exchange between species occurs. Collectively, existing experimental and theoretical data imply strong kinetic Cr isotope fractionation associated, with Cr(VI) reduction to Cr(III) and Cr(III) chelation with relatively modest fractionations associated with other Cr reactions.

Cr exists in Earth's continental crust primarily as Cr(III) hosted in minerals like chromite (Cr_2O_3) and in silicates like amphiboles and pyroxenes. The stable isotopic composition of most crustal rocks is similar to igneous rocks and mantle derived rocks are also comparable (Schoenberg et al. 2008). Weathering of the crust primarily delivers these minerals as detritus to the oceans, but also leads to the limited dissolution of Cr and its delivery to seawater as dissolved Cr(III), or Cr(VI), if oxidized as described above (D'Arcy et al. 2016; Wu et al. 2017). Weathering is accompanied by Cr isotope fractionation and Cr(VI) in rivers is isotopically heavy relative to igneous rocks. Cr accumulates in seawater (concentrations), where it variably exists as Cr(III) and Cr(VI) (Pettine and Millero 1990). The isotopic composition of Cr in seawater is also variable and exhibits an inverse, log-linear, relationship with Cr concentration (Scheiderich et al. 2015). This log-linear relationship, colloquially referred to as the global-Cr-array, implies a

defined isotope fractionation factor ($0.08 \pm 0.03\%$ (2 SD)) associated with the removal of Cr from seawater. Marine sediments contain Cr mostly as detrital minerals, which thus have isotopic compositions similar to or identical to the continental crust (Schoenberg et al. 2008; Gueguen et al. 2016). Authigenic Cr, derived from seawater, can be enriched in chemical sediments (e.g., carbonates (Bonnand et al. 2013), or iron oxides) or siliciclastic sediments deposited under anoxic conditions (Gueguen et al. 2016). Authigenic Cr can have Cr isotope ratios offset from seawater due to fractionation associated with Cr removal to the sediment (Gueguen et al. 2016). When fractionation associated with Cr removal is known, analyses of Cr isotopes in authigenic Cr preserved in sediments and sedimentary rocks can be used to reconstruct the isotope composition of seawater, which itself is set by a combination of the isotope fractionation associated with removal and that associated with weathering and runoff. Given that large fractionations are only known to occur as the result of Cr(VI) reduction and Cr(III) chelation, the sedimentary stable Cr isotope record is most sensitive to Cr redox reactions and possibly the presence of strongly binding Cr(III) ligands in the weathering environment and oceans.

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Chromophore

John H. Chalmers

Scripps Institute of Oceanography Geosciences Research Division, University of California, San Diego, La Jolla, CA, USA

Definition

Chromophores are chemical groups that absorb ► **electromagnetic radiation**, for example, in the visible, near-infrared, or ultraviolet ranges, though the original derivation of the word comes from the Greek for color, implying absorption of visible radiation. They may contain systems of conjugated multiple bonds, transition element ions, or both. In biological systems, light absorption by chromophores forms the basis of vision, ► **photosynthesis**, and, in the case of ultraviolet light, ► **mutation** and vitamin D synthesis. In the context of astrobiology, chromophores have been found, for example, in simulated cometary ices. Chromophores are responsible for the colors of dyes, pigments, minerals, and many organisms, though some colors, particularly blues and iridescent effects, are produced by diffraction.

Cross-References

- **Bacteriochlorophyll**
- **Chlorophylls**
- **Circular Dichroism**

- ▶ [Electromagnetic Radiation](#)
- ▶ [Extreme Ultraviolet Light](#)
- ▶ [Fluorophore](#)
- ▶ [Mutation](#)
- ▶ [Photosynthesis](#)
- ▶ [Photosynthetic Pigments](#)

Chromosome

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Chromosome is a structure consisting of or containing ▶ [DNA](#) with essential genetic information for the cell. In most prokaryotes, it is a circular, double-stranded DNA, normally attached to the cell membrane, with a folded structure (also known as nucleoid) with some attached proteins. In eukaryotic cells, usually the number of chromosomes is characteristic of the species – polyploid plants are a remarkable exception. Somatic cells possess two sets of homologous chromosomes (diploid number or $2n$), one originating from the male progenitor, the other from the female. In contrast, germ-line cells are haploid (n). Eukaryotic chromosomes are located inside the ▶ [nucleus](#) and consist of a double-stranded DNA molecule highly folded and complexed with proteins (histones) also known as chromatin. The term chromosome also applies to the DNA molecules located in mitochondria and plastids and to the genome of DNA viruses.

Cross-References

- ▶ [DNA](#)
- ▶ [Genome](#)
- ▶ [Nucleus](#)
- ▶ [Replication \(Genetics\)](#)
- ▶ [Transcription](#)

Chronostratigraphy

Stephan van Gasselt and Gerhard Neukum
Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Keywords

Cratering chronologies · Impact crater · Production function · Radiometric ages · Stratigraphy

Synonyms

[Cratering chronology](#); [Planetary chronostratigraphy](#); [Planetary surface ages](#)

Definition

The term chronology with respect to planetary surfaces generally refers to the timing of events when rock surface units were formed or modified and describes the position of a geologic unit within its stratigraphic context. The term chronology furthermore encompasses the method of deriving ages of planetary surface units by means of radiometric age determinations as well as by analyses of impact crater size-frequency distributions based on knowledge or assumptions of the flux and size distribution of planet-impacting bodies in the history of the Solar System.

Overview

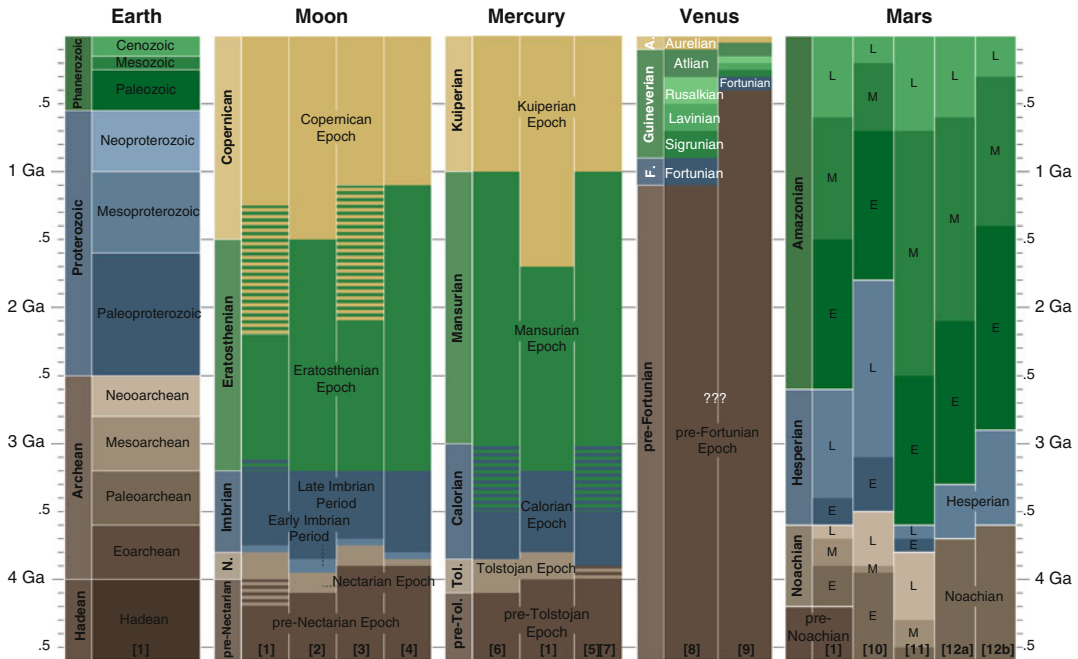
The chronology of planetary surfaces refers to the sequence of geological events that have led to deposition and emplacement of rock-forming units on a planetary surface. The sequence of events and the geologic materials, i.e., the rock-forming units (Wilhelms 1987; Greeley and Batson 1990), are the planet's chronostratigraphic record and have to be seen in a specific planetary context as each planetary body evolves in a different way.

While the chronology in general refers to the timing and sequence of such events, the stratigraphic record of a planet is defined by divisions of geologic time and boundaries of geologic units on a global scale. Divisions of time are characterized by primary or secondary markers considered to be characteristic of that surface. While the geologic time unit (chronologic unit; see Fig. 1) refers to an age derived by various methods as discussed below, a chronostratigraphic unit consists of rocks formed on a global scale during a specific geologic time (Ogg et al. 2008).

The knowledge we have today about the chronostratigraphy and chronology of terrestrial planetary surfaces other than the Earth is based upon the knowledge we have gained during planetary exploration of the ► [Moon](#) (Wilhelms et al. 1971) and was later expanded to other terrestrial surfaces, in particular ► [Mercury](#) and ► [Mars](#) for which formal stratigraphic systems have been developed (Tanaka and Hartmann 2008).

The establishment of timescales for planetary surfaces is based upon geological mapping of planetary surfaces as defined by surface properties, e.g., morphologies, textures, spectral compositions, and, as delineated by geologic contacts, the superposition of individual units following basic stratigraphic principles. Relative ages can be derived by measuring the size-frequency distribution of ► [impact craters](#) that have accumulated in a planet's history through time, which means that densely cratered surfaces are older than less-densely cratered surface units. Thus, a geologic unit records the age as expressed by the number of impact craters formed during meteoritic bombardment and the time a unit was exposed to the projectile impact flux (Öpik 1960; Baldwin 1964; Hartmann 1966; Neukum et al. 1975).

Absolute ages for surface units are constrained by samples returned from the Moon in the course of the lunar Apollo and Luna mission programs. Derived radiometric ages of surface samples have



Chronostratigraphy, Fig. 1 Chronology units in terms of epochs and periods for the terrestrial planets as compiled from different sources; see main text for description; the two columns for Venus' chronology depict the upper and lower estimates for $T = 800$ Ma and $T = 288$ Ma, respectively (1, Ogg et al. (2008), 2, Neukum and Ivanov (1994), 3,

Stöffler and Ryder (2001), 4, Wilhelms (1987), 5, Neukum et al. (2001a), 6, Strom and Neukum (1988), 7, Spudis and Guest (1988), 8, Basilevsky and Head (1998), 9, Basilevsky and Head (2002), 10, Tanaka (1986), 11, Neukum and Wise (1976), 12a, Hartmann and Neukum (2001) Neukum model, and 12b, Hartmann and Neukum (2001) Hartmann model)

established a calibration for the size-frequency distribution of the Moon's surface as observed by remote-sensing imaging. This process allows us to measure model ages for other planetary surfaces either (a) by estimating the relative cratering rates in comparison with the Moon or (b) by directly assessing cratering rates under consideration of impact probabilities and impactor sizes and sources (Neukum and Ivanov 1994; Tanaka and Hartmann 2008) as well as crater scaling laws that describe the relationship between projectile size and impact condition parameters, e.g., velocity, angle, density, and surface parameters, such as surface gravity, density, compositions, and strength of surface materials (Croft 1985; Holsapple 1987; Schmidt and Housen 1987).

For planetary surface chronologies, the number of stratigraphic systems for planetary objects has advanced with new data that have become available in the context of planetary exploration mission. Stratigraphic systems cover the terrestrial (inner) planets as well as the Moon and also the major icy satellites of the Jovian and Saturnian planetary systems.

Basic Methodology

There are different methods of assessing the stratigraphy of planetary surfaces with respect to the relative or absolute age of individual geologic units and their relation to neighboring units. Ages of rocky planetary surface material are determined by means of the decay of radioactive isotopes and decay products if decay rates are known and if samples of surface material are available. In cases where planetary surfaces are observed by remote-sensing methods, ages of surface forming units can only be determined by analyses of impact crater size-frequency measurements, i.e., by comparing the size-frequency distribution of impact craters with the modeled size distribution and impact flux of meteorites on a given planetary surface.

While *relative* age determinations of units allow to assess and estimate the relative sequence of unit-forming events within an area of interest

and in comparison with an established global distribution of impact crater size-frequency observations, age determinations of geologic units based on remotely sensed data with the help of either appropriate scaling laws or modeling of impactor flux allow us to derive *absolute* ages. Except for the Earth, only the Moon has been directly sampled thus far and therefore forms the only natural calibration target for establishing planetary chronostratigraphies and surface chronologies.

Radiogenic Isotope Measurements

Radioactive (or radiometric) dating, i.e., determination of radiogenic isotope ages of rock samples in the context of chronology, makes use of the constancy of rates of radioactive decay by which a radioactive nuclide is transformed to its daughter product. Radiogenic isotope ages for lunar material have been derived using decay measurements of Rb-Sr, Sm-Nd, and $\text{Ar}^{40}\text{-Ar}^{39}$. Such methods are described in detail by, e.g., Dalrymple and Ryder (1991) and Albarède (2009).

For the Moon, over 380 kg of rock material in over 2,000 samples was returned to Earth during the six manned Apollo missions. During the Soviet robotic Luna missions, several hundred grams were collected during three Luna missions and analyzed after return to Earth. Samples are mainly from basaltic rock and impact glass from the lunar mare areas (Apollo 11, 12, 15, 17; Luna 16, 24) as well as from highland terrain (Apollo 14–17, Luna 20). In addition, a number of meteorites found on Earth have a lunar origin (or Martian) and could be radiometrically dated in laboratory measurements; their exact location of origin is, however, unknown.

Lunar rocks on the surface are exposed to cosmic weathering processes and recurrent meteoritic bombardment and therefore are altered. This leads to reprocessing of rocky material and to formation of second- or third-generation rocks (Stöffler et al. 2006). By making use of radioisotope measurements, different ages are usually derived, i.e., (a) crystallization ages, (b) ages of formation of impact breccia, and (c) exposure ages. The crystallization age gives the age of events that led to formation of rock minerals by magmatic or in situ melting processes. Ages for

formation of impact breccia give insight into the age rock material and minerals were transformed to breccias, while the exposure age of rock material gives the age since the rock was exposed to cosmic weathering by cosmic rays (Stöffler et al. 2006). It has, however, been shown that direct radiometric age determinations are only possible for lunar mare basalts, as highland material collected at the lunar surface cannot be related directly to its source area. None of the collected samples were derived from bedrock material due to a several meters thick surface coverage of lunar regolith (e.g., Heiken et al. 1991 and references therein).

Radiogenic isotope measurements for deriving absolute ages of localized samples help to establish boundary age values, but without a careful interpretation of the photogeological settings and the geological context, such measurements cannot contribute to establishing a planet-wide chronology and chronostratigraphic system.

Relative Age Determinations

The easiest accessible approach to assess the time sequence of rock-forming events on a planetary surface is to measure the size-frequency distribution of impact diameters within a geologic unit and to compare this to other geologic units of the same planetary body: the higher the number of impact craters that have accumulated over time per area, the older the surface, which means that a crater frequency measured on a specific geologic unit is representative of the relative age or crater retention age of that unit (Arvidson et al. 1979). A geologic unit or rock-stratigraphic unit is a morphologically distinct entity formed at a specific time by a distinct geologic process (Stöffler et al. 2006). The derived relative surface age does not necessarily reflect the true relative age when a geologic unit was formed, as subsequent processes, generally termed resurfacing, might have led to eliminating impact craters in a given diameter-size range. The main problems arise from accurately identifying and delineating a geologic unit at a given scale, as this significantly depends on the appearance of a particular unit and its relation to surrounding units in the image

data used for photogeologic interpretations (Shoemaker and Hackman 1962; Wilhelms 1987).

By employing cumulative crater size-frequency diagrams, the measured impact crater diameters of all impact craters within a given geologic unit are usually plotted against their cumulative frequency in a log-log diagram. The impact crater size-frequency distribution derived in such a way provides a measure for the surface age with older units, i.e., units with increasing crater retention ages, shifted upwards on the frequency axis (apparent shift toward larger impact crater diameters), while distributions of younger units are shifted downwards on the frequency axis leading to an apparent shift toward smaller impact crater diameter sizes (Hartmann et al. 1981; Wilhelms 1987).

While relative surface age determinations are based upon the interpretation of remotely sensed data by means of determining the superposition of individual rock surface units and by determining impact crater size frequencies, age determinations leading to absolute age values need additional pieces of information.

Absolute Age Determinations

There are two methods of obtaining absolute ages of rock surface units of planetary bodies. One method links radiogenic isotope ages obtained for the Moon with crater retention ages, i.e., relative ages, obtained through photogeological mapping (Hartmann et al. 1981; Neukum 1983; Neukum and Ivanov 1994). In the other approach, models for rates for formation of impact craters are employed and are transferred to other planetary objects considering their specific environment, e.g., position and size, atmosphere, and target properties (Neukum and Wise 1976; Neukum and Hiller 1981; Hartmann et al. 1981; Croft 1985; Holsapple 1987; Schmidt and Housen 1987).

For the ► [terrestrial planets](#) in the Inner Solar System, surface ages can only be obtained by models of the crater forming rates on each one of these bodies. Shapes of crater size-frequency distributions (SFDs) measured on the terrestrial planets, including the Moon, were shown to be

more or less similar which indicates (a) the same family of bodies, preferentially asteroids (Main Belt, Near-Earth asteroids, etc.), impacting these planets, and (b) that time dependences of impact and cratering rates are similar to that for the Moon (Neukum and Hiller 1981; Neukum and Wise 1976; Neukum and Ivanov 1994; Neukum et al. 2001a; Strom et al. 2005).

Lunar-like cratering chronology models were derived for Mercury (Strom and Neukum 1988; Neukum et al. 2001b), ► **Venus** (McKinnon et al. 1997), and Mars (Neukum and Wise 1976; Neukum and Hiller 1981; Hartmann and Neukum 2001). Crater size-frequency measurements were conducted also for a number of asteroids, e.g., 951 Gaspra (Neukum and Ivanov 1994; Chapman et al. 1996), 243 Ida (Neukum and Ivanov 1994), and 253 Mathilde (Chapman et al. 1998).

The impact-cratering chronology model for the Moon is characterized by an exponentially declining impact and crater formation rate in the first 1 Ga following planetary formation 4.55 Ga (e.g., Neukum 1977; Neukum and Ivanov 1994).

Since about 3.8 Ga ago, impact and cratering rates have dropped considerably and reached a more or less constant level at 3–3.3 Ga ago (Wetherill 1975; Neukum 1983; Neukum and Ivanov 1994; Neukum et al. 2001a). Some authors interpreted a peak in radiometric ages of lunar rocks at about 3.9 Ga as an indication for a strong peak in impact and cratering rate (e.g., Tera et al. 1974). They concluded that this so-called Late Heavy Bombardment (LHB) was characterized by a terminal lunar cataclysm rather than by a smooth, exponential decay in impact rate with time. The lunar cataclysm theory has been challenged by dynamic, geologic, and stratigraphic arguments (Wetherill 1975; Neukum and Ivanov 1994; Baldwin 2006).

Absolute ages obtained with an impact chronology model are generally termed cratering model ages, and their units are given in gigayears (Ga = 1 billion years) or megayears (Ma = 1 million years).

Crater size-frequency distributions obtained from crater size-frequency measurements are represented using several techniques, of which

three are commonly adopted. In principle, crater size diameters are grouped into pseudo-logarithmic or logarithmic bins and plotted on the abscissa (Arvidson et al. 1979; Neukum et al. 2001a; Michael and Neukum 2010). The ordinate gives the crater size-frequency values as a function of log diameters. This frequency can either be based upon the cumulative crater diameter sizes (cumulative plots) in which the number of craters with diameters equal or greater than D : $N = N(\geq D)$ is presented or in differential form where the derivative dN/dD of the cumulative size-frequency distribution gives the number of craters in equal diameter bins. The incremental form provides the frequency as a function of the geometric average of fixed-diameter increments (usually $\sqrt{2}$). The relative distribution (R-plot) is the deviation of the size-frequency distribution from a power law: $R = D^3 (dN/dD)$. The choice depends on the details that need to be depicted and highlighted and the analyses that are carried out subsequently.

The size-frequency distribution of an impact crater population can be approximated using either three stepwise power-law segments (Hartmann et al. 2000) obtaining coefficients for the approximation that are characteristic for each SFD. In contrast to the approach by Hartmann, Neukum proposed an analytical polynomial fit (Neukum 1983; Neukum and Ivanov 1994; Ivanov 2001; Neukum et al. 2001a). These functions are termed production functions and are characteristic of each planetary body and derived from numerous observations and measurements of impact craters. Once the production function is fitted, the frequency of impact craters larger than a given diameter (usually N for $D \geq 1$ or N for $D \geq 10$ km) is obtained. This frequency value is subsequently used to derive a surface age from the chronology function obtained earlier which represents the impact-cratering record in the planet's history.

Stratigraphic schemes have been established in principle for all terrestrial bodies. These schemes are based upon stratigraphic marker horizons that are defined by geologic criteria which are different for each object, and they take into account the

superimposed crater size frequencies considered to be a characteristic of a particular unit (Wilhelms 1987). The geologic history of each planet is subdivided into the so-called time-stratigraphic systems. Such chronostratigraphic divisions are termed systems and are further divided into several (e.g., lower, middle, or upper) series. Time-stratigraphic systems and series correspond to periods and epochs as chronologic or chronometric divisions (Wilhelms 1987). The beginning of each period or epoch is defined by the cratering model age derived from the SFD measurement on the unit which defines the base of each system.

Key Research Findings

Stratigraphic sequences have been established in principle for all terrestrial bodies in the Solar System, in particular for the Inner Solar System planets and the Moon. The main stratigraphic sequences and unit-forming events are summarized below, and ages are provided whenever possible. However, age uncertainties are excluded for all model ages, and the reader is referred to references listed in each section. While for several bodies, such as the Moon and Mars, chronostratigraphic systems are well established and applicable, other objects are partly still unknown when it comes to high-resolution data needed for cratering analysis and statistics. Consequently, differences in absolute age dating for each planet between various groups of investigators are due to differences in assumptions of the impact and cratering rates, and many preliminary results are expected to be improved in the course of ongoing planetary missions.

The Moon

The Earth and its Moon are the only bodies in the Solar System for which radiometric ages of rock surface units and soil samples have been obtained. Robotic and manned missions to the Moon have provided the most extensive data set concerning stratigraphy and surface ages available (Wilhelms 1987).

The lunar geologic history is subdivided into periods defined by impact events and impact

crater occurrences ranging from the pre-Nectarian (oldest period), Nectarian, Imbrian, Eratosthenian to the Copernican period (youngest). The Imbrian period is subdivided by the Orientale impact into a late (upper) and early (lower) Imbrian epoch (Wilhelms 1987).

- The pre-Nectarian covers that section of geologic history which predates the Nectarian period, i.e., older than 3.92 (Wilhelms 1987; Stöffler and Ryder 2001) to 4.1 Ga (Neukum and Ivanov 1994). The chronostratigraphic system comprises a number of 30 impact basins, among which is the South Pole-Aitken basin. No traces for volcanic or tectonic processes during the pre-Nectarian period have been found thus far. Traces of pre-Nectarian surface units are mainly found on the lunar farside, and samples returned during the Apollo and Luna missions are later-generation material reworked as breccias in the course of subsequent impact processes (Wilhelms 1987; Stöffler et al. 2006).
- The Nectarian period is defined as the time period between the formation of the Nectaris basin (Janssen Formation) and the Imbrium impact event and comprises at least 11 other large impact-basin forming events. Although some Nectarian-aged volcanic material has been observed (Wilhelms 1987), much of this unit is covered by later impact events that masked Nectarian units. According to recent studies, mare volcanism started already during the Nectarian period with ages of 3.92 Ga and continuing up to 1.2 Ga (Hiesinger et al. 2003). The chronostratigraphic basis, i.e., the lowermost unit, for the Nectarian system is set between 3.92 (Wilhelms 1987; Stöffler and Ryder 2001) and 4.1 Ga (Neukum and Ivanov 1994).
- The Imbrian period is defined by the impact-basin event forming the Imbrium impact crater on the lunar nearside with the Fra Mauro Formation at its base. The Late Imbrian epoch starts with the Orientale basin formation (Hevelius Formation); its upper limit is defined through impact crater sizes only. Two thirds of the lunar mare volcanic deposits are of Late

Imbrian age. Apart from extensive mare-type volcanism, dark mantling deposits are thought to be of Late Imbrian age (Stöffler et al. 2006). Formation of the Orientale basin is suggested to be 3.72 Ga (Stöffler and Ryder 2001) to 3.8 Ga (Wilhelms 1987) or 3.84 Ga (Neukum and Ivanov 1994; Neukum et al. 2001a) depending on the chronology model.

The Early Imbrian epoch covers the time range between Imbrium (Fra Mauro Formation) and Orientale basin formation (Hevelius Formation) corresponding to 3.77 Ga (Stöffler and Ryder 2001) to 3.84 Ga (Wilhelms 1987) or even 3.92 Ga (Neukum and Ivanov 1994; Neukum et al. 2001a) depending on the chronology model. The epoch is characterized by extensive volcanism and impact cratering but without formation of larger impact basins, except for the Schrödinger basin. Many of the light plains have a Lower Imbrian age (Stöffler et al. 2006).

- The Eratosthenian period is defined through the appearance of younger impact craters covering most of other lunar units but showing no signs of rayed ejecta – a criterion that has led to discussions regarding boundary ambiguities (Stöffler et al. 2006; Stöffler and Ryder 2001). Some of the mare basalts were emplaced during the Eratosthenian, but these units are much less extensive than those in the Imbrian period. The basis of the Eratosthenian is generally set to 3.2 Ga (Wilhelms 1987; Stöffler and Ryder 2001; Neukum and Ivanov 1994; Neukum et al. 2001a).
- The Copernican period is defined through the occurrence of rayed craters on the Moon with Copernicus being the most prominent rayed impact crater. These impact craters are superimposed on all other units and show traces of ejecta material all over the Moon despite their relatively small size. Due to its definition, the basis for the Copernican period is not well constrained with ages ranging from 1.1 (Wilhelms 1987) to 1.5 Ga (Neukum and Ivanov 1994; Neukum et al. 2001a) up to 1.1–2.1 Ga (Stöffler and Ryder 2001). The Copernican period continues up to the present time.

Mercury

Mercury's surface is visually comparable to the lunar one as expressed by numerous impact craters and large impact basins, as well as a rich variety of tectonic features probably caused by rapid cooling and tidal despinning (Spudis and Guest 1988; Neukum et al. 2001a). Mercury's surface shows a global dichotomy in terms of major geologic units: the densely cratered terrain (highlands) with interspersed smoother areas (intercrater plains) and the less-densely cratered lowland plains (smooth plains) (Trask and Guest 1975; Spudis and Guest 1988). In contrast to the lunar surface, the smooth plains and highland terrain are comparable in relative albedo. Notwithstanding the surficial resemblance of Mercury and the Moon, crater size frequencies of the heavily cratered highland terrain of Mercury are less than that of the Moon (Spudis and Guest 1988) with a general paucity of impact craters in the 30 km diameter range (Neukum et al. 2001b). The stratigraphic system of Mercury was established by geologic mapping at scales of 1: 5,000,000 in the late 1970s and early 1980s on image data of Mariner 10 flybys.

Mercury's surface resemblance to the Moon led to establishing a stratigraphic system comparable to that of the lunar one with impact events characterizing bases of stratigraphic periods. Mercury's geologic history is therefore subdivided into five periods starting with the pre-Tolstojan as the oldest unit to the Kuiperian as the youngest period (Spudis and Guest 1988).

- The pre-Tolstojan period closely compares to the lunar pre-Nectarian and encompasses geologic units older than 3.97 Ga (Neukum et al. 2001a) to 4.1 Ga (Strom and Neukum 1988) and is related to crater materials and multiring basins as well as intercrater plains (Neukum et al. 2001a; Tanaka and Hartmann 2008; Spudis and Guest 1988).
- During the Tolstojan period which is equivalent to the lunar Nectarian period, the dominant geologic units are the Goya formation that marks the basis of the Tolstojan system and which hosts deposits of the Tolstoj basin as well as materials of small impact basins and

craters. Its base is estimated to be approximately 3.9–4.0 Ga (Spudis and Guest 1988) up to 4.06 Ga (Strom and Neukum 1988) old. Recent age estimates based on new chronology models put the Tolstojan basis at 3.97 Ga ago (Neukum et al. 2001b).

- The Calorian period compares to the lunar Imbrian period and is mainly characterized by Caloris-group units, i.e., mountain material, intermontane plains, hummocky plain, the Calorian plains, as well as impact crater materials and materials of small impact basins. Its time-stratigraphic base is estimated to be in the range of 3.77 Ga (Neukum et al. 2001a), 3.85 Ga (Strom and Neukum 1988) to 3.9 Ga (Spudis and Guest 1988) and is defined by the Caloris impact event that is considered to be the youngest impact basin on Mercury (McCauley et al. 1981).
- The Mansurian period is equivalent to the lunar Eratosthenian period, and its chronostratigraphic base is defined by the impact event of Mansur. With some uncertainties, its crater model age is estimated at 3–3.5 Ga (Spudis and Guest 1988; Strom and Neukum 1988; Neukum et al. 2001a). As for the Kuiperian system, major units are of impact crater origin mainly.
- The Kuiperian period represents the youngest period in Mercury's history, and its base is defined by the age of impact crater Kuiper which occurred ~ 1 Ga ago, equivalent to the lunar Copernican system (Wilhelms 1987; Spudis and Guest 1988; Strom and Neukum 1988; Neukum et al. 2001a). As for the Moon, the period is predominantly characterized by young impact crater materials.

Venus

Radar mapping investigations of Venus' surface in the context of the 1990s Magellan mission have shown that the impact crater frequency on Venus is extremely low. This indicates that the surface as it is observed today has an age of few 100 Ma only (Basilevsky and Head 1998). Widespread volcanism and intensive tectonic disruptions have shaped the surface and deleted most of the older geologic units and the planet's impact crater

record. Consequently, the stratigraphic system is not constrained throughout all of Venus' history and could not be established until the late 1990s, on the basis of photogeologic interpretation of a few selected regions that proved to be statistically significant for establishing a global stratigraphic system (Basilevsky and Head 1998).

The current stratigraphic record represents only 10–20% of Venus' history and covers only 30% of Venus' surface as mapped at scales of 1:3–1:10 M (Basilevsky and Head 1998). Specific geologic time units (periods) are defined mainly on the basis of large impact events and volcanic plain formation events, which helped to establish four major periods: the pre-Fortunian (oldest), Fortunian, Guineverian, and Aurelian (youngest unit). Due to the paucity of impact craters and statistically relevant average estimates of surface ages, absolute ages are usually provided as ratios with respect to the global impact crater frequency ($T = 1.98 \times 10^{-6}$ craters/km²) corresponding to an average surface age of 288 Ma (+311/–98 Ma) according to Strom et al. (1994), 400–800 Ma according to Phillips et al. (1992), or as high as 800 Ma (+800/–400) according to Zahnle and McKinnon (1996) as discussed in Basilevsky and Head (1998) in detail.

- The pre-Fortunian period is not constrained in terms of geologic surface units and spans the time before 1.47 T.
- The Fortunian period is characterized by intensive tectonic deformation with formation of the ancient ► *tessera* terrain that covers about 8% of Venus' surface. Tesserae formation occurred at 1.47 T (1.93–1.01 T in previous estimates) which is considered to form the time basis of the Fortunian period (Basilevsky and Head 1998).
- During the Guineverian period, extensive volcanic plains were formed with a peak at 1.1 T (Tanaka et al. 1997). The period has been proposed to be a supergroup consisting of four plain-forming subunits by Basilevsky and Head (1998). These groups (youngest to oldest unit) follow the proposal by Basilevsky and Head (1998): the Atla Group consisting of relatively undisturbed mafic lava, the Rusalka

- Group lava materials covering up to 75% of Venus' surface, the Lavinia Group characterized by ridged and fractured plains, and the Sigrun Group consisting of densely fractured plain material emplaced as mafic lavas. The Guineverian period covers most of Venus' known geologic record and terminates at around 0.1–0.2 T according to most recent estimates (Basilevsky and Head 1998). A period of younger volcanic activity peaking at 0.4–0.5 T ago with formation of Venus' coronae and rifts as well as formation of large volcanoes at 0.3 T was proposed as a fourth major unit in Tanaka et al. (1997).
- The Aurelian period is characterized by materials associated with the youngest impact craters; its basis is set to 0.1 T containing approximately 10% of Venus' visible cratering record (Tanaka et al. 1997 and references therein) and translating to an age of ~50 Ma using a conservative estimate of the mean surface age.

Mars

On Mars, impact cratering and plain volcanism played a dominant role in shaping the planet's surface throughout history. Additionally, a rich variety of processes related to fluvial, glacial, and eolian resurfacing have significantly contributed to the morphologies that are observed nowadays. Mars' global topography is divided into the densely cratered and old highland terrain in the south and the smooth, less-densely cratered younger northern plains. The subdivision of the stratigraphic system of Mars is based on marker horizons that are formed by plain-forming volcanism (Scott and Carr 1978; Tanaka 1986; Tanaka et al. 1992). Martian geologic time periods are from oldest to youngest: the Noachian (with late, middle, and early epochs), the Hesperian (with a late and early epoch), and the Amazonian (with a late, middle, and early epoch) (Scott and Carr 1978; Tanaka 1986; Tanaka et al. 1992). For Mars, several chronology models were proposed and modified in the course of the availability of new higher-resolution data. Some of these efforts have been combined lately to form the recent chronology model by Hartmann and Neukum (2001). Stratigraphic

boundaries (boundaries of time periods) are slightly different, which has led to a Hartmann model (HM) and a Neukum model (NM).

- A pre-Noachian period is informally established although the Noachian basis is not exposed; however, radiometrically derived ages for the Martian meteorite ALH84001 with a crystallization age of 4.5 Gyr fit into this period (Mittlefehldt 1994).
 - The Noachian system is characterized by the oldest, densely cratered units in the highlands covering a time range of older than 3.97–3.74 Ga for the Noachian system (Tanaka et al. 1992; Hartmann and Neukum 2001). Its basis is defined by highland material of the Noachis Terra located between the Argyre and Hellas Planitia impact basins (Tanaka et al. 1992). The system is generally characterized by Heavy Bombardment impacts, large-scale volcanism peaking in the Tharsis region and the highland volcanic provinces, global tectonism and extensive valley network formation indicating fluvial processes, and a much denser atmosphere and warmer climate.
- The Late Noachian period spans 3.86–3.74 Ga (Hartmann and Neukum 2001) and is characterized by cratered plateau material mainly. During that period, the crustal dichotomy has been morphologically shaped. The Middle Noachian epoch which covers the time span between 3.97 and 3.86 Ga (Hartmann and Neukum 2001) is characterized by cratered highland terrain shaped by impact cratering and the Argyre Planitia impact-basin event. During the late Early Noachian (>3.97 Ga), the Hellas and Isidis impact basins formed, and global volcanism shaped the Tharsis region with the formation of Paterae and Tholi and the circum-Hellas Planitia Highland volcanoes (Tanaka et al. 1992). Recently, the Noachian period was characterized in terms of geochemical alteration by Bibring et al. (2006), suggesting that formation of clay minerals, i.e., phyllosilicates, peaked during the Early and Middle Noachian epochs.
- The Hesperian period is subdivided into the Early and Late Hesperian epochs spanning

3.74–2.9 Ga and is characterized by the Hesperia Planum ridged plain material northeast of the Hellas Planitia impact basin. Impact-cratering rates were significantly lower when compared to the Noachian period, marking the end of the Heavy Bombardment period. Vanishing fluvial activity was replaced by large-scale volcanism in the lowland units (Tanaka et al. 1992 and ref's therein). The disappearance of surface water has led to the assumption that most of the water is stored as permafrost under the surface. Catastrophic release of water led to formation of outflow channels on Mars in the circum-Chryse and eastern Hellas Planitia regions along with formation of the Martian chaotic terrain and the Valles Marineris system (Tanaka et al. 1992). The Hesperian is also characterized by extensive sulfate deposits (Bibring et al. 2006) primarily in the Valles Marineris region. The Early Hesperian period covers the age range of 3.74–3.65 Ga (Hartmann and Neukum 2001) and is defined through the Hesperia Planum ridged plain units. Geologic materials of the Late Hesperian, covering the period between 3.65 and 2.9 Ga (Hartmann and Neukum 2001), are defined through the plain material of the northern plain Vastitas Borealis unit.

- The Amazonian period spans much of Martian history and starts 2.9 Ga ago according to the Hartmann model (HM) and up to 3.31 Ga ago according to the Neukum chronology model (NM). The period is generally defined through processes related to the northern lowland units and plain materials and is characterized by extensive resurfacing processes. Late-stage volcanism and eolian resurfacing shaped large areas of Mars and obliterated older units (Tanaka et al. 1992). The Amazonian also shows late-stage outflow activity in the circum-Chryse Planitia area and an abundance of ice-related surface processes predominantly near the global dichotomy escarpment and circum-Tharsis volcanoes as well as the circum-Hellas/Argyre Planitia regions. Surface alteration by formation of anhydrous ferric oxides led to the planet's characteristic red surface color (Bibring et al. 2006).

The basis of the Upper Amazonian series (Late Amazonian epoch) is defined by flood plain material of the southern Elysium Planitia area and starts 0.3 Ga (HM) to 0.6 Ga (NM) ago (Tanaka 1986; Hartmann and Neukum 2001). Characteristic materials of the Upper Amazonian are predominantly found near the seasonally changing polar caps of Mars and in the young deposits and flow fields delineating the northern hemispheric volcanoes. The Middle Amazonian is defined by the age of Amazonis Planitia lava flow materials (Tanaka 1986; Hartmann and Neukum 2001) and covers the time range between 2.1 and 0.6 Ga (NM) or 1.4–0.3 Ga (HM). The basis for the Early Amazonian epoch is set to 3.3 Ga (NM) to 2.9 Ga (HM) ago and is defined by the smooth plain materials of Acidalia Planitia (Tanaka 1986; Hartmann and Neukum 2001).

Outer Solar System Objects

In contrast to the currently accepted chronology models proposed for the inner planets which are based upon the lunar chronology model with impactors from the asteroid belt, planetary objects in the Outer Solar System are treated in a different way. While one group favors the lunar-like distribution and chronology model for all objects in the Solar System, i.e., lunar-like time dependence of the cratering rate, the second group favors nearly constant cratering rates by cometary impactors. A number of researchers developed lunar-like chronology models for the Jovian and Saturnian system (Shoemaker and Wolfe 1982; Boyce and Plescia 1985; Neukum 1985, 1997). Based on present-day estimates of sizes and dynamics, a constant cratering rate chronology for the icy satellites was put forward with impactors originating in the Kuiper Belt (Zahnle et al. 1998).

The two competing cratering chronology models agree well for old, densely cratered surfaces on the icy satellites, but they are different by more than an order of magnitude for younger, resurfaced units. These issues are discussed in detail in, e.g., Neukum (1997, 1998) and Zahnle et al. (1998).

Imaging data of the Voyager and Galileo missions to the Outer Solar System provided the basis

for impact crater size-frequency statistics and estimates of surface ages of the Galilean satellites. The surface of Europa is considered to be relatively young under assumption of primarily cometary impacts with average ages in the range of 30–70 Ma, as suggested by the less-densely cratered surface of Europa when compared to Callisto or Ganymede (Lucchitta and Soderblom 1982; Zahnle 2003). Employing a lunar-like chronology model with the asteroid belt as main impactor source, surface ages of Europa are in the range of 0.5–1.5 Ga. However, individual units can be as young as approximately 200 Ma or less (Neukum et al. 1998).

The heavily cratered dark plains on Callisto and Ganymede are on the order of 4 Ga and older in both asteroidal and cometary-source chronology models (Neukum et al. 1998; Zahnle et al. 1998, Zahnle 2003). For the younger resurfaced, tectonically disrupted terrain on Ganymede, the lunar-like chronology model gives ages in the range of 3.6–3.9 Ga (Neukum 1997, 1998), while the cometary chronology model gives an age of about 2 Ga (Zahnle 2003) up to few hundred million years (Zahnle et al. 1998).

The densely cratered surfaces of Saturn's icy satellites are estimated to be in the range 3.8–4 Ga old by applying the lunar-like impact chronology model. However, resurfaced units, in particular on Enceladus and Dione, show lower ages at approximately 1.5 Ga (Boyce and Plescia 1985; Neukum 1985).

Current efforts focus on updating existing chronology models with the help of new spacecraft data (e.g., Zahnle 2003) and imply ages far below 1 Ga for the resurfaced terrain on Enceladus and ages as old as 4 Ga for the older terrain, using a constant-rate chronology model with mainly cometary contribution of impactors. Mimas' surface crater impact density is close to saturation, suggestive of an old age, but it lacks larger impact craters beyond 30 km implying a much younger surface age. For Saturn's moon Titan, the small number of observed impact craters suggests very young surface ages. A closer look at the data and impact conditions, however, shows that much of Titan's surface is probably as old as 2 Ga (Jaumann and Neukum 2009).

Cross-References

- [Crater, Impact](#)
- [Mare, Maria](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Terrestrial Planet](#)
- [Tessera, Tesseræ](#)
- [Venus](#)

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67P/Churyumov–Gerasimenko

Hervé Cottin
Univ Paris Est Creteil and Université de Paris,
CNRS, LISA, Créteil, France

Keywords

Comet · ROSETTA

Synonyms

67P

Definition

Comet 67P/Churyumov–Gerasimenko was the target of the ESA Rosetta mission. This comet was selected because its orbit allowed its exploration by the European spacecraft for a launch scheduled in 2004 and an encounter in 2014. It was also of particular interest since it is thought that the comet had not a long history in the inner Solar System and therefore could contain primitive material kept at low temperature and far from the Sun since the formation of the Solar System.

Overview

Comet 67P/Churyumov–Gerasimenko was the target of the ESA Rosetta mission. →Rosetta Spacecraft reached the comet in August 2014 and delivered on the nucleus a lander called →Philae on November 12, 2014, after a global mapping of the surface in order to choose the best landing site. The comet was discovered by Klim Ivanovich Churyumov and Svetlana Ivanovna Gerasimenko in September 1969. Its current orbital period is 6.44 years, with an aphelion at 5.68 AU and a perihelion at 1.24 AU. Observations of the nucleus with ROSETTA have revealed a stunning unexpected irregular shape with two lobes, displaying different physical, mechanical, and layering properties, signing that the comet is made of two distinct objects that came into contact. The surface of the nucleus is a heterogeneous succession of terrains with pits, depressions, boulders, or rather smooth areas. Comet 67P nucleus (Fig. 1) is about $4.1 \times 3.3 \times 1.8$ km in size for the larger lobe and $2.6 \times 2.3 \times 1.8$ km for the smaller one. Its mass is 1.0×10^{13} kg and density about 0.5 g cm^3 . It rotates in about 12.4 h. It has been inferred from the various instruments of Rosetta that the nucleus



67P/Churyumov–Gerasimenko, Fig. 1 Picture of the nucleus of comet 67P/Churyumov–Gerasimenko seen from the ROSETTA spacecraft on September 19, 2014, from a distance of about 30 km. The two lobes can be seen as well as the irregular terrains made of pits, cliffs, boulders, and rather smooth areas (Credit: ESA/Rosetta/NAVCAM)

refractory to ice ratio bulk composition could range from 3 to 6, with higher values being possible. A high uncertainty remains attached to this value. Regarding the refractory component of the nucleus, it is a mixture (roughly 50/50 in mass) of a mineral component with a high molecular weight organic material, bearing similarities with →Insoluble Organic Matter extracted from →chondritic meteorites. Dominated by water, the volatile fraction of the nucleus contains a large diversity of molecules such as CO_2 , CO , CH_3OH , and other small organic compounds among which →glycine was detected. N_2 , O_2 , as well as noble gases argon, krypton, and xenon including their major isotopes were also detected in the gaseous phase, showing they were trapped in the water ice within the nucleus and that the ice was formed and kept at a low temperature.

It has been calculated that before 1840, the comet perihelion was about 4 AU and that successive dynamical interactions with Jupiter progressively shifted it to its current position. After Rosetta mission, comet 67P reached another perihelion on November 2, 2021.

Comet 67P/Churyumov–Gerasimenko is the first cometary nucleus so closely scrutinized by a spacecraft, for such a long period of time (about 2 years), and on which an automated module has landed.

Cross-References

- ▶ [Carbonaceous Chondrite](#)
- ▶ [Comet \(Nucleus\)](#)
- ▶ [Glycine](#)
- ▶ [Insoluble Organic Matter](#)
- ▶ [Philae Lander](#)
- ▶ [Rosetta Spacecraft](#)

CIP Rules

- ▶ [Cahn Ingold Prelog Rules](#)

Circular Dichroism

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[CD](#)

Definition

In chemistry, circular dichroism (CD) refers to the differential absorption of left- and right-handed circularly polarized light by optically active chiral molecules. Electromagnetic radiation consists of electric and magnetic fields that oscillate

perpendicular to one another and to the direction of propagation. Linearly polarized light occurs when the electric field vector oscillates only in one plane and changes in magnitude, while circularly polarized light occurs when the electric field vector rotates about its propagation direction and retains constant magnitude. It thus forms a helix propagating in space.

When circularly polarized light passes through an optically active light-absorbing medium, the velocities of its right and left polarizations differ as does the extent to which they are absorbed. CD is a measure of the difference in the amount of absorption between the two. Since circularly polarized light is “chiral,” it interacts differently with the two enantiomers of chiral molecules. Depending on the wavelength employed, CD can be used to investigate the structures of proteins, nucleic acids, small organic molecules, and charge-transfer transitions.

Cross-References

- [Chirality](#)
- [Polarized Light and Homochirality](#)

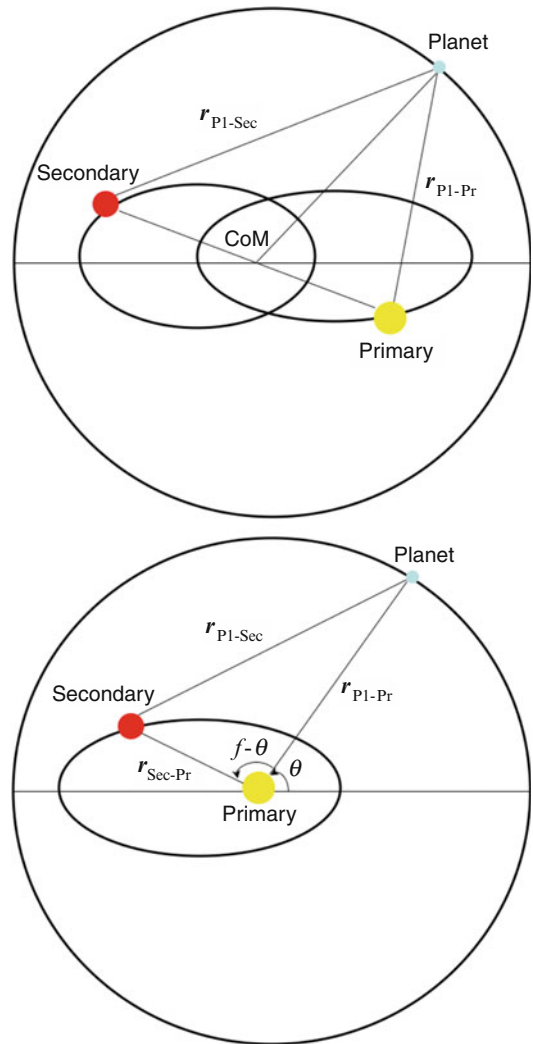
Circumbinary Planet

Nader Haghighipour
Institute for Astronomy, University of
Hawaii-Manoa, Honolulu, HI, USA

Definition

From dynamical point of view, three types of orbits are recognized for the motion of a planet in a binary star system. These orbits have been historically labeled as:

1. The S-type (or Satellite-type) orbit where the planet revolves around one of the stars of the binary (see ► [circumprimary planet](#))
2. The P-type (or Planetary-type) orbit where the planet revolves around the entire binary system (circumbinary orbit)



Circumbinary Planet, Fig. 1 General schematic presentation of a P-type system. The *top panel* shows the general orbital configuration of the planet and the binary stars. Both stars and the planet rotate around the center of mass of the binary (shown by CoM). However, it is customary to consider the primary star to be stationary and both the secondary and planet rotate around this star (*bottom panel*) (Figures from Haghighipour and Kaltenegger (2013))

3. The L-type (or Libration-type) where the planet moves in the same orbit as the secondary star, but 60° ahead or behind it

Figure 1 shows a circumbinary (P-type) orbit. In general, the planet and the binary revolve around their common center of mass. However, it is customary to consider the primary star to be stationary and both, the secondary and planet rotate around it.

Although observations of disks in circumbinary orbits had indicated that planets must exist in these orbital configurations, it was not until 2011 that using the data from the *Kepler* Space Telescope, a team of scientists lead by Laurant Doyle discovered the first circumbinary planet (Kepler 16b). During the following years, scientists discovered many more circumbinary planets using the *Kepler* telescope (see references below).

Cross-Reference

► Circumprimary Planet

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Circumprimary Planet

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Definition

From a dynamical point of view, three types of orbits are recognized for the motion of a planet in a binary star system. These orbits have been historically labeled as:

1.

The S-type (or satellite-type) orbit where the planet revolves around one of the stars of the binary (see circumprimary planet)

2.

The P-type (or planetary-type) orbit where the planet revolves around the entire binary system (circumbinary orbit)

3.

The L-type (or libration-type) where the planet moves in the same orbit as the secondary star, but 60° ahead or behind it

Figure 1 shows a circumprimary (S-type) orbit. In general, the planet and the binary revolve around their common center of mass. However, it is customary to consider the primary star to be stationary, and both the secondary and planet rotate around it.

Many circumprimary planets have been discovered during the past 20 years. A complete and up-to-date list of these planets can be found at <http://www.univie.ac.at/adg/schwarz/multiple.html>.

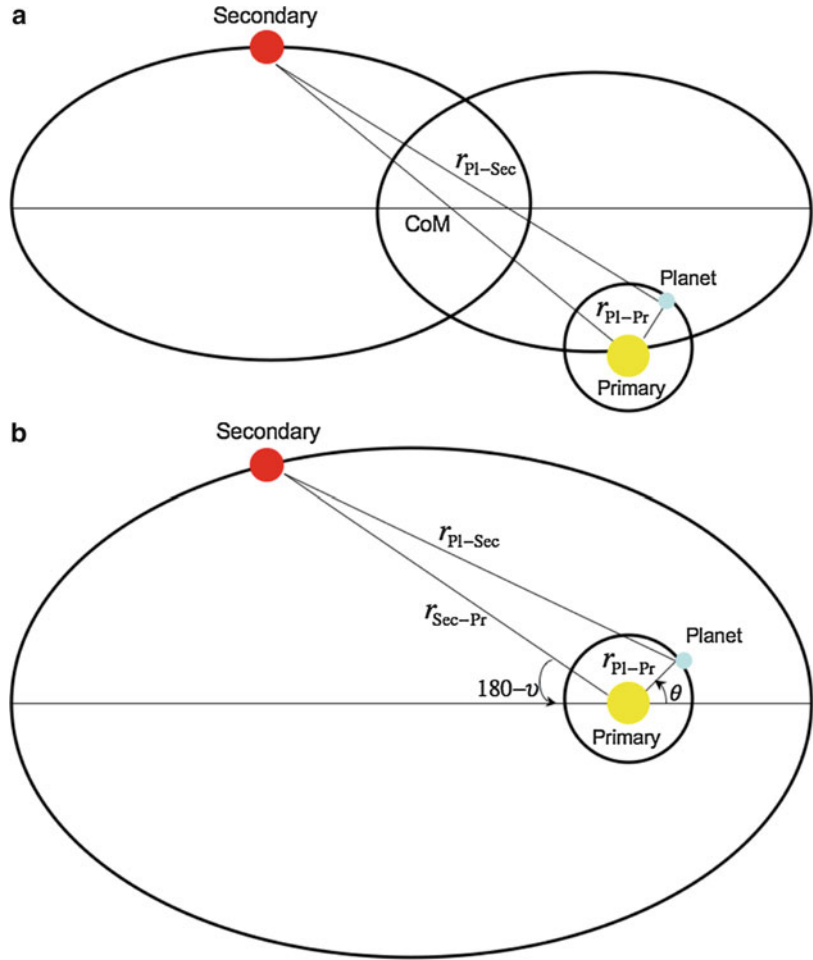
Almost all these binary systems are wide with separations between 250 and 6000 AU. There are, however, six circumprimary systems in which the binary stars have small separations (20 AU): GL 86, γ Cephei, HD 41004, HD 196885, HD 176051, and α Centauri (note that the existence of the planet around the secondary star of this system has been challenged; see Alpha Centauri Bb). The formation of these planets in such tight binaries is one of the most outstanding questions in theoretical exoplanetary science. See the book *Planets in Binary*

Circumplanetary Disk

► Planetary Rings

Circumprimary Planet,

Fig. 1 Schematic presentation of an S-type system. The two stars of the binary (primary and secondary) revolve around their center of mass (CoM), while the planet orbits only one of the stars (*top panel*). It is, however, customary to neglect the motion of the binary around its CoM and consider the motion of the secondary around a stationary primary (*bottom panel*). (Figure from Kaltenegger and Haghighipour (2013))



Star Systems by Haghighipour (2010, Springer) for a comprehensive and detailed review.

Cross-References

► [Circumbinary Planet](#)

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Circumstellar Chemistry

Marcelino Agúndez

Instituto de Física Fundamental, CSIC, Madrid,
Spain

Keywords

Circumstellar envelopes · Evolved stars ·
Chemical reactions · Dust · Mass loss ·
Molecular lines · Molecules · (Sub-)millimeter
observations · Thermochemical equilibrium

Definition

Circumstellar chemistry is the group of processes able to transform the chemical nature of a cloud of gas and dust surrounding a star. This general definition encompasses both young and evolved stars out of the main sequence, the ones which may host an envelope with a non-negligible mass. Most authors, however, use the term “circumstellar chemistry” to refer to the chemical processes occurring in the ejecta of an evolved star, rather than in a cloud feeding the formation of a star or a planetary system. This entry focuses on this second more restricted definition. For a description of the chemistry in clouds around protostars and young stars see ► [hot cores](#), ► [hot corinos](#), and ► [protoplanetary disk, chemistry](#).

Overview

During their last stages, stars experience important mass loss processes, which serve to recycle the stellar material back to the interstellar medium. Massive stars ($8 M_{\odot}$) end up with a sudden and violent explosion in the form of ► [supernova](#), while low- and intermediate-mass stars ($8 M_{\odot}$) lose their mass through more gentle stellar winds, which are particularly intense during the ► [asymptotic giant branch](#) (AGB) phase. These stellar ejecta might be contaminated to a large extent by material processed through ► [stellar nucleosynthesis](#) in the interior of the star, and thus the elemental composition may be quite

different from that of the primordial cloud from which the star formed, with abundance enhancements of some elements heavier than helium, such as nitrogen and carbon (Iben and Renzini 1983; Woosley and Weaver 1986). Stellar mass loss processes give rise to circumstellar envelopes, which are sites of an extraordinary interest from a chemical point of view as they act as factories of a population of tiny dust grains and a rich variety of molecules. In fact, most circumstellar envelopes are made up of molecular gas and dust.

Stellar ejecta provide the environment where dust grains are synthesized by condensation of refractory elements and the mechanism to inject them into the interstellar medium. It is well-known that dust is a minor (about 1 % in mass) but ubiquitous component of interstellar clouds and that it is to a large extent responsible of their physical and chemical state. Dust grains, for example, provide an efficient protection against external ultraviolet radiation, and their solid surfaces can act as catalysts in the formation of molecules as important as H_2 . It is currently thought that most of the interstellar dust is in fact synthesized and supplied by the ejecta of dying stars (Gehrz 1989).

Stellar ejecta do also provide a suitable environment to synthesize and host a rich variety of molecules, some of them quite exotic by terrestrial standards. Only in IRC +10216, a prototypical circumstellar envelope around an AGB star, the molecular inventory accounts for about half of all the molecules ever discovered in space (► [molecules in space](#)). In fact, molecules make up most of the mass of envelopes around low- and intermediate-mass evolved stars and are a very important constituent of envelopes around massive evolved stars such as the red supergiant VY Canis Majoris (Ziurys et al. 2007) and yellow hypergiants (Quintana-Lacaci et al. 2007). In the case of supernova ejecta, molecules such as CO and SiO might still be present at non-negligible levels, as in the case of SN 1987A (Petuchowski et al. 1989; Liu and Dalgarno 1994), but in general the formation and survival of molecules is severely hampered by the harsh irradiation conditions to which these ejecta are subjected. Molecules in circumstellar envelopes around evolved

stars are relatively short-lived in astronomical terms (usually less than a few 10^4 years), since in their way from the star to the interstellar medium, they become completely exposed to the ultraviolet interstellar radiation field at the outer edge of the envelope, where they are ultimately photodissociated. Therefore, unlike in the case of dust, molecules are destroyed before incorporating into the interstellar medium.

Mass loss processes in evolved stars enrich the interstellar medium with metals (which in astronomical terms refer to any element heavier than helium) and dust grains and provide the main mechanism by means of which the interstellar medium is recycled with fresh material.

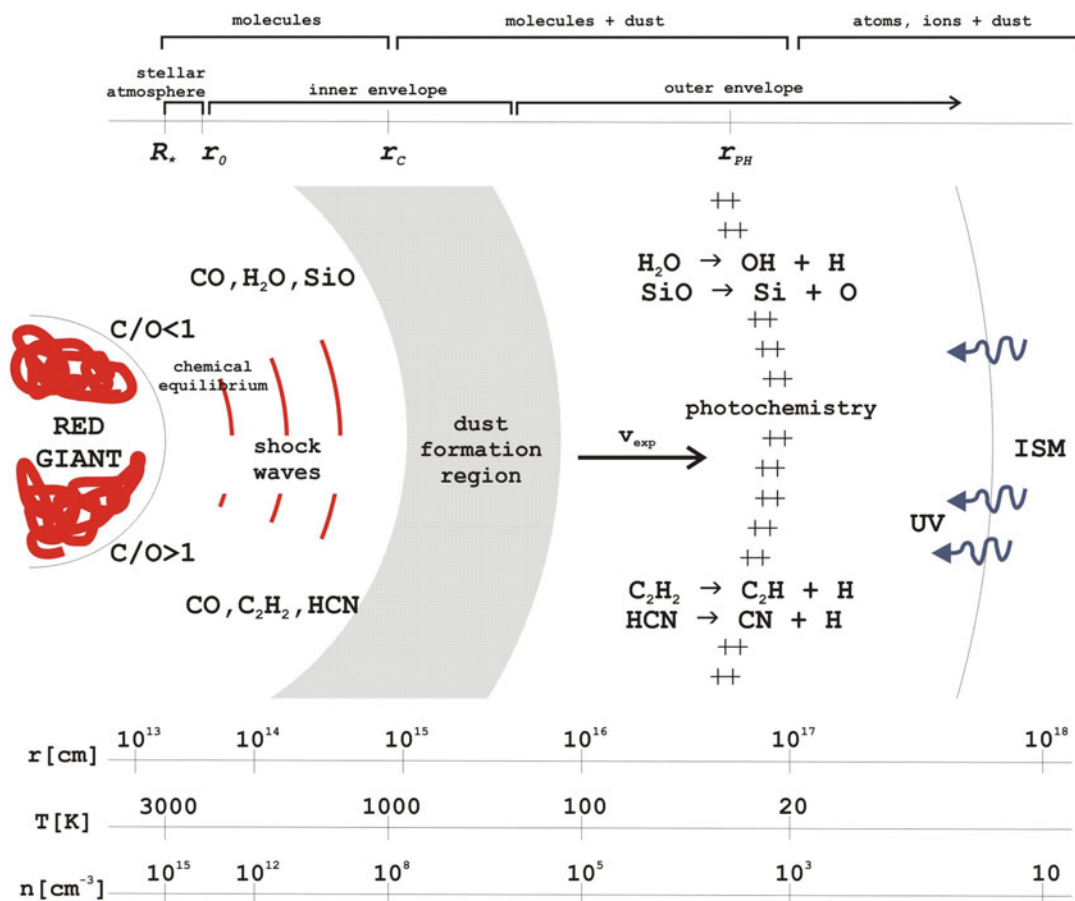
While matter is expelled from the stellar atmosphere and expands into outer space, it assumes a wide range of physical conditions. The number density of particles decreases by several orders of magnitude and the temperature drops from thousands of K to just 10–20 K. Along the outflow, matter is chemically processed by a wide variety of processes, such as three-body and endothermic chemical reactions in the hot surroundings of the atmosphere, condensation of dust grains a few stellar radii away from the star, and photodissociation and photoionization in the outer layers, whose resulting radicals and ions take part in exothermic and rapid neutral-neutral and ion-neutral chemical reactions. Hereafter, an overview is given on the chemical state and chemical processes at work along the various regions travelled by matter in its journey from the star to the interstellar medium (see Fig. 1).

Stellar Atmosphere and Inner Envelope

One of the most important parameters that define the chemistry of a circumstellar envelope is the elemental C/O abundance ratio at the photosphere of the central star. During the AGB phase, convective (dredge up) processes inside the star may bring out to the stellar surface an amount of carbon high enough to exceed that of oxygen (Iben and Renzini 1983). Therefore, depending on whether the elemental C/O abundance ratio at the stellar surface is lower or higher than 1, AGB stars may be either oxygen- or carbon-rich, respectively. At the temperatures and pressures of

the atmospheres of AGB stars, ► [thermochemical equilibrium](#) governs the chemical composition, which is essentially molecular but quite different depending on the elemental C/O abundance ratio. The high stability of CO makes this molecule to reach very high abundances, locking most of the limiting element and allowing for the element in excess to form, either oxygen-bearing molecules such as H_2O and SiO if $\text{C/O} < 1$, and the opposite, i.e., carbon-bearing-molecules such as C_2H_2 and HCN , if $\text{C/O} > 1$. This fact is firmly established by theoretical calculations (Tsuji 1973) and has been also extensively confirmed by observations. AGB stars have a spectral type M (effective temperature between 2000 and 3700 K), but it is interesting to note that distinct spectral signatures allow to classify them according to their elemental C/O abundance ratio into M stars (reserved for stars with $\text{C/O} < 1$), C stars (with $\text{C/O} > 1$), and S stars (with $\text{C/O} \sim 1$). The chemical composition at the stellar surface propagates to the base of the envelope and, to a large extent, to the outer layers, and it is thus of great importance for the overall chemical composition of the circumstellar envelope. In fact, observations of molecular lines arising from outer circumstellar layers (e.g., Bujarrabal et al. 1994) have confirmed the existence of circumstellar envelopes with two different types of chemical composition, which correspond to the oxygen- or carbon-rich character of the star.

The ultimate mechanism leading to the ejection of matter from a red giant star, and thus to an effective mass loss, is not completely understood, although it is very likely related to both waves induced by the pulsation of the star and radiation pressure on dust grains (Gilman 1972; Kwok 1975; Bowen 1988). This scenario, called Pulsation-Enhanced Dust-Driven Outflow (PEDDRO), is actually the most promising to explain mass loss from AGB stars (Höfner and Olofsson 2018). Mass loss processes during the AGB phase are particularly intense, with mass loss rates between 10^{-7} and $10^{-4} M_{\odot} \text{ yr}^{-1}$ and expansion velocities around $10\text{--}20 \text{ km s}^{-1}$ (Olofsson 2008). Whatever the exact mechanism of the mass loss, it occurs within a few stellar radii from the AGB star, a region which is probably the one hosting the most complex, and yet



Circumstellar Chemistry, Fig. 1 Circumstellar chemistry. Scheme of a circumstellar envelope around an AGB star. The envelope is divided into three regions: stellar atmosphere, inner envelope, and outer envelope. The top axis indicates various characteristic radii from the star: R_* is the stellar radius, r_0 indicates the end of the stellar

atmosphere, r_c is the radius of condensation of dust, and r_{PH} indicates the region where molecules start to be photo-dissociated by the ambient interstellar ultraviolet field. The bottom axes indicate the typical temperatures and number densities of particles at the various locations in the envelope

to be understood, physical and chemical processes that take place throughout the whole envelope. On the one side, the periodic pulsation of the star gives rise to shock waves which are formed between the gas infalling from the previous cycle and material pushed out by the emerging wave (Hinkle et al. 1982). On the other, a few stellar radii away from the AGB star, once the kinetic temperature has fallen below about 1000 K, those elements with a higher refractory character begin to condensate out of the gas phase in the form of tiny dust grains. The chemical composition, originally established by thermochemical equilibrium at the stellar photosphere and surroundings, is then modified a few

stellar radii away from the star due to the combined action of, at least, these two processes, i.e., shock waves and dust formation.

There are evidences of deviations from thermochemical equilibrium in the chemical composition of the inner regions of circumstellar envelopes, which come from the observation of anomalously high abundances of HCN in oxygen-rich objects (Duari and Hatchell 2000; Schöier et al. 2013), water vapor in carbon-rich envelopes (Decin et al. 2010; Neufeld et al. 2011), and ammonia (NH_3) in both oxygen- and carbon-rich envelopes (Keady and Ridgway 1993; Justannont et al. 2012). Results obtained with the Herschel

Space Observatory have widely contributed to highlight the departure from thermochemical equilibrium of inner layers of envelopes around evolved stars. Endothermic and three-body chemical reactions are effective at the high temperatures and densities of these inner layers and must play an important role in the departure from chemical equilibrium. However, the ultimate mechanism triggering this nonequilibrium is currently not well understood. Efforts have been made to model the impact of shock waves on the chemical composition of the inner envelope around an AGB star (Cherchneff 2006, 2012; Agúndez and Cernicharo 2006). It has been also suggested that the clumpy character of circumstellar envelopes may allow interstellar ultraviolet photons to penetrate into the inner regions and to induce a warm photochemistry (Decin et al. 2010; Millar 2020). Dust formation is also likely to affect the abundances of gas phase molecules in these inner regions, on the one side, because the formation of dust must occur at the expense of the gaseous material, and thus some molecules must decrease their abundances, and on the other, because chemical reactions may occur on the surface of grains resulting in an important chemical processing of the gas. An adequate theoretical description of the formation of dust is hampered by the fact that it probably occurs out of chemical equilibrium (Gail and Sedlmayr 1988). Many uncertainties exist on the interplay between the various physical and chemical processes at work in the inner regions of envelopes around AGB. In fact, this is perhaps the area of circumstellar chemistry less well understood, so that it will certainly experience significant advances in the future, in part thanks to the possibility of observing high excitation molecular lines at mm- and submm wavelengths with the unprecedented angular resolution of ► ALMA. In particular, ALMA is starting to provide a, yet not clear, picture of the processes that take place in the innermost regions around AGB stars, where dust formation occurs (Kamiński et al. 2017; Decin et al. 2017).

A further interesting aspect of the chemistry of these inner parts of circumstellar envelopes is that, due to the warm temperatures, a wide variety of refractory elements may survive in the gas phase

and participate in the formation of some exotic molecules. This is not the case of interstellar clouds, where the cold temperatures make most refractory elements to readily condense out of the gas phase. Metals (in the chemical, not astronomical, sense) such as Na, K, Al, and Ti take part in the formation of molecules such as NaCl, AlCl, KCl, AlF, NaCN, AlO, AlOH, TiO, and TiO₂ (Cernicharo and Guélin 1987; Kamiński et al. 2013). The observed abundances of these molecules are generally in good agreement with the predictions of thermochemical equilibrium calculations (Agúndez et al. 2020).

Outer Circumstellar Layers

It is well established by interferometric maps of molecular line emission that molecules in circumstellar envelopes are either concentrated around the central star or distributed in a hollow shell located far from the star. In the case of IRC +10216, for example, molecules such as HCN, CS, and SiS fall in the former category, while others such as CN, HNC, HC₃N, C₂H, and C₄H belong to the latter group (Guélin et al. 1997). These two distributions are clearly denoting two different origins for each group of molecules. Those which are concentrated around the star are formed at chemical equilibrium in the stellar atmosphere or through any of the nonequilibrium processes at work in the warm inner layers. On the other hand, those molecules which appear at a certain radial distance from the star must be originated by some process, which seems to be triggered by the penetration of ultraviolet radiation from the ambient interstellar medium. Indeed, as matter expands from the star, it is geometrically diluted (the number density of particles falls with the square of the radial distance to the star for an isotropic expansion), and molecules and dust become increasingly exposed to the external ultraviolet field. It has been argued that the appearance of a good number of molecules at about the same radial distance from the star in IRC +10216 may be related to their photodesorption from dust grain surfaces, onto which they would have been formed or deposited in advance (Guélin et al. 1993).

The most widely accepted mechanism however, which is supported by quantitative modelling

calculations by different authors, proposes that molecules distributed in the cool outer layers are formed in situ by gas phase chemical reactions, which are ultimately driven by the photodissociation, and to a lower extent photoionization, of the parent molecules injected into the expanding envelope from the inner layers (Millar et al. 2000). A circumstellar envelope around an AGB star may be, in fact, viewed as a dynamically expanding ► **photon-dominated region** (PDR). As an example to illustrate how the chemical synthesis works in this scenario, we may focus on the case of carbon-rich envelopes, where the photodissociation of the parent molecules C_2H_2 and HCN produces the radicals C_2H and CN, respectively, which in turn participate in a chain of exothermic and fast neutral-neutral reactions leading to the growth of carbon chains, such as polyynes and cyanopolyynes (Agúndez et al. 2017). A wide variety of polyynes and cyanopolyynes, and their related radicals, has been observed in carbon-rich circumstellar envelopes, noticeably in IRC +10216, a source that concentrates much of the observational and theoretical research on circumstellar chemistry (Cernicharo et al. 2000). Ion-neutral chemical reactions occur also in the outer layers of IRC +10216, but their ability to take part in the synthesis of complex molecules is limited by the relatively low ionization fraction in these regions ($\sim 10^{-7}$).

Among the families of molecules observed in circumstellar envelopes, the last incorporation has been that of molecular anions. No negatively charged molecule was known in the interstellar or circumstellar medium prior to 2006. To date, up to six different molecular anions (C_4H^- , C_6H^- , C_8H^- , CN^- , C_3N^- , and C_5N^-) have been discovered in the expanding gas of IRC +10216 (see Agúndez et al. 2010 and references therein). The formation of these molecules benefits from the extremely large rate constants of radiative association between the neutral counterparts (usually a radical with a moderately large size and a high electron affinity) and an electron (Millar et al. 2017).

It is quite remarkable to note that metals survive to an important extent in the cool outer layers of circumstellar envelopes, in spite of their high

refractory character, which tends to bring them out of the gas phase as solid condensates. Neutral and ionized atoms of Na, K, Ca, Cr, and Fe have been observed in the outer layers of IRC +10216 (Mauron and Huggins 2010) with abundances that represent a few percent of the total abundance of the element. Also, metal-containing molecules of the family of the cyanides, such as $MgNC$, $MgCN$, $HMgNC$, $AlNC$, and $FeCN$, have been observed in the outer layers of some circumstellar envelopes (see, e.g., Guélin et al. 1993). Unlike the case of NaCl and the other molecules formed at chemical equilibrium in the surroundings of the star, these molecules seem to benefit from the survival of metal atoms in the gas phase and form in situ in the cool outer layers by non-equilibrium chemical processes (Petrie 1996).

The variety and complexity of the molecules observed in carbon-rich circumstellar envelopes outstand over that observed in oxygen-rich sources. This is not very surprising taking into account the larger availability of carbon, not locked up into CO, in carbon-rich sources and the extraordinary chemical properties of this element, which can easily form carbon skeletons giving rise to a wide variety of complex molecules. The large differences in terms of variety and complexity of molecules between oxygen- and carbon-rich envelopes may be to some extent an observational bias, consequence of the overwhelming attention paid by observers to carbon-rich sources, in particular to IRC +10216. Our view on the relatively poor molecular content of oxygen-rich sources might change to some extent in the near future, thanks to the great improvement of the capabilities of radio telescopes, with particular regard to their sensitivity and spectral coverage, which allows to carry out more sensitive molecular line surveys and may extend significantly the molecular inventory of oxygen-rich envelopes (see, e.g., Ziurys et al. 2007).

Beyond the AGB Phase

The evolution of a red giant star into a white dwarf brings drastic changes on the chemical composition of the surrounding nebula. The star shrinks enormously (the stellar radius decreases from a few astronomical units down to about the radius of the

Earth), but it becomes also much hotter (the effective temperature increases from 2000–3000 K up to 8000–40,000 K) injecting an intense ultraviolet radiation field in the surrounding medium. This energetic radiation photodissociates most circumstellar molecules and ionizes the resulting atoms, leading to the formation of a ► [planetary nebula](#) (PN). The transition from the AGB to the PN phase occurs rapidly (in about 10^3 years). It is however possible to identify some objects in this transition stage, which is known as ► [protoplanetary nebula](#). The characteristics of protoplanetary nebulae are in between those of the AGB and PN phases (Kwok 1993), i.e., they still host a circumstellar envelope of gas and dust with a high molecular content, although the effects of the ultraviolet radiation field which emanates from the central star begin to be visible. For example, there is an important amount of ionized gas, and the spectra shows a series of unidentified infrared bands, which are usually assigned to polycyclic aromatic hydrocarbons (PAHs). Another important distinctive sign of protoplanetary nebulae is the appearance of fast bipolar winds (with velocities of hundreds of km s^{-1}).

The chemical processing to which circumstellar envelopes are subjected during the evolution from the AGB to the PN phase can be appreciated by comparing the molecular inventory in various well-known carbon-rich objects in different evolutionary stages, such as IRC +10216 (still in the AGB phase), CRL 2688 (a young protoplanetary nebula), CRL 618 (a protoplanetary nebula in a later stage), and NGC 7027 (a planetary nebula). The protoplanetary nebula CRL 2688, although more evolved than IRC +10216, still shares many similarities with this latter object in its chemical composition, with high abundances of unsaturated carbon chains such as C_2H , C_4H , and HC_3N . The protoplanetary nebula CRL 618 is clearly in a more advanced stage than CRL 2688, so that some important chemical differences can be appreciated, such as the relatively high abundances of the ions HCO^+ and N_2H^+ , and oxygen-bearing molecules such as H_2CO and H_2O . It is also worth to note that some abundance ratios such as HNC/HCN and $\text{HC}_3\text{N}/\text{HCN}$ increase in CRL 618, and aromatic molecules such as benzene appear. Most of these

changes are thought to be the result of the strong chemical processing driven by the ultraviolet field of the star (Cernicharo 2004). Finally, the planetary nebula NGC 7027 shows some clear chemical differences with respect to their less evolved counterparts. The circumstellar gas contains new molecules such as the cations CO^+ , CH^+ , and HCS^+ , and in general the chemical complexity, in the sense of molecules with a high number of atoms, decreases noticeably.

One of the latest findings relative to the chemistry of post-AGB objects has been the discovery of the fullerenes C_{60} , C_{70} , and C_{60}^+ in some planetary nebulae (e.g., Cami et al. 2010). Indeed, it seems that there exists a clear difference between the chemistry of circumstellar envelopes around AGB stars and post-AGB objects, with regard to the appearance of some large ring and cluster carbon-based molecules, such as benzene, PAHs, and fullerenes, in late evolutionary stages. The formation of such molecular structures in these environments is yet to be understood.

Basic Methodology

The methodology employed to study circumstellar chemistry is highly multidisciplinary, as occurs in general in molecular astrophysics. It involves astronomical observations from radio to optical wavelengths, radiative transfer models, chemical models, and laboratory experiments.

Key Research Findings

There have been several key findings that have allowed to shape our understanding of circumstellar chemistry. The radioastronomical detection of numerous molecules, some of them exotic by terrestrial standards, in the circumstellar envelope around the carbon-rich AGB star IRC +10216 was clearly one of the first key findings. This allowed to draw a picture of the different processes at work in circumstellar envelopes, such as thermochemical equilibrium, grain processes, and photochemistry (see, e.g., Lafont et al. 1982). The construction of chemical models allowed to

provide more quantitative predictions on molecular abundances (Millar et al. 2000), including the presence of molecular anions, which was later on confirmed by observations (Millar et al. 2017). The discovery of benzene in the protoplanetary nebula CRL 618 (Cernicharo et al. 2001) was also a turning point that provided evidence that the synthesis of polycyclic aromatic hydrocarbons, which are widespread in the interstellar medium, probably occurs around evolved stars. In line with this, fullerenes were later on detected in planetary nebulae (Cami et al. 2010).

Applications

The study of circumstellar chemistry is an important scientific driver of advances in other areas. For example, the observation of unidentified features in astronomical spectra motivates spectroscopic studies of new molecules in the laboratory. Also, the goal of understanding how dust is formed around evolved stars and how molecules are processed in these environments drives technological advances (e.g., Martínez et al. 2020).

Future Directions

The future will be highly shaped by recent or incoming observatories such as ALMA and JWST. ALMA has the potential to unveil the building blocks of dust in the atmospheres of AGB stars (McCarthy et al. 2019). JWST is expected to provide a significant advance in our understanding of the origin of polycyclic aromatic hydrocarbons.

Cross-References

- Asymptotic Giant Branch Star
- Interstellar Chemical Processes
- Interstellar Chemistry
- Molecules in Space
- Photochemistry
- Photon Dominated Region
- Protoplanetary Disk, Chemistry
- Protoplanetary Nebula

- Red Giant
- Thermochemical Equilibrium

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Circumstellar Disk

- [Protoplanetary Disk](#)

Circumstellar Grains

- [Star Dust](#)

Cirrus Cloud

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

In astronomy, cirrus clouds are sources of infrared (IR) emission detected by the ► [InfraRed Astronomy Satellite \(IRAS\)](#), a joint project of the USA,

the UK, and the Netherlands which surveyed the sky at wavelengths of 12, 25, 60, and 100 μm . The spatial distribution of this IR emission is similar in appearance to terrestrial cirrus clouds, although the latter have nothing to do with the interstellar clouds. The astronomical emission arises from interstellar dust in our galaxy, particularly that associated with the diffuse portions of interstellar clouds.

Cross-References

- [Infrared Astronomical Satellite](#)
- [Interstellar Dust](#)

Cistron

- [Gene](#)

Citric Acid Cycle

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Keywords

Anaplerosis · Cataplerosis · Catalytic cycle ·
Oxidative metabolism

Synonyms

[Krebs cycle](#); [Tricarboxylic acid \(TCA\) cycle](#)

Definition

Citric acid cycle is a metabolic pathway often regarded as the final step for the complete oxidation of fuel molecules. Stoichiometrically, a 2-C molecule (acetyl CoA) condenses with a 4-C molecule (oxaloacetate) to yield citrate (Fig. 1a). Two consecutive oxidative decarboxylations transform

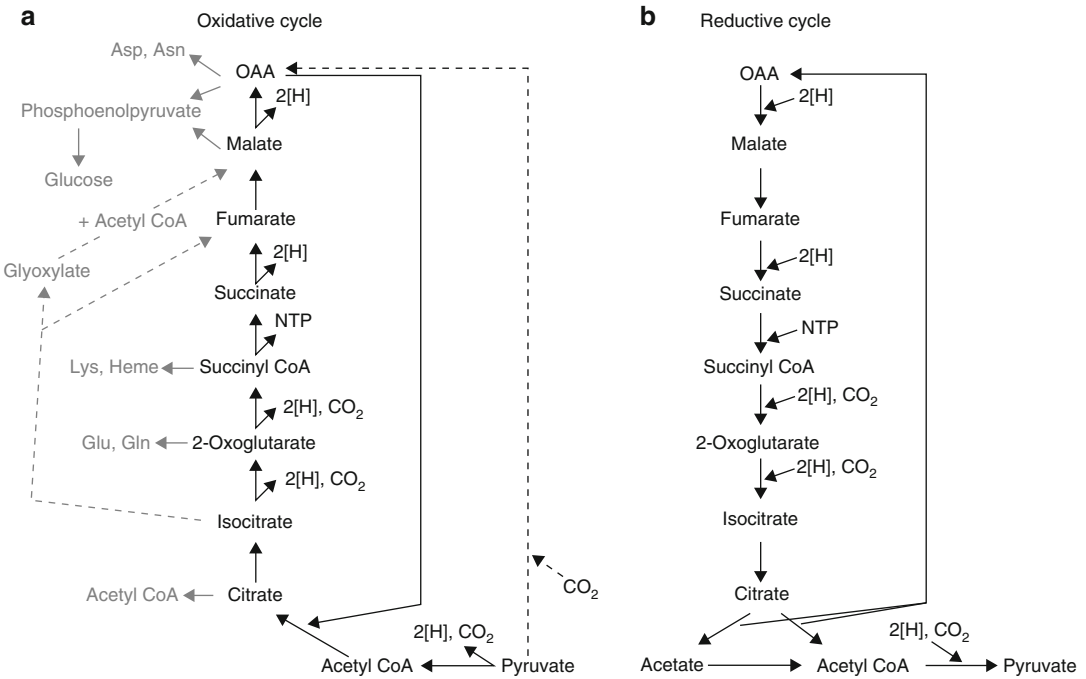
the initial 2-C unit into two CO_2 molecules. The regeneration of oxaloacetate closes the cycle through an oxidative process. In addition to the electrons taken up by redox coenzymes (NAD(P)^+ and FAD), a part of the energy is conserved in a substrate-level phosphorylation step yielding GTP. The citric acid cycle can also be regarded as a source of biosynthetic precursors. In some organisms, the cycle operates in reverse, reductively, thus functioning as an autotrophic pathway (Fig. 1b).

History

In an elegant series of experiments on substrate oxidation in respiratory animal tissues, performed among others by Albert Szent-Györgyi (1893–1986), Carl Martius (1906–1993), and Franz Knoop (1875–1946), fragments of a sequence of the metabolic transformations were established. Those observations were completed by Hans A. Krebs (1900–1981) who proposed, in a paper coauthored by William A. Johnson, the cyclic nature of the pathway in 1937 (Krebs and Johnson 1937).

Overview

The citric acid cycle occupies a central position in the metabolic network both as a catabolic, oxidative process and as a supplier of biosynthetic precursors. The cycle is more a roundabout (or traffic circle) than a carrousel: There is a permanent flux of metabolites in and out the cycle. Some metabolites are used for biosynthetic purposes (e.g., 2-oxoglutarate as glutamate precursor or succinyl CoA for the biosynthesis of heme group or lysine, see Fig. 1a). The catalytic nature of the citric acid cycle, as well as the consumption of intermediates as biosynthetic precursors, imposes the necessity of the net synthesis and replacement of those intermediates. This process is termed anaplerosis. Anaplerotic reactions include the synthesis of oxaloacetate by pyruvate carboxylation and the synthesis of oxaloacetate or 2-oxoglutarate from aspartate or glutamate, respectively, by



Citric Acid Cycle, Fig. 1 The citric acid cycle. **(a)** Oxidative cycle. An anaplerotic reaction is shown (broken black line), as well as some biosynthetic branches starting

from cycle intermediates (in gray). The glyoxylate shunt is also shown (broken gray line). **(b)** Reductive cycle

transamination. On the other hand, the 4-C and 5-C skeletons derived from amino acid catabolism must leave the cycle to be fully oxidized (this process has been called cataplerosis (Owen et al. 2002)).

In some autotrophic microorganisms, the citric acid cycle operates in a reverse, reductive way (Fig. 1b). This pathway (also known as the Arnon-Buchanan cycle) allows the net synthesis of Acetyl CoA from CO₂. Firstly described by Daniel I. Arnon and Robert B. Buchanan in 1966 as the autotrophic carbon fixation pathway in the green sulfur bacterium *Chlorobium limicola* (Evans et al. 1966), it is also present in some proteobacteria and some members of the domain Archaea (Berg et al. 2010).

- Glycolysis
- Metabolism

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Cross-References

- Anabolism
- Carbon Dioxide
- Catabolism

Classification

- Taxonomy

Clathrate

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, a clathrate is an inclusion complex, also known as a clathrate compound, cage, or a host-guest complex, in which a molecule, aggregate of molecules, or crystal lattice of molecules (the “host”) noncovalently traps or encloses another, usually small, gas molecule (the “guest”), rendering it incapable of escaping by diffusion. The word is derived from the Latin word *clatratus*, meaning “with bars” or “a lattice.”

Especially important naturally occurring types of clathrates are ► [clathrate hydrates](#), formed from water ice and various gases such as methane, ammonia, or CO₂, and zeolite minerals.

Cross-References

► [Clathrate Hydrate](#)

Clathrate Hydrate

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Clathrate hydrates are ice-like solids in which a “host” hydrogen-bonded H₂O lattice entraps a nonpolar “guest” gas molecule such as CH₄ or CO₂. It has been speculated that clathrate hydrates are important components of many outer solar system bodies including comets, the outer planets,

and their icy moons. Methane clathrate hydrates are also widely distributed in terrestrial seafloor sediments where the ambient temperature and pressure allows their existence. It is thought that their breakdown during periods of increasing temperature releases methane, a strong greenhouse gas, which may contribute significantly to global warming.

Cross-References

► [Clathrate](#)

Clay

Alicia Negrónk-Mendoza
Instituto de Ciencias Nucleares, Universidad
Nacional Autónoma de México, Circuito Exterior
s/n, Ciudad Universitaria, Coyoacán, Mexico

Keywords

Chemical evolution · Clay · Clay minerals ·
Montmorillonite · Phyllosilicates

Synonyms

[Argillaceous earth](#); [Clay minerals](#)

Definition

Clay is a generic term for a mineral group of complex hydrated aluminophyllosilicates that mainly form as a result of feldspar weathering and low-temperature hydrothermal alteration of many rocks.

Clays are natural, soft, earthy, fine-grained materials (less than 2 μm); they are plastic when mixed with an appropriate amount of water and hard when fired. Clays are fundamentally composed of a silicon tetrahedral layer and an aluminum octahedral layer with water trapped between the silicate sheets (Guggenheim and Martin 1995).

History

Clays and clay minerals have been mined since the Stone Age, when prehistoric man first discovered their useful properties. Clay tablets were used as the first writing medium, and clays sintered in fire were used to make the first ceramic objects. In many ancient religions and philosophies, mankind was originally created from clay; for example, in the Bible, the first man, Adam, whose name means “of the **▶ earth**,” was made from clay.

Overview

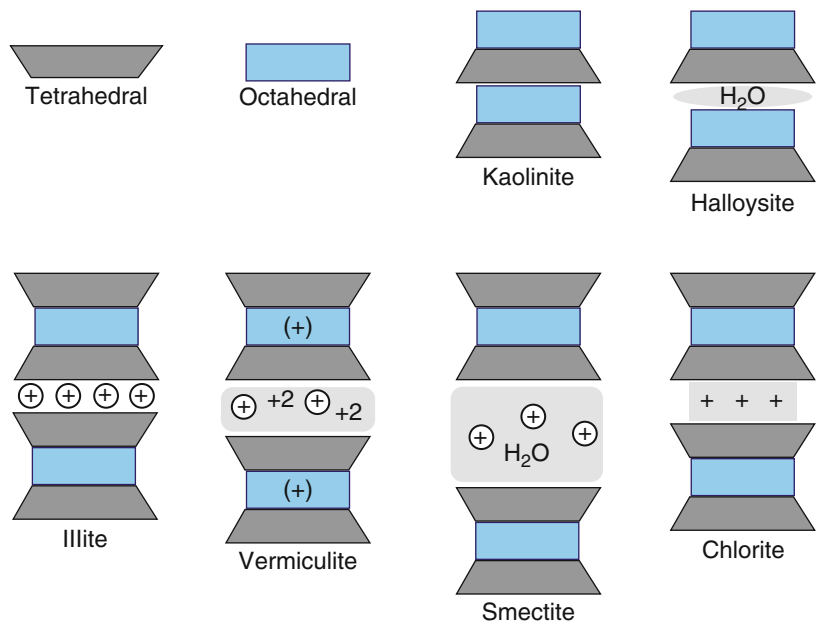
Structure

The simple crystal structure of clay consists of two basic components: a silicon tetrahedron-oxygen layer (the tetrahedral silicon can be partially replaced with Al^{3+} or Fe^{3+}) and an octahedron layer, in which an atom of aluminum, magnesium, and/or iron is surrounded by six anions (oxygen or hydroxyls). The individual units are stacked in parallel plates, one above the other, and depending upon the arrangement, different types of clay are produced. They are classified first into “layer types,” according to the

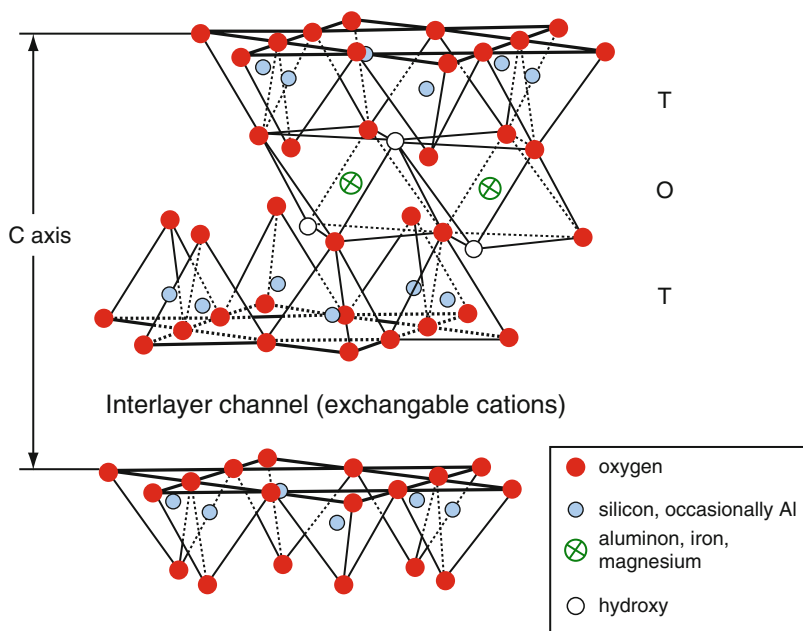
number of tetrahedral and octahedral sheets, and then into “groups,” which are differentiated by the type of isomorphic cation substitutions present. The layer types are illustrated in Fig. 1. The 1:1 (or TO) layer type consists of one tetrahedral sheet fused to an octahedral sheet and is represented by the **▶ kaolinite** group. Type 2:1 clay (or TOT) is made up of an octahedral sheet sandwiched between two tetrahedral sheets; examples include kaolinite, illite, and smectites, such as **▶ montmorillonite**. This composite unit is continuous in two directions of a plane in the c-direction (see Fig. 2) and forms packets of 2–15 elementary units (Meunier 2010). Figure 2 depicts a TOT layer-type crystal structure.

At **▶ pH** values above 2, clay particles carry a net negative charge in the space between the silica layers, referred to as the interlayer or interlamellar channel. The distance between these layers varies depending upon the layers of water or intercalated organics (Swartzen-Allen and Matijevic 1974). The negative charge can originate from several different factors, including lattice imperfections, isomorphic substitution, broken bonds, and exposed structural hydroxyl groups. The presence of a positive counterion, such as Na^+ , K^+ , or Ca^{2+} , compensates for the negative charge. The edges of

Clay, Fig. 1 Types of clays (see text)



Clay, Fig. 2 TOT layer-type crystal structure



the crystal are positively charged in at neutral and acidic pH (Swartzen-Allen and Matijevic 1974). These structural characteristics are responsible for the special properties of clays. For example, montmorillonite can take up various types of organic molecules. The molecule may be adsorbed on the clay lattice by cationic interchange, ion-dipole forces, ► [van der Waals forces](#), or hydrogen bonds.

Distribution

Clays are ubiquitous minerals on Earth; their presence can likely be traced to the early stages of the planet's formation. While various types of clays most likely formed on the continents of Earth in the Archean, the largest area of clay production would have been the ocean floor. The genesis of continental smectites can be traced back 3 or 4 billion years ago (Odin 1988).

The presence of clays in extraterrestrial environments, such as ► [meteorites](#), ► [Mars](#), and the ► [comet Tempel 1](#) (Lisse et al. 2006), helps us to understand the aqueous conditions that prevailed in the early stages of the history of the solar system, as the primary requirement for the formation of clay minerals is the presence of liquid water.

Importance

Clays are important minerals in nature and in industry. They play an integral part of terrestrial ► [biogeochemical cycles](#). These processes influence microbial ► [life](#) and the cycling of elements on planetary surfaces. Clay also plays a role in the buffering capacity of the oceans.

Clays are among the most important minerals used in the manufacturing and environmental industries; for example, the construction of ceramics, including tiles, bricks, and pottery. In addition to sand and silt, clay is one of the three principal types of sediment and primarily results from the weathering of rocks and soil on the surface of the Earth.

Importance in Chemical Evolution

Many authors have proposed that clays played a central role in ► [chemical evolution](#) and ► [origin of life](#) (Negrón-Mendoza et al. 2010; Hashizume 2012). This role is a result of the capacity of clay to adsorb organic molecules and catalyze reactions (Theng 1974; Laszlo 1987; Yariv and Cross 2002). Clay minerals are important for several purposes: (1) to concentrate the organic molecules present in a dilute ocean by adsorption on clay deposits, (2) to catalyze the polymerization of

adsorbed organic compounds, (3) to protect these organic molecules from destruction by ultraviolet light or other energy sources, and (4) as a probable mechanism to induce chirality in contemporary molecules. Investigations of the role of clays in prebiotic organic synthesis range from their capability to act as adsorbents and/or catalysts to the controversial claim that clays were the first functional templates (Cairns-Smith 1966; Cairns-Smith 1982; Cairns-Smith and Hartman 1988). Mud beds, shores, and hydrothermal vents at the bottom of the sea are all possible prebiotic scenarios in nature. In addition, these regions can be alternately wet and dry, as in tidal estuaries. These environments stress the significance of multiphase systems containing clay minerals in prebiotic processes.

An important step from chemical to biological evolution is the formation of cell membranes. Szostak and his group (2003) reported that montmorillonite accelerates the spontaneous conversion of fatty acid micelles into vesicles, which could serve as a pathway for the prebiotic encapsulation of catalytically active surfaces within membrane vesicles.

Cross-References

- Biogeochemical Cycles
- Buffer
- Chemical Evolution
- Comet Tempel 1
- Earth
- Earth, Formation, and Early Evolution
- Environment
- Hydrogen Bond
- Hydrothermal Reaction
- Kaolinite
- Life
- Mars
- Meteorites
- Mineral
- Montmorillonite
- Organic Molecule
- Origin of Life
- pH
- Silicate Minerals
- Van der Waals Forces

- Water
- Weathering

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Clay Minerals

- Clay
- Phyllosilicates, Extraterrestrial

Cleanliness

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

For ► [planetary protection](#), the cleanliness of an environment or spacecraft hardware element is the level of contamination by something undesirable for the achievement of a space exploration goal. The maximum amount of the unwanted material is generally specified, e.g., biological cleanliness can be quantified by the number of remaining microorganisms after a cleaning process. Depending on the exploration goal, quantitation of living microorganisms, dead microorganisms, or both could be of concern. Chemical cleanliness refers to maximal specified amounts of each chemical (or group of chemicals) per unit of surface area or volume.

Cross-References

- [Bioburden](#)
- [Planetary Protection](#)
- [Sterilization](#)

Cleanroom

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

A cleanroom is a working environment controlled to maintain the cleanliness of articles or processes taking place in that working environment. The principal control is filtration, to remove particles from the atmosphere of the cleanroom, both when air from an uncontrolled environment is flowed into the cleanroom, and when air in the cleanroom

is recycled. A continuous filtration is maintained, often with a positive pressure relative to the outside (uncontrolled) environment to maintain the particle levels at a low level. Often, other environmental parameters such as temperature and humidity will also be controlled to support particulate control.

A cleanroom standard (*ISO 14644-1*) for cleanrooms with different levels of cleanliness on a scale 1 through 8 is maintained by the International Organization for Standardization (ISO). Under previous standards (e.g., Fed209E), cleanrooms have been known by the number of particles with size under 0.5 μm /cubic foot of air (class 100,000, class 1000, class 100, etc.). Class 100,000 approximates to ISO 8, and class 1000 approximates to ISO 5, but in both standards the lower the number, the cleaner the cleanroom.

Additionally, controls are placed on personnel accessing the cleanroom and processes taking place in the cleanroom. The more stringent the cleanroom, the more controls are in place, for example: the protective garments that are worn by operators to prevent shedding of hair and skin flakes; the training needed to operate in the cleanroom; the number of operators permitted at any one time; and the types of hardware and operations that are allowed, all to limit the introduction and spread of dust and particles.

Cleanrooms are used in industry in the manufacture of articles sensitive to the presence of dust and other particulate contaminants, such as aerospace mechanisms, microelectronic devices, and precision optical devices. However, limiting the number of particles also controls the number of airborne ► [microorganisms](#) present in the cleanroom and subsequently the microbial bioburden of surfaces. For this reason, cleanrooms are also used in food manufacturing, production of sterile medical devices, and in particular the assembly of interplanetary spacecraft to support compliance with planetary protection policy.

These cleanroom standards can also be applied in smaller environments, such as cabinets, and in temporary structures, such as tents, to perform specific processes under controlled cleanliness conditions.

Cross-References

- [Bioburden](#)
- [ISO](#)
- [Microorganism](#)
- [Planetary Protection](#)

Cleverness

- [Intelligence](#)
- [Intelligence, Evolution of](#)

Climates, Diversity in the Solar System

Martin Turbet

Observatoire Astronomique de l'Université de Genève, Sauverny, Switzerland

Definition

The climate of a (solar system) planet describes the long-term average of its main meteorological components (atmospheric temperature, pressure, composition, winds, clouds, aerosols, precipitation). The climate of the terrestrial planets – with a well identified surface – is also defined by the surface meteorological components (surface temperature, precipitation, distribution of ices and liquids on the surface).

Solar system planets (and by extension, moons) have a wide diversity of climates.

Overview

The climates of the planets of the solar system can be arbitrarily separated into two distinct categories.

The first category corresponds to the telluric planets (and by extension, moons) which (1) have a clearly identified solid and/or liquid surface and (2) are endowed with a secondary atmosphere

with a high mean molecular weight. The diversity of climates of solar system terrestrial planets has been discussed in the chapter ► [“Climates, Terrestrial Planets.”](#)

The second category corresponds to the giant planets, which includes two gas giants (Jupiter and Saturn) and two ice giants (Uranus and Neptune). These four planets are characterized by a very deep (light mean molecular weight) primary atmosphere whose composition is dominated by hydrogen and helium. Giant planets do not have a clearly defined surface.

While most of the observations we have on the climates of giant planets concern the outermost layers (at pressures typically lower than 1 bar) of their atmosphere, mainly due to the presence of opaque clouds that prevent deep probing, a more complete picture can be drawn with the help of numerical atmospheric and interior models. Together observations and models taught us that the climates of solar system giant planets are characterized by (see Sánchez-Lavega et al. 2019, Fletcher et al. 2020 and references therein):

- (1) The presence of photochemical hazes, very high in the atmosphere, but much more importantly the presence of optically thick clouds, whose composition can vary between the four planets, depending on the insolation they receive (which controls atmospheric temperature) as well as their level of enrichment in heavy elements (oxygen, nitrogen, carbon, sulfur, etc.) – sometimes also known as metallicity. The clouds are made of layers of ammonia, ammonium hydrosulfide, and water on the two gas giants Jupiter and Saturn; they are mostly made of methane and hydrogen sulfide on the two ice giants Uranus and Neptune.
- (2) The existence of powerful, atmospheric jets, which move air parcels alternatively between westward (retrograde) and eastward (prograde) directions. This characteristic – common to the four solar system giant planets, and more generally to planets that have a large size and a short rotation period – produces banded appearance, with regions (or bands) of different temperatures,

composition, aerosol properties, and dynamics separated by strong meridional and vertical gradients in the zonal (east-west) winds, which can reach several hundred meters per second (Fletcher et al. 2020). The jets have been shown to reach a depth of several thousand km on Jupiter and Saturn (Kaspi et al. 2020).

- (3) The presence of (i) large scale low- and high-pressure weather systems (cyclonic and anti-cyclonic structures, respectively) and (ii) smaller scale convective storms. Many cyclonic structures and convective storms have been observed on Jupiter (e.g., the Great Red Spot, which is the largest anticyclone in the solar system; the large-scale polar cyclones seen by Juno), Saturn (e.g., the Great White Spots, which are transient convective storms), and the ice giants Neptune and Uranus (e.g., the Dark Spots seen by Voyager 2 and Hubble on Neptune). These regional transient weather phenomena are an integral part of the climate of giant planets because they can last for very long periods (e.g., the Great Red Spot of Jupiter has existed for at least several centuries) or form recurrently (e.g., the Great White Spots appear periodically each Saturnian year).

The various climatic characteristics (e.g., temperatures and winds) of giant planets can also vary with seasons, as it has now been well documented for Saturn. For instance, a seasonal change in color (from a blue to an ochre hue) of Saturn's North Pole observed by Cassini has been associated with increased photochemical haze production as the northern hemisphere summer solstice approaches.

The nature of a planet's climate is likely the most important ingredient for the habitability of a planetary surface and thus its astrobiological potential. Of the ten objects of the solar system that have an atmosphere, the Earth is the only one known to have liquid water on its surface today, an essential ingredient for life as we know it to emerge and develop. The other planets of the

solar system are, however, a great natural laboratory to better understand the functioning of the climate of the planets in the broad sense, and thus of the Earth and of the planets likely to shelter life as we know it.

Cross-References

- [Aerosols](#)
- [Atmospheric Circulation](#)
- [Cassini](#)
- [Climates, Terrestrial Planets](#)
- [Clouds](#)
- [Giant Planets](#)
- [Habitability, Role of the Atmosphere](#)
- [HST](#)
- [Juno](#)
- [Jupiter](#)
- [Metallicity](#)
- [Molecular Weight](#)
- [Neptune](#)
- [Photochemical Hazes](#)
- [Saturn](#)
- [Solar System](#)
- [Terrestrial Planet](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)
- [Water, Solvent of Life](#)

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Climates, Exoplanets

Martin Turbet

Observatoire Astronomique de l'Université de
Genève, Sauverny, Switzerland

Definition

The climate of an exoplanet describes the long-term average of the main meteorological components (temperature, pressure, atmospheric composition, winds, clouds, aerosols, precipitation) of the atmosphere (and possibly the surface, which in this case also includes the distribution of ices and liquids on the surface) of an exoplanet, i.e., a planet revolving around other stars than our Sun.

Overview

While the climates of solar system planets are now fairly well depicted, in particular thanks to many successful space exploration missions, our knowledge of the climates of exoplanets is still rather limited. In fact, we have only had astronomical observatories and instruments for about a decade now that allow us to probe the atmosphere and surface, and thus the climate of exoplanets.

Observations that have been made so far – by transit spectroscopy, secondary eclipse, phase curves, direct imaging or interferometry – have provided an increasing amount of information on atmospheric composition (Sing et al. 2016), thermal structure (Stevenson et al. 2014), winds (Snellen et al. 2010), clouds (Kreidberg et al. 2014), and even precipitation (Ehrenreich et al. 2020). Most of these observations are essentially restricted to large and hot exoplanets because these are the easiest exoplanets to observe and thus to study. However, the use of increasingly large telescopes and increasingly powerful instruments has made it possible in very recent years to gain information about the climates of relatively

small (Kreidberg et al. 2019) or cool (Tsiaras et al. 2019; Benneke et al. 2019) planets. Likewise, future observatories such as the James Webb Telescope or the European Extremely Large Telescope are expected to provide atmospheric and/or surface data for the first time on exoplanets that have similar characteristics (in size, mass, and insolation) to the Earth (Turbet et al. 2016; Lustig-Yaeger et al. 2019; Fauchez et al. 2019).

To fully reconstruct the climates of exoplanets for which little (for hot and large exoplanets) or no (for small and cold exoplanets) observations are available, numerical atmospheric models have proven to be very useful. These are mathematical models that equate the various physical and chemical processes in the atmosphere in order to simulate the climate of planets and exoplanets directly on a computer (Forget and Lebonnois 2013). These models are not only very useful for interpreting the available observations, but also for predicting climate components for which no observations are available. In fact, these models are the main source of information on the possible climates of exoplanets of similar size, mass, and insolation than Earth – these are also the planets with the highest astrobiological potential – for which no direct atmospheric or surface observation is available.

Observations of the atmosphere and surface of exoplanets, together with numerical atmospheric simulations, have taught us a lot about the climate(s) of exoplanets. The main lesson so far is that there is a very wide variety of possible climates on exoplanets (Forget and Leconte 2014), much greater even than in the solar system. This stems mostly from the fact that exoplanets span a much wider range of insolation, atmospheric composition, size, mass, etc., than solar system planets do.

More specifically, we have learned that the climate of the warmest, most massive planets we know of – the so-called hot Jupiters – is characterized by extreme temperatures, violent winds that can efficiently redistribute heat from the day-side to the nightside of the planet, and atmospheric composition impacted by both complex

chemistry and phase change thermodynamics (Kataria et al. 2016; Drummond et al. 2020).

We have also learned that a significant fraction of these planets (from hot Jupiters to mini-Neptunes) are covered with cloud layers that can reach very exotic compositions (Charnay et al. 2015; Parmentier et al. 2016; Sing et al. 2016) compared to what we know of planets in the solar system.

On a more speculative basis, we have begun to anticipate the possible climates of rocky and temperate planets, using atmospheric models, for various formation and evolutionary scenarios (Turbet et al. 2016, 2018; Komacek and Abbot 2019; Shields 2019). This is a major aspect of the study of the climates of exoplanets, as climate determines the ability of a planet to maintain liquid water on its surface, thus allowing life as we know it to emerge and develop.

Cross-References

- Aerosols
- Climates, Diversity in the Solar System
- Clouds
- Direct-Imaging, Planets
- Eclipse
- GCM
- Hot Jupiters
- Interferometry
- JWST
- Mini-Neptunes
- Water, Solvent of Life

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Climates, Terrestrial Planets

Martin Turbet

Observatoire Astronomique de l'Université de Genève, Sauverny, Switzerland

Definition

The climate of a (solar system) terrestrial planet describes the long-term average of the main meteorological components (atmospheric and surface temperature, pressure, composition, winds, clouds, aerosols, precipitation, distribution of ice and liquids on the surface) of the atmosphere and surface of terrestrial planets, which includes Venus, Earth, and Mars. Mercury is excluded from the list because it has no atmosphere. However, by extension, the climate of terrestrial planets also often refers to the climate of Titan, Pluto, and Triton because these objects share two main properties: they have a surface and an atmosphere with a high mean molecular weight.

Overview

Strictly speaking, the climate of terrestrial planets refers to the climate of Venus, Earth, and Mars. But in a broader sense, it also often refers to the climate of the icy moons Titan and Triton and the dwarf planet Pluto. The main specificity of these six terrestrial bodies is that (compared to gas giants) they all have a solid and/or liquid surface and an atmosphere with a high mean molecular weight (i.e., heavier than hydrogen and helium). Their atmospheres are mainly composed of H₂O, CO₂, CH₄, SO₂, O₂, N₂, etc., which can condense and/or be photochemically altered by the photons from the Sun. This can lead to the formation of

clouds and/or hazes and subsequently to the deposition or precipitation of the molecules on the surface (in solid or liquid form), which can have a fundamental role on the state of the surface and thus by feedback on the climate.

The diversity of bulk atmospheric and surface compositions and insolation are at first order the two main factors (there are other secondary factors such as the size and mass of the object, its rotation speed, obliquity, etc.) in the richness and diversity of climates across terrestrial planets and objects in the solar system. More descriptive (but not exhaustive) elements of the climate of the six terrestrial objects mentioned above are presented below.

Venus is sufficiently irradiated ($\sim 1.9 \times$ the insolation on Earth) for all molecular species – mainly CO_2 – to be present in the gas phase. Combined with other molecular species (SO_2 , H_2O , etc.), CO_2 produces a strong greenhouse effect which warms efficiently the lower atmosphere and the surface, up to ~ 740 K. Venus' thick atmosphere (with a surface pressure $\sim 92 \times$ that of Earth) efficiently redistributes heat in the lower atmosphere, reducing temperature variations across the Venusian surface. While the middle atmosphere of Venus is characterized by the presence of a thick global layer of photochemical sulfuric acid hazes, its upper atmosphere is in a state of superrotation, i.e., with very strong zonal winds.

Earth has the right insolation and atmosphere for the water cycle (evaporation, precipitation, cloud formation) to be active and thus deeply impact Earth's climate. The Earth's atmospheric circulation (and thus cloudiness and precipitation) is dominated by large latitudinal circulation cells (Hadley, Ferrel, polar). For more than a hundred years now, humans have been emitting a significant amount of greenhouse gases (e.g., CO_2) which leads - exacerbated by the water cycle - to significant warming of the lower atmosphere and significant climate changes.

Mars is cold enough ($\sim 0.43 \times$ the insolation on Earth) for both water and CO_2 (the main atmospheric constituent) to condense on the surface, in particular at the poles. The seasonal CO_2 condensation strongly impacts the pressure, temperature

and winds in the atmosphere of Mars. Because Mars has a thin atmosphere (with a surface pressure $\sim 0.006 \times$ that of Earth) and a dry surface, the climate on Mars is hyper-continental, i.e., with extreme variations of surface temperature over the course of diurnal and seasonal cycles. Last but not least, the dust cycle has a strong effect on the Martian climate.

Titan is low enough irradiated ($\sim 0.011 \times$ the insolation on Earth) that methane and other heavier hydrocarbons (C_2H_6 , C_3H_8 , etc.; they are produced by photochemistry in the upper atmosphere) can condense in the atmosphere and at the surface, producing a hydrological cycle similar in some respects to that on Earth.

Pluto ($\sim 6.10^{-4} \times$ the insolation on Earth) is so cold that its very thin (with a surface pressure $\sim 10^{-5} \times$ that of Earth), N_2 -dominated atmosphere condenses on the surface mainly at the equator because of Pluto's high obliquity and peculiar topography. Although to date very little information is known about **Triton**, its climate is probably similar to that of Pluto.

The nature of a planet's climate is likely the most important ingredient for the habitability of a planetary surface, and thus its astrobiological potential. Of the six terrestrial objects of the solar system that have an atmosphere, the Earth is the only one known to have liquid water on its surface today, an essential ingredient for life as we know it to emerge and develop.

Cross-References

- [Aerosols](#)
- [Atmospheric Circulation](#)
- [Clouds](#)
- [Earth](#)
- [Greenhouse Effect](#)
- [Habitability, Role of the Atmosphere](#)
- [Hadley Cells](#)
- [Hydrocarbons](#)
- [Mars](#)
- [Molecular Weight](#)
- [Obliquity and Obliquity Variations](#)
- [Photochemical Hazes](#)
- [Photochemistry](#)

- [Pluto](#)
- [Polar Caps \(Mars\)](#)
- [Solar System](#)
- [Superrotation](#)
- [Terrestrial Planet](#)
- [Titan](#)
- [Triton](#)
- [Venus](#)
- [Water, Solvent of Life](#)

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Cloning

Juli Peretó
 Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Cloning is the process of obtaining replicative molecules, cells, or organisms that are genetically identical to a common ancestor. DNA

recombinant techniques – or ► [genetic engineering](#) – allow the synthesis, replication, and expression of DNA fragments of any size, up to complete synthetic molecules the size of a small bacterial genome, in appropriate receptor cells. The cloning of cells and organisms – e.g., plants and animals – using the methods of tissue culture and in vitro cell differentiation is also possible.

Cross-References

- [Amplification \(Genetics\)](#)

Clouds

Mark S. Marley¹, Lisa Kaltenegger² and Daniel Kitzmann³

¹NASA Ames Research Center, Moffett Field, CA, USA

²Cornell University, Ithaca, NY, USA

³University of Bern, Bern, Switzerland

Keywords

Albedo · Atmosphere · Clouds · Extrasolar planets · Spectra · Spectroscopy

Synonyms

[Condensate layer](#)

Definition

Clouds are condensates (either liquid or solid) of gaseous atmospheric constituents, which play an important role in planetary atmospheres. Since clouds scatter and absorb incident stellar radiation as well as emergent thermal radiation and release ► [latent heat](#) during their formation, they control both the appearance and thermal structure of a planet. Furthermore, a cloud deck can both limit the depth an external observer can “see” into an atmosphere and thus hide molecular species, and it can alter a planet’s ► [albedo](#). For such reasons, a basic understanding of the role clouds play is

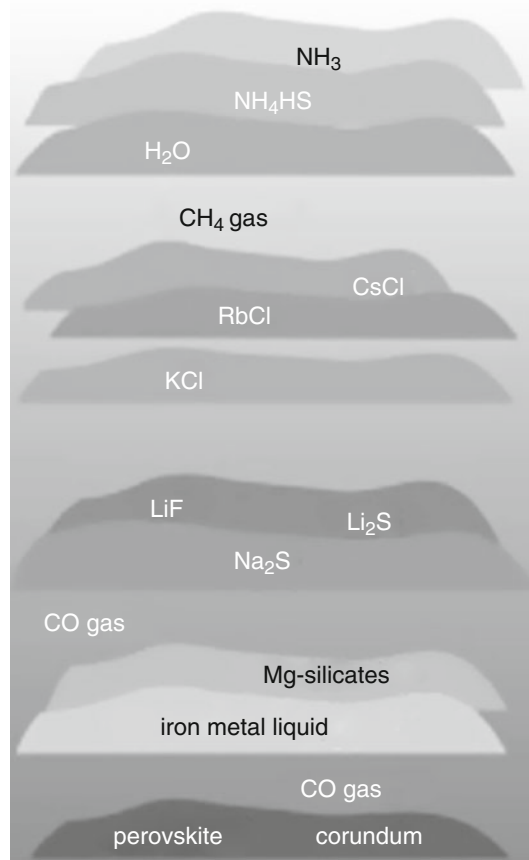
required to interpret exoplanet spectra or to obtain consistent temperature profiles and surface temperatures.

Overview

Clouds can form when the partial pressure of a chemical species exceeds its saturation vapor pressure. The initial distribution of cloud nuclei is formed by either homogenous or heterogeneous nucleation from the gas phase, where the first process needs a highly supersaturated vapor phase, while the latter one already operates at very low supersaturations but requires the a priori presence of some form of seed particles (e.g., ► [aerosol particles](#)). The resulting initial distribution of nuclei undergoes numerous microphysical processes, such as growth, evaporation, coagulation, or sedimentation, which determine the temporal and spatial evolution of the cloud's particle size distribution (Pruppacher and Klett 1997). Because exoplanetary atmospheres can span a very wide range of chemical compositions as well as temperature and pressure conditions, a large number of species may form clouds.

Jupiter's atmosphere provides a point of departure for understanding the diversity of giant planet atmospheres that we expect to encounter outside of the solar system. Assuming we start at a temperature of about 2,000 K (Fig. 1), the first constituents to condense in a rising gas parcel are refractory oxides such as perovskite and corundum, followed by various magnesium silicates including enstatite and forsterite. As we move upward in the atmosphere, the temperature continues to fall and eventually water clouds form, removing H_2O from the gas phase. Above the water clouds, the atmosphere continues to cool until ammonia clouds form. It is the ammonia clouds of Jupiter, dusted by various photochemical pollutants, that we see reflecting sunlight back from the planet. In a warmer Jupiter, the atmosphere would never become saturated in water and ammonia vapor, and these species would stay in the gas phase, thus removing the bright clouds and substantially altering the appearance and color of the planet.

Direct evidence for the presence of clouds has been found in transmission spectra of several



Clouds, Fig. 1 Cloud structure expected on a Jupiter-like planet depending on its temperature (hot: bottom, cool: top). (Figure modified from Lodders (2004))

transiting extrasolar gas giants. Currently, the best example for the occurrence of high-altitude clouds is the transiting hot Jupiter HD 189733b (Sing et al. 2011). The possible existence of clouds is also debated for super-Earth planets, such as GJ 1214b (Morley et al. 2013), although better observational constraints are required to obtain more accurate estimates on the clouds' properties.

Clouds play also a crucial role for terrestrial planets. For habitable planets, the most important cloud species are water droplet and carbon dioxide and water ice clouds. Typically, the reflectivity of water clouds in the visible and near-infrared wavelength range is high in comparison to surface features. Thus, a cloudy planet is brighter and has a higher albedo than either a rocky, airless world or a planet with a deep, clear atmosphere. Cold,

high-level clouds can limit the height from which thermal flux is emitted in an atmosphere and thus hide underlying regions which might otherwise produce significant spectral features. They can also directly influence important spectral features of molecules (e.g., the potential ► [biomarker ozone](#)) originating from above the cloud layer (Vasquez et al. 2013). Clouds must be considered in any calculation of the location and extension of the ► [habitable zone](#), as they can both raise the Bond albedo, thus cooling the surface (Kasting 1991) and limit thermal emission, exhibiting a ► [greenhouse effect](#) (Kitzmann et al. 2010; Forget and Pierrehumbert 1997).

Future Directions

Clouds are intrinsically difficult to model from a priori physical considerations (see, e.g., Ackerman and Marley 2001; Helling et al. 2008; Marley et al. 2013). The detailed behavior of the terrestrial cloud cover as a function of atmospheric temperature is the leading source of uncertainty in global climate models. Predicting cloud behavior for extrasolar planets, including such issues as particle sizes, vertical distribution, and any horizontal patchiness is, therefore, difficult. Accounting for the effects of these clouds has proven challenging, and such issues must be carefully considered when spatially resolved exoplanet spectra eventually become available.

Cross-References

- [Adiabatic Processes](#)
- [Albedo](#)
- [Atmosphere, Structure](#)
- [Greenhouse Effect](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)
- [Jupiter](#)

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CMB

- [Cosmic Background Radiation](#)

CN

- [Cyanogen Radical \(CN\)](#)

CNES, France

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[French Space Agency](#)

Definition

The French Space Agency was established in 1961 and was tasked to implement and coordinate space policy as decided by the government, through its own teams and with national and international partners in science and industry. France is a founding member of the European Space Agency (ESA) and the Centre National d'Études Spatiales (CNES) represents the country in its council and boards. The 2368 employees working in 2020 at CNES are spread among the four main centers. The headquarters are located downtown Paris, as well as the directorate for launchers now co-located with the ESA launcher directorate. The large technical center is located in Toulouse in the south of France. Finally, CNES is also in charge of the launch base of Kourou located in French Guyana. This base is the European spaceport from which the European launchers are operated since 1973. Besides Ariane V, Vega rockets and Russian-built Soyuz rockets are launched also from there. The CNES is supporting through grants and industrial contracts most of the French activities related to space prototyping either commercial or institutional applications, supporting science in space or activities related to defense and security.

CNES was involved in manned space flight through cooperation with the Soviet Union leading to the flight of Jean-Lou Chretien in 1981 and with the United States leading to the flight of Patrick Baudry in 1985. Since then, several flights and experiments related to exobiology flew onboard the Mir space station (► [COMET](#), Exo-bio) as well as the US space shuttle. Since the international space station era, CNES is supporting manned space flight activities mainly under the auspices of ESA. Ten French astronauts flew in space. The first ones flew in the frame of bilateral agreements, later 5 of them, as, lately, Thomas Pesquet, flew under the auspices of ESA as “European astronauts with a French nationality.”

CNES is also playing a major role in the exploration of the solar system through numerous

contributions to missions sponsored by the United States, the Soviet Union then Russia, India, Japan, and China. Redundant, to be suppressed France is the first contributor to ESA mixing the mandatory and the optional programs.

CNO Cycle

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

The CNO cycle is a series of nuclear reactions converting H to He and using C, N, and O isotopes as catalysts; thus, the total amount of these latter species is not affected by the operation. There are three such cycles, each converting four protons to one ${}^4\text{He}$ nucleus and releasing about 6.6 MeV/nucleon or $5 \cdot 10^{18}$ erg/g. At temperatures higher than $17 \cdot 10^6$ K, encountered in stars more massive than $1.3\text{--}1.5 M_{\odot}$, depending on metallicity, rotation, etc., the CNO cycle is the dominant source of energy production, while in lower-mass stars, the proton-proton ► [\(p-p\) chains](#) dominate. Although the sum of C + N + O abundances is conserved, ${}^{12}\text{C}$ and ${}^{16}\text{O}$ are converted to ${}^{14}\text{N}$, thus ${}^{14}\text{N}$ is the main product of the CNO cycle from the chemical evolution point of view.

History

The CNO cycle is also called the Bethe-Weizsäcker cycle. Hans Bethe won the 1967 Nobel Prize in physics for his 1938 discovery of energy production in stars.

Cross-References

- [High-Mass Star](#)
- [P-P Chains](#)

CNSA, China

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Definition

China National Space Administration (CNSA) is the national space agency of the People's Republic of China and is responsible for the national space program and for the planning and development of space activities. China has signed governmental space cooperation agreements with Brazil, Chile, France, Germany, India, Italy, Pakistan, Russia, Ukraine, the United Kingdom, and the United States, although the 2011 Wolf Amendment by the US Congress severely limits cooperation between the CNSA and NASA. The CNSA has four launch sites within China, in Jiuquan, Taiyuan, Xichang, and Wenchang.

History

CNSA has pioneered a number of achievements in space, including becoming the first space agency to land on the far side of the Moon with Chang'e 4, bringing material back from the Moon with Chang'e 5, and being the second agency to successfully landed a rover on Mars with Tianwen-1.

Cross-References

► [NASA](#)

CO

► [Carbon Monoxide](#)

CO₂

► [Carbon Dioxide](#)

CO₂ Ice Cap (Mars)

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, UMR 8539, Université
Paris 6, Paris, France

Definition

CO₂ ice caps on ► [Mars](#) are mantles of CO₂ ice deposited above 50° latitude in both hemispheres during fall and winter. They form by condensation of CO₂ gas, the main constituent of the atmosphere, and can reach thicknesses of 50 cm to 1 m. Their surface temperature is controlled by solid-gas equilibrium with the atmosphere and ranges between 142 and 150 K. In the northern hemisphere, the CO₂ ice cap completely disappears during spring. In the southern hemisphere, the CO₂ ice does not completely sublime, leaving a perennial ► [polar caps \(Mars\)](#) 300 km across and several meters thick near the south pole.

Cross-References

► [Carbon Dioxide](#)
► [Mars](#)
► [Polar Caps \(Mars\)](#)

CO₂ Ice Clouds (Mars)

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, UMR 8539, Université
Paris 6, Paris, France

Definition

Clouds composed of CO₂ ice form when CO₂ gas (the main constituent of the ► [Mars](#) atmosphere) condensates in the atmosphere. CO₂ ice clouds have been observed in the lower Martian

atmosphere during the northern and southern winter polar nights (Pettengill and Ford 2000) and in Mars's mesosphere (80–100 km altitude) near the equator (Montmessin et al. 2007). Thick CO₂ ice clouds may have been present in the planet's denser early atmosphere, more than 3.5 billion years ago. They could have contributed to warming the surface through the process of the scattering ► [greenhouse effect](#) (Forget and Pierrehumbert 1997); however, the extent of this effect is debated.

Cross-References

- [Carbon Dioxide](#)
- [Greenhouse Effect](#)
- [Mars](#)
- [Planet](#)

References and Further Reading

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Coagulation in Planetary Disks

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

Coagulation is the first stage in ► [planet formation](#) in which small solid grains collide and grow. In the context of planet formation models, coagulation refers to a statistical model for particle growth in ► [protoplanetary disks](#).

Cross-References

- [Planetesimals](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)

Coagulation, Interstellar Dust Grains

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Low-energy collisions of interstellar grains can result in the growth of the grains or grain aggregates, a process sometimes referred to as coagulation. The structure of the grains or aggregates presumably depends on the size and structure of the colliding particles and possibly on the presence or absence of an icy grain mantle.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Ices](#)

Code

Hugues Bersini
IRIDIA, Université Libre de Bruxelles, Brussels,
Belgium

Keywords

ASCII code · Genetic code · Programs ·
Semaphore · Turing machine

Definition

At first and most basically, a code defines a mapping between one type of information and another. For instance, the ASCII code in computer science

is the binary translation of our alphabet, mapping, for instance, the lowercase character “a” onto “1100001” and making possible for computers to store, treat, and exploit information expressed in words. “Code” is one of those terms that testify to the strong intellectual connection and mutual conceptual enrichment that, since Turing, Von Neumann, and the former systemic and cybernetic schools, has always existed between biology and computer science. Interestingly enough, the different meanings of this term in computer science is mirrored by a progressive semantic enrichment also of its use in biology.

Overview

The most celebrated biological code is without doubt the “genetic” one which maps triplets of four possible ► [nucleotides](#) (“A,” “T,” “G,” “C”) onto 1 of the 20 ► [amino acids](#) found in the ► [proteins](#) of living organisms. For instance, the triplet “AAT” is mapped onto the “Leucine” amino acid. Although the ► [genetic code](#) is not as arbitrary as the ASCII one, still a mapping table is really what defines the coding in both cases.

There is an extended, more sophisticated definition of “code” in computer science, such as when a programmer is writing a “code” to be executed by his computer. The mapping is not anymore between one type of representation and another, but pieces of the code serve as an index to executable processes, such as when a traffic light turns red requiring the driver to stop his car. An essential part of elementary instructions in computers is indeed expressed according to a specific code (like “add” or “load”), making both the central process unit and the memory participate in the execution of a whole process (such as adding numbers or copying information from one zone of the computer to another). The ambiguity recognized by many biologists in the meaning of ► [“gene”](#) can be considered in the light of these basic and extended meanings. As a matter of fact, a gene can be seen not only as coding for the associated protein but, more and more in a richer manner, as indexing a whole and sophisticated biological process that might even execute differently according to the surrounding

environment (rendering the distinction between innate and acquired characteristics much more subtle and interesting). When Richard Dawkins evolves his biomorphs (Dawkins 1996 [1986]), as described in his book “The Blind Watchmaker,” the sophistication of the obtained creatures is not so much a reflection of the genetic code used by him but rather appears as an outcome of the recursive program simply parameterized by this code. The genes boil down to a simple parameterization of a very sophisticated process responsible for the major part of the resulting complexity. A mapping is still in place, but the action/process/object mapped by the gene (such as the action/process/object mapped by a software instruction in a program) is far from static. It turns out to be a very rich one-to-many mapping, from one gene to many potential dynamical processes, the latter being capable to behave in a very sophisticated manner and very sensitively to the surrounding environment. In the most complex cases, these dynamic processes can even interfere back on the genes, requiring then to include the temporal dimension in the definition of this mapping.

Cross-References

- [Artificial Life](#)
- [Genetic Code](#)

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Codon

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

A codon is each of the nonoverlapping nucleotide triplets in the coding sequence of an mRNA,

which specifies an amino acid, following the equivalences of the ► [genetic code](#).

Cross-References

- [Anticodon](#)
- [Genetic Code](#)
- [Ribosome](#)
- [RNA](#)
- [Translation](#)
- [Wobble Hypothesis \(Genetics\)](#)

Codon Table

- [Genetic Code](#)

Co-elution

- [Chromatographic Coelution](#)

Coenzyme

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Cofactor](#)

Definition

Coenzyme is any organic, low-molecular-mass, freely dissociable factor, which is essential for the activity of an enzyme. For example, some dehydrogenases require NAD^+ as electron carrier and some reductases use NADPH.

Cross-References

- [NADH, NADPH](#)

Coevolution

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

History

The concept of coevolution was developed in 1964 by Paul R. Ehrlich (1932) and Peter H. Raven (1936). It consists in the evolutionary interaction between two species. Coevolution notably concerns the linked evolution in the some host-parasite relationship, each of them interacts with the evolution of the other, and the relationship stays stable.

In 1973, Leigh Van Valen (1935–2010) proposed the famous parabola of the “Red Queen’s model,” inspired by Lewis Carroll’s novel, *Through the Looking-Glass, and What Alice Found There* (1871). Alice and the Red Queen run together and they stay under the same tree all the time. The Red Queen explains to Alice: “Now, here, you see, it takes all the running you can do, to keep in the same place.” This sentence resumes the idea of coevolution in which the two species have evolved simultaneously to maintain their relationship in the same state.

Cross-References

- [Evolution, Biological](#)

Cofactor

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Cofactor is a nonprotein (organic or inorganic) factor necessary for the activity of an ► [enzyme](#). This

factor can be firmly bound to the enzyme (i.e., prosthetic group, e.g., ► [cytochromes](#)) or freely dissociable (i.e., ► [coenzyme](#), e.g., NAD(P)H).

Cross-References

- [Coenzyme](#)
- [Cytochromes](#)
- [Enzyme](#)
- [NADH, NADPH](#)

Cognition

- [Intelligence](#)
- [Intelligence, Evolution of](#)

Coleman-Sagan Equation

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

The Coleman-Sagan equation is a method for estimating the probability of contaminating another planetary body by Earth microorganisms and was first published by S. Coleman and C. Sagan in [1965](#).

This formula can be written as $P_c = N_0 R [P_s] P_i P_R P_g$.

In planetary protection, the formulation is often used by first determining the initial number of microorganisms (N_0) that could be present on or in a spacecraft (the bioburden), and then multiplying this number by an appropriately selected set of factors representing the amount by which this number could be reduced. The first reduction in proportion (R) is dependent on parameters that would reduce the number of surviving organisms, including conditions to which the spacecraft is exposed both before and after launch. Then, while present on the spacecraft, the microorganisms have to reach the surface of the planet

(or other solar system target). The value P_i describes the probability of the spacecraft to hit the planet. This value can range from less than 1×10^{-5} for a flyby, up to one for a landing probe. The probability for a microbe to be released (P_R) in the planet's environment while the spacecraft is on the ground is generally set to one in case of crash landing. The probability of growth (P_g) in the particular extraterrestrial environment is also included in the calculation, but for targets with accessible liquid water, it is assumed to be one. The "probability of contamination" is taken to be equivalent to the fractional number of organisms that are present on a spacecraft after these various reduction factors are combined.

Cross-References

- [Bioburden](#)
- [Microorganism](#)
- [Planetary Protection](#)

References

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Collection en Orbite de Matériel Extra Terrestre

- [COMET \(Experiment\)](#)

Colonization, Biological

Silvano Onofri
Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

Keywords

Archaea · Dormant state · Ecological niche · Eukarya · Extremotolerance · Habitat · Microbial community · Origin of life · Panspermia

Synonyms

Settlement

Definition

Colonization is the occupation of a ► [habitat](#) or territory by a biological community or of an ecological niche by a single population of a species. Biological colonization relates to all species, from microbes – including bacteria, archaea, and ► [fungi](#) – to more complex organisms, like plants and animals. The term also applies to the occupation of new territories, including planets, by the human species. Biological colonization is a dynamic process that begins when unoccupied habitats, territories, or niches become available or when organisms acquire the ability to survive and reproduce under environmental conditions of new niches, by a process of adaptation (Fig. 1).

Overview

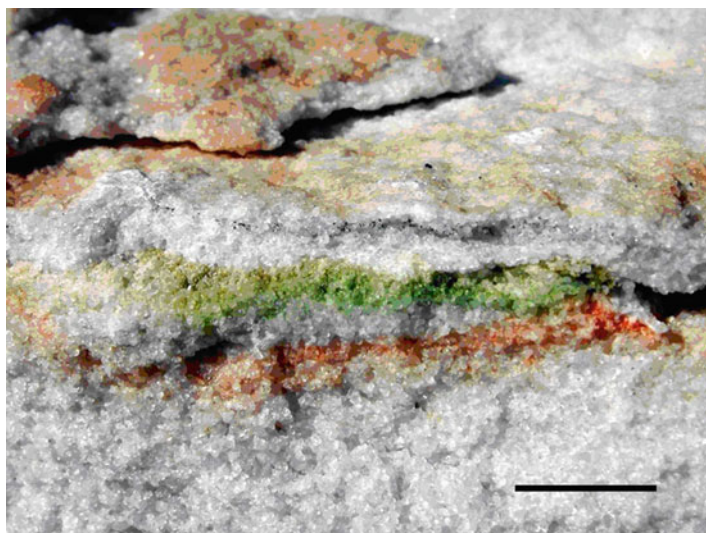
The colonization of new habitats involves a succession of biological communities that can be studied and, to some extent, predicted. In many cases, the biological colonization of new habitats

and territories begins with microorganisms, which has particular relevance to astrobiology. All known life forms are based on ► [carbon](#) chemistry and are related to the availability of ► [water](#). Organisms are able to colonize all environments that fall within the limits of habitability, i.e., conditions of low (Kappen et al. 1996; Cavicchioli 2006) to high temperatures (up to 122 °C, Kashefi and Lovley 2003; Takai et al. 2008), low water availability (Billi and Potts 2002; Leong et al. 2011), extreme acidity (Amaral Zettler et al. 2002; Schleper et al. 1996) or alkalinity, high pressure, salinity (Oren 2000, 2002; Pikuta and Hoover 2007), and radiation (Billi et al. 2000; Bagwell et al. 2008; Dadachova and Casadevall 2008). We find life, primarily microbial, in hot springs on the ocean floor, within the crust to depths over 3000 m (Cockell 2003), in deserts (Friedmann 1982) and on the highest mountains, in the Arctic and Antarctic ► [permafrost](#) (Rivkina et al. 2000), high in the stratosphere, in salt crystals, in acidic (up to pH 0 or negative) to very basic waters (Schleper et al. 1996; Takai et al. 2001), and in sites contaminated by nuclear radiation (Dadachova and Casadevall 2008) (Figs. 2 and 3).

The limits of metabolically active life define the habitability of celestial bodies. Biological colonization is thought to be possible wherever water could be available, such as in the permafrost of ► [Mars](#) or on ► [Europa](#) Jupiter's moon. The notion

Colonization, Biological,

Fig. 1 Cryptoendolithic (hidden within rock) microbial community colonizing sandstone, McMurdo Dry Valleys, continental Antarctica (bar 1 cm). (Copyright © 2009 Laura Zucconi (permission obtained))



of biological colonization beyond Earth leads to speculation about the transfer of life from one celestial body to another. Today, we know that the conditions suitable for the origin of life could have existed on Mars and perhaps on other planets. Many organisms are capable of surviving in a dormant state in conditions far more prohibitive than those suitable for active metabolism. Some organisms, e.g., bacteria (Horneck et al. 1994), microfungi (Onofri et al. 2008, 2012), and lichens (Sancho et al. 2007), have been shown to withstand

space vacuum, temperatures, and radiation. Thus, they are valuable model organisms for studying possible extraterrestrial life. Bacterial spores within rocks are able to withstand the shock of an [asteroid](#) impact and could therefore have been ejected from the parent planet and could also have survived the landing process. Life could thus have been transferred from one planet to another ([Lithopanspermia](#)), beginning the biological colonization of new territories (Horneck and Baumstark-Khan 2002) (Figs. 4 and 5).

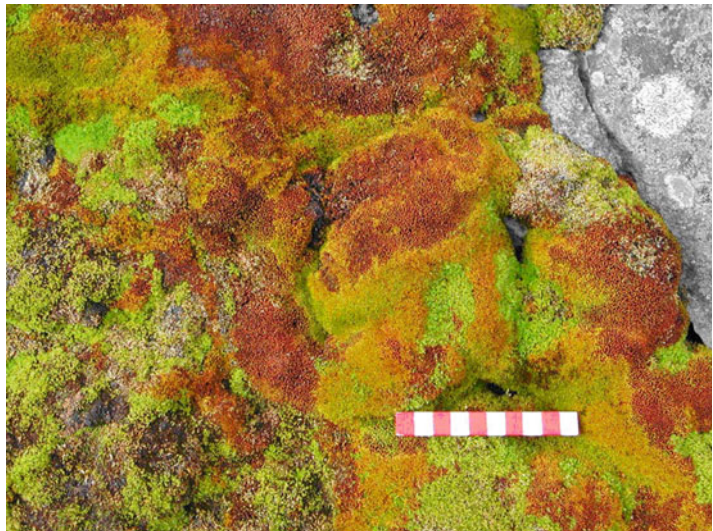
Colonization, Biological,

Fig. 2 A “lichen’s grass” (*Usnea antarctica*) in King George Island, Antarctica (bar 10 cm). (Copyright © 2001 Silvano Onofri)



Colonization, Biological,

Fig. 3 Mosses colonizing rocks in King George Island, Antarctica (bar 10 cm). (Copyright © 2001 Silvano Onofri)

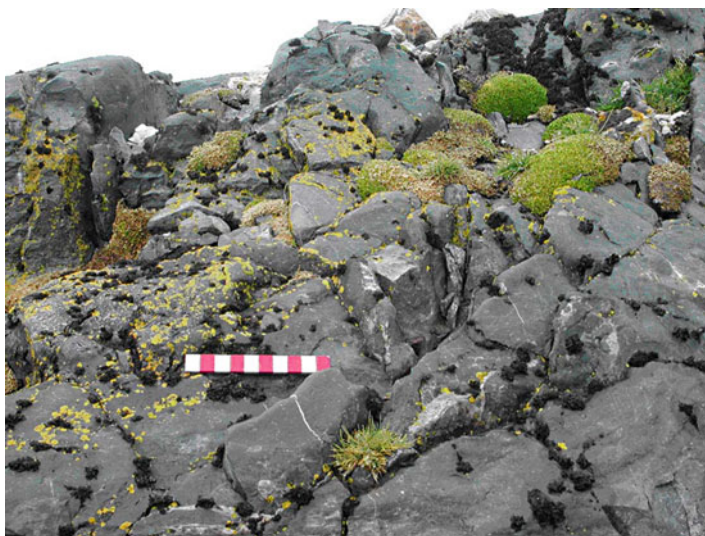


Colonization, Biological,

Fig. 4 A higher plant (*Colobanthus quitensis*) colonizing soil in King George Island, Antarctica (bar 10 cm). (Copyright © 2001 Silvano Onofri)

**Colonization, Biological,**

Fig. 5 Lichens (*Umbilicaria* and *Xanthoria*) and higher plants (*Colobanthus quitensis* and *Deschampsia antarctica*) colonizing rocks in King George Island, Antarctica (bar 10 cm). (Copyright © 2001 Silvano Onofri)

**Cross-References**

- ▶ Asteroid
- ▶ BIOPAN
- ▶ Black Smoker
- ▶ Carbon
- ▶ Deep Subsurface Microbiology
- ▶ Deep-Sea Microbiology
- ▶ Epilithic
- ▶ Europa
- ▶ Expose
- ▶ Extreme Environment
- ▶ Fungi
- ▶ Habitable Zone
- ▶ Habitat
- ▶ Lithopanspermia
- ▶ Mars
- ▶ Meteorites
- ▶ Panspermia
- ▶ Permafrost
- ▶ Rock
- ▶ Space Environment

- [Space Vacuum Effects](#)
- [Spallation Zone](#)
- [Spore](#)
- [UV Radiation, Biological Effects](#)
- [Water](#)

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Color Excess

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Definition

The color excess is the difference between the observed ► [color index](#) of a star and the intrinsic color index predicted from its spectral type. It is a quantity that is always positive and that gives a measure of the absorption of starlight by the intervening ► [interstellar medium](#). The apparent

reddening of the starlight comes from a stronger absorption in the blue than in the red by dust particles. Generally, it's the excess of the [B-V] color index of the Johnson photometric system which is used: it is denoted E_{B-V} . The interstellar extinction, denoted A_v , is directly proportional to E_{B-V} ($A_v \approx 3 E_{B-V}$).

Cross-References

- [Color Index](#)
- [Dust Grain](#)
- [Interstellar Medium](#)
- [Magnitude](#)
- [Reddening, Interstellar](#)

Color Index

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A color index is the difference between the ► [magnitude](#) of a star measured at one standard wavelength and the magnitude at another, albeit longer, standard wavelength: this is a quantitative measure of a star's color. A positive color index indicates a star redder (generally cooler) than an A0 star, such as Vega, and a negative one, a bluer (hotter) star.

Cross-References

- [Color Excess](#)
- [Magnitude](#)

Color-Magnitude Diagram

- [Hertzsprung-Russell Diagram](#)

Column Density

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The column density between two points in a medium is the projected number density of a given species (H atoms, dust particles) contained in a cylinder whose length is the distance between the two points. The unit is m^{-2} . When applied to the interstellar matter lying between an object and the Earth, the hydrogen column density is proportional to the extinction, with the approximate relation: $A_v = 5 \cdot 10^{-26} N(H)$, where $N(H)$ is the column density or projected number of H atoms per square meter and A_v is the visual extinction.

Cross-References

- [Extinction, Interstellar or Atmospheric](#)

Combinatorial Library

Burckhard Seelig
Department of Biochemistry, Molecular Biology
and Biophysics & BioTechnology Institute,
University of Minnesota, St. Paul, MN, USA

Definition

Combinatorial libraries are mixtures of large numbers of compounds. To study the origin and evolution of biomolecules such as nucleic acids or proteins, vast combinatorial libraries have been synthesized that contain up to 10^{15} different random RNA molecules or up to 10^{13} random polypeptides. These libraries are used in conjunction with *in vitro* selection techniques such as SELEX (systematic evolution of ligands by exponential

enrichment) or mRNA display to test the hypothesis of the emergence of functional biomolecules from random sequence space.

Cross-References

- [mRNA Display](#)
- [Protein](#)
- [RNA](#)

Combinatorial Nucleic Acid Library

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Nucleic acid pool of random sequence](#); [Oligonucleotide library](#)

Definition

A combinatorial nucleic acid library is a large pool of DNA or RNA molecules used as the starting point of an in vitro selection or evolution experiment. Such libraries usually contain 10^{12} – 10^{16} nucleic acid molecules showing a central region – typically, 20–100 nucleotides long – of random or mutagenized sequence, flanked by two primer-binding sites of defined sequence. Since 1990, combinatorial nucleic acid libraries have been used to isolate specific nucleic acid ligands for a variety of target molecules – aptamers –, as well as nucleic acid-based catalysts for different reactions – ribozymes and deoxyribozymes–.

Cross-References

- [Aptamer](#)
- [Evolution, In Vitro](#)

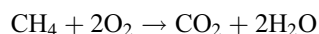
- [Evolution, Molecular](#)
- [Nucleic Acids](#)
- [Ribozyme](#)
- [Sequence](#)

Combustion

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In chemistry, combustion is the complete or incomplete oxidation of a fuel by oxygen or other oxidants to give oxidized carbon species, such as CO (for incomplete combustion) and CO₂ (for complete combustion), water and the concomitant production of heat. For example,



Respiration is an example of a biological combustion reaction.

Cross-References

- [Oxidation](#)
- [Respiration](#)

Comet

Jacques Crovisier
LESIA, Observatoire de Paris, Meudon, France

Keywords

Small body · Coma

Definition

A comet is a small body, formed in the outer region of the Solar System, generally in a highly eccentric orbit, and containing a large fraction of volatiles. When coming close to the Sun, ► [sublimation](#) of the ices causes the development of spectacular cometary phenomena: the coma and the dust and ion tails.

History

Comets are among the most remarkable sky phenomena for both the layman and the scientist (Fig. 1; Table 1). For a long time, their unexpected apparitions and their unknown nature induced both fascination and fear. Nowadays, they are considered as natural laboratories meeting extreme physical conditions and as key objects for understanding the history of the Solar System.

Important milestones for the science of comets were:

- The understanding that comets are not atmospheric phenomena, which was demonstrated by Tycho Brahe (1546–1601) and his colleagues who measured the parallax of the comet of 1577
- The determination of cometary orbits with the works of Isaac Newton (1644–1727) and Edmond Halley (1656–1742)
- The knowledge of the comet phenomenon, formation, and development of both the coma and the tails (end of the eighteenth and nineteenth centuries)
- The determination of the composition of comets with the emergence of spectroscopy (end of the nineteenth century) and the opening of new spectral domains (end of the twentieth century)
- The active exploration of comets with flyby and encounter space missions nowadays

Cometary science is the topic of several books and reviews (see Further Reading).

Overview

Names of Comets

The nomenclature system for comets has changed several times. The Central Bureau for Astronomical Telegrams (CBAT) and now the Minor Planet Center (MPC) of the International Astronomical Union (IAU) are in charge of attributing names to comets. A registration code is given according to the order of discovery. It consists of “C/” followed by the year of discovery, then by a letter corresponding to the half-month of the discovery, and then by an order numeral. In addition, the name of the discoverer (or of the first two discoverers) is traditionally associated. Thus, C/1995 O1 (Hale-Bopp) is the first comet discovered in the second half of July 1995, by Alan Hale and

Comet, Fig. 1 Comet C/2006 P1 (McNaught) over the Pacific. This comet became spectacular as it passed perihelion at 0.17 AU from the Sun on 12 January 2007. (© Sebastian Deiries (ESO))



Comet, Table 1 A selection of well-known comets

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
C/1577 V1	1577 I		27 Oct. 1577	0.178	1.0		First parallax measurement
C/1680 V1 “Kirch’s comet”	1680		18 Dec. 1680	0.0062	1.000		Sungrazer
C/1729 P1 “Sarabat’s comet”	1729		16 Jun. 1729	4.05	1.0		Intrinsically very bright
C/1743 X1 “Chézeaux’s comet”	1744		1 Mar. 1744	0.222	1.0		
D/1770 L1 (Lexell)	1770 I		14 Aug. 1770	0.67	0.786	5.6	Approached Earth at 0.015 AU
C/1811 F1 (Great comet)	1811 I		12 Sep. 1811	1.04	0.995		
C/1819 N1 (Great comet)	1819 II		28 Jun. 1819	0.342	1.0		First polarization observation
C/1843 D1 (Great March comet)	1843 I		27 Feb. 1843	0.0055	0.999	513	Sungrazer
C/1858 L1 (Donati)	1858 VI		30 Sep. 1858	0.578	0.996	2000	
C/1861 J1 (Great comet)	1861 II		12 Jun. 1861	0.82	0.985	409	
C/1864 N1 (Tempel)	1864 II		16 Aug. 1864	0.91	0.996		First spectral observations
C/1868 L1 (Winnecke)	1868 II		26 Jun. 1868	0.58	1.0		
C/1874 H1 (Coggia)	1874 III	1874c	9 Jul. 1874	0.68	0.998		
C/1881 K1 (great comet)	1881 III	1881b	16 Jun. 1881	0.73	0.996		
C/1882 R1 (Great September comet)	1882 II	1882b	17 Sep. 1882	0.00775	0.9999	759	Sungrazer
C/1887 B1 (Great southern comet)	1887 I	1887a	11 Jan. 1887	0.0048	1.0		Sungrazer
C/1901 G1 (Great comet)	1901 I	1901a	24 Apr. 1901	0.245	1.0		
C/1907 L2 (Daniel)	1907 IV	1907d	4 Oct. 1907	0.512	0.999		
C/1908 R1 (Morehouse)	1908 III	1908c	26 Dec. 1908	0.945	1.0007		
C/1910 A1 (Great January comet)	1910 I	1910a	17 Jan. 1910	0.129	0.9999		
C/1911 O1 (Brooks)	1911 V	1911c	28 Oct. 1911	0.49	0.997		
C/1927 X1 (Skjellerup-Maristany)	1927 IX	1927k	18 Dec. 1927	0.176	0.9998		
C/1940 (R2 Cunningham)	1941 I	1940c	16 Jan. 1941	0.368	1.0005		
C/1947 X1 (Southern comet)	1947 XII	1947n	2 Dec. 1947	0.110	0.9995		
C/1948 V1 (Eclipse comet)	1948 XI	1948 l	27 Oct. 1948	0.135	0.99994		
C/1956 R1 (Arend-Roland)	1957 III	1956h	8 Apr. 1957	0.316	1.0002		
C/1957 P1 (Mrkos)	1957 V	1957d	1 Jul. 1957	0.355	0.9994		
C/1959 Y1 (Burnham)	1960 II	1959k	29 Mar. 1960	0.355	0.9994		
C/1961 R1 (Humason)	1962 VIII	1961e	10 Dec. 1962	2.13	0.990		
C/1965 S1 (Ikeya-Seki)	1965 VIII	1965f	21 Oct. 1965	0.00779	0.99992		Sungrazer
C/1969 Y1 (Bennett)	1970 II	1969i	20 Mar. 1970	0.538	0.996		
C/1973 E1 (Kohoutek)	1973 XII	1973f	28 Dec. 1973	0.142	1.000		International obs. campaign
C/1975 V1 (West)	1976 VI	1975n	25 Feb. 1976	0.197	1.000		
C/1980 E1 (Bowell)	1982 I	1980b	12 Mar. 1982	3.364	1.057		Active far from the Sun
C/1983 J1 (Sugano-Saigusa-Fujikawa)	1983 V	1983e	1 Apr. 1983	0.471	1.000		Approached Earth at 0.063 AU

(continued)



Comet, Table 1 (continued)

C/1983 H1 (IRAS-Araki-Alcock)	1983 VII	1983d	21 May 1983	0.991	0.990		Approached earth at 0.031 AU
C/1983 O1 (Cernis)	1983 XII	1983l	21 Jul. 1983	3.33	1.002		Active at more than 20 AU
C/1986 P1 (Wilson)	1987 VII	1986l	20 Apr. 1987	1.200	1.0003		
C/1989 X1 (Austin)	1990 V	1989c1	10 Apr. 1990	0.350	1.0002		
C/1990 K1 (Levy)	1990 XX	1990c	24 Oct. 1990	0.939	1.0004		
D/1993 F2 (Shoemaker-Levy)	1994 X	1993e					Crashed on Jupiter
C/1996 B2 (Hyakutake)			1 May 1996	0.230	0.999	89,000	Approached Earth at 0.10 AU
C/1995 O1 (Hale-Bopp)			1 Apr. 1997	0.914	0.995	2400	Extensive obs. campaign
C/1999 S4 (LINEAR)			26 Jul. 2000	0.765	0.9994		Nucleus broke at perihelion
C/2001 A2 (LINEAR)			24 May 2001	0.779	0.9993		Successive nucleus breakings
C/2002 T7 (LINEAR)			23 Apr. 2004	0.615	1.0006		
C/2001 Q4 (NEAT)			15 May 2004	0.962	1.0006		
C/2004 Q2 (Machholz)			24 Jan. 2005	1.205	0.9995		
C/2006 P1 (McNaught)			12 Jan. 2007	0.171	1.0000		Reached mv = −5 at perihelion
C/2012 S1 (ISON)			28 Nov. 2013	0.0124	1.00		Sungrazer
C/2014 Q2 (Lovejoy)			30 Jan. 2015	1.290	0.998		
C/2016 R2 (PanSTARRS)			9 May 2018	2.602	0.996		Atypical composition
2I/Borisov			8 Dec. 2019	2.006	3.34		Interstellar comet
C/2020 F3 (NEOWISE)			3 Jul. 2020	0.296	0.999		
Some numbered short-period comets							
(a)	(d)	(e)	(f)	(g)	(h)		
1P/Halley	9 Feb. 1986	0.587	0.967	76.0		Target of several space missions	
2P/Encke	9 Sep. 2000	0.340	0.847	3.30		Comet of shortest period	
3D/Biela	23 Sep. 1852	0.861	0.756	6.62		Split comet now lost	
9P/Tempel 1	5 July 2005	1.505	0.518	5.51		Target of Deep Impact mission	
17P/Holmes	4 May 2007	2.053	0.432	6.88		Huge outburst in October 2007	
19P/Borrelly	14 Sep. 2001	1.358	0.624	6.86		Target of Deep Space 1 mission	
21P/Giacobini-Zinner	5 Sep. 1985	1.028	0.708	6.59		Target of ICE space mission	
26P/Grigg-Skjellerup	22 July 1992	0.995	0.664	5.10		Target of Giotto extended mission	

(continued)

Comet, Table 1 (continued)

29P/Schwassmann-Wachmann 1	10 July 2004	5.724	0.044	14.7	Centaaur, nearly circular orbit
46P/Wirtanen	12 Dec. 2018	1.005	0.658	5.43	Close approach to Earth
55P/Tempel-Tuttle	28 Feb. 1998	0.977	0.906	33.2	Assoc./Leonid meteor stream
67P/Churyumov-Gerasimenko	12 Aug. 2015	1.243	0.641	6.45	Target of Rosetta mission
73P/Schwassmann-Wachmann 3	7 June 2006	0.939	0.693	5.36	Split comet
81P/Wild 2	25 Sep. 2003	1.590	0.539	6.40	Target of Stardust mission
95P/Chiron	14 Feb. 1996	8.454	0.383	50.7	Centaaur, also listed as asteroid
103P/Hartley 2	28 Oct. 2010	1.059	0.695	6.47	Target of EPOXI mission
109P/Swift-Tuttle	12 Dec. 1992	0.958	0.964	133.3	Assoc./Perseid meteor stream
133P/Elst-Pizarro	29 June 2007	2.642	0.164	5.61	Main-belt comet

(a) Official IAU designation

(b) Old-style designation before 1995

(c) Provisional designation before 1995

(d) Date of perihelion. For short-period comets, this date is chosen to be either that close to their space exploration, or that close to a near approach to Earth, or another recent one

(e) Perihelion distance [AU]

(f) Eccentricity

(g) Period (years)

(h) Remarks

Thomas Bopp. Short-period comets with a period <200 years are registered “P/” instead of “C/.” Those that have been observed at several returns are given subsequently a number: 1P/Halley, 2P/Encke, etc. See <https://www.minorplanetcenter.net/iau/lists/CometResolution.html> for more details, exceptions, and oddities.

One should be careful to comply with these IAU rules to avoid ambiguities. In particular, using only the discoverer(s) name(s), as is often the case in popular articles and even in some professional papers, should be discouraged (some discoverers were very prolific).

Cometary Orbits, Cometary Families, and Cometary Reservoirs

There are now several thousand cometary apparitions for which secure orbits could be determined. The Catalog of Cometary Orbits (Marsden and

Williams 2008) listed 3708 of them. As of April 2021, 420 comets have been observed at multiple returns and are now “numbered” short-period comets.

Some comets have slightly hyperbolic orbits, such as C/1980 E1 (Bowell). As far as this could be investigated, they just recently underwent gravitational perturbations with a planet (Jupiter in most of the cases) which changed their orbit from elliptic to hyperbolic. The apparition of a genuine interstellar comet, expelled from an extra-solar system with a high eccentricity, came only recently with 2I/Borisov discovered in September 2019. A new class, “I”, was created by the IAU for such interstellar small bodies. The first one was 1I/’Oumuamua, devoid of cometary activity.

The inspection of the Catalog of Cometary Orbits shows that there are two main families of comets:

- Short-period comets with low inclination over the ecliptic. Most of them have orbital periods close to 6 or 12 years. Their orbital evolution is governed by strong gravitational interaction with Jupiter. They are named “ecliptic comets” or “Jupiter-family comets.”
- Comets with random inclination over the ecliptic. They may have a long orbital period (“new” comets with a nearly parabolic orbit) or a short period (such as Halley’s comet). They are named “nearly isotropic comets.” To explain the continuing supply of new comets, the existence of a distant, spherical reservoir of comets was postulated (► [Oort Cloud](#)). Thus, these comets are alternatively named “Oort-cloud comets.”

Nearly isotropic comets are not believed to have formed in the Oort Cloud but in the traditional Solar System. They were subsequently ejected to the Oort Cloud following gravitational interaction with giant planets. In turn, ecliptic comets could have formed in the trans-Neptunian region, among the ► [Kuiper Belt](#). They subsequently evolved to shorter-period orbits, preserving their low inclination.

Also related to comets are Centaurs, which are intermediate objects between Kuiper-Belt objects and main-belt asteroids. Some of them, like Chiron (which is registered both as asteroid (2060) Chiron and comet 95P/Chiron), show cometary activity.

“Main-belt comets” are main-belt asteroids which occasionally show a low level of cometary activity. They are also known as “activated asteroids.” About half a dozen of such objects (e.g., 133P/Elst-Pizarro) have been recently identified. Their activity might be triggered by impacts from other small bodies (Jewitt et al. 2015; Snodgrass et al. 2017).

“Sungrazing comets” pass within a few solar radii from the Sun and are generally only detectable at that moment. More than 1900 objects have been registered as sungrazing comets from observations with space coronagraphs (SOHO or STEREO). Most of these bodies are meter-sized objects that do not survive after perihelion (Jones et al. 2018).

The Nature of Comets and Basic Cometary Processes

We now know that comet nuclei are solid icy conglomerates and that the sublimation of ices in the comet nuclei is the motor of cometary activity, following the popular model of the “dirty snowball” of Fred Whipple (1906–2004). We now realize that “snowball” is a misnomer since comet nuclei are very dark. These later are kilometer-sized low-density porous and fragile bodies (see the ► [Comet \(Nucleus\)](#) entry).

Water ice sublimates in the vacuum at temperatures greater than about 150 K. For cometary nuclei, this occurs at distances smaller than about 4 AU from the Sun; this results in the development of a cometary atmosphere: the gaseous coma. The gravity of the comet nucleus is too small to retain this atmosphere, which expands with a velocity ranging from 0.5 to a few km/s, depending on the distance to the Sun and the gas production rate. Thus, the gas density drops rapidly with increasing distance from the nucleus, and the flow becomes collision-free. The inner collisional region has a size of a few hundred to a few thousand kilometers, depending on the comet outgassing. As in laboratory molecular flows, the gas temperature drops rapidly: Temperatures in the range 10–100 K are typically observed.

The production rate of water at a distance of about 1 AU from the Sun is typically 10^{28} molecules per second (300 kg/s) for small short-period comets such as 9P/Tempel 1 and 67P/Churyumov-Gerasimenko, both the targets of space missions. It was 10^{30} molecules s^{-1} (30 t/s) for 1P/Halley and as large as 10^{31} molecules s^{-1} (300 t/s) for the giant comet C/1995 O1 (Hale-Bopp).

Comets can still be active at distances larger than 4 AU from the Sun, where water sublimation is inefficient. This situation requires the sublimation of more volatile species, such as CO, CO₂, or CH₄, that are responsible for the cometary activity. Indeed, the production of carbon monoxide was observed in ► [comet Hale-Bopp](#) at distances as far as 14 AU.

The dominant chemical process in cometary atmospheres is the progressive molecular photolysis by the solar UV radiation. The lifetime of the water molecule at 1 AU from the Sun is about 1 day, but it may be significantly shorter for complex, organic molecules. Two-body reactions are inefficient because molecules spend only a short time in the collision region where temperature is low and where the fraction of reactive ions and radicals is still low.

The primary radiation mechanisms for molecules, radicals, atoms, and ions are the ► [fluorescence](#) of their electronic and vibrational bands excited by solar radiation and thermal emission of rotational lines. Prompt (non-fluorescence) emission from radicals and atoms, following their creation in an excited state as a result of photolysis, may also occur. For rotational lines of molecules in the radio and far-infrared domains, thermal excitation by collisions with molecules, ions, and electrons is another important mechanism.

Cometary particles are dragged from the nucleus by gas. Their initial velocity is much smaller than that of the gas and depends on the particle size. The biggest “boulders” cannot escape the nucleus, which contributes to the formation of a regolith. Dust particles are repelled by the Sun, forming the sometimes spectacular dust tail, following the kinematic model first proposed by Bessel (1784–1846) and Bredichin (1831–1904). The physical process at work – the solar radiation pressure – was later explained by Svante Arrhenius (1859–1927). The biggest dust particles migrate along the cometary orbit where they form cometary trails that were first imaged by the infrared satellites IRAS and ISO. When the Earth encounters such a cometary trail, a meteor shower may be observed (the link between comets and meteor streams was first established for the case of the Perseid meteors and comet 109P/Swift-Tuttle).

Cometary ions in the coma are accelerated through magnetohydrodynamic interaction with the solar wind to velocities of several hundred km s^{-1} . They form a thin straight tail, easily distinguishable from the broad, curved dust tail. This tail is mainly composed of CO^+ and H_2O^+

ions. It is remarkable that this interaction was proposed by Ludwig Biermann (1907–1986) and modeled by Hannes Alfvén (1908–1995) before the solar wind was actually observed by space probes.

Atoms and molecules that undergo fluorescence excited by the Sun are also accelerated away from the Sun. The process is especially efficient for the resonant D lines of sodium at 589 nm. A neutral sodium tail results, which was peculiarly conspicuous in ► [comet Hale-Bopp](#) (Cremonese et al. 1997). The same process is responsible for a significant distortion of the large hydrogen coma.

Space Missions to Comets

A table listing space missions to comets is given in the ► [Comet Nucleus](#) entry. The main steps of cometary exploration were:

- The ► [VEGA](#) and ► [Giotto missions](#), which flew by 1P/Halley in March 1986, revealed the reality of a solid comet nucleus.
- The ► [Stardust mission](#), which flew through the coma of 81P/Wild 2 on 2 January 2004, sampled cometary grains and returned them to Earth for analysis on 15 January 2006.
- The ► [Deep Impact](#) mission, an active experiment, sent an impactor to the nucleus of 9P/Tempel 1 on 4 July 2005. The plume which developed after the impact was observed from the spacecraft and from the Earth. The same spacecraft, in a mission renamed EPOXI, explored 103P/Hartley 2 on 4 November 2010.
- The ► [Rosetta mission](#) (Schulz et al. 2009 and Rosetta Spacecraft entry) encountered ► [67P/Churyumov-Gerasimenko](#) in 2014–2016. An orbiter stayed in the comet vicinity for all these years, witnessing the development of cometary activity. A lander (see Philae Lander entry) reached the comet’s surface and made in situ analyses of the nucleus material.
- Comet Interceptor, an accepted mission scheduled to be launched in 2028, will place three spacecraft at the L2 Lagrange point, ready to be redirected towards target-of-opportunity new comets.

Key Research Findings

Composition of Comets: Ices and Volatiles

For a long time, the chemical study of comets was restricted to visible spectroscopy. Radicals, atoms, and ions, such as CN, CH, C₂, C₃, NH, NH₂, OH, CO⁺, etc., were observed. It was proposed in the mid-twentieth century by Karl Wurm (1899–1975) and Pol Swings (1906–1983) that these unstable species were “daughter molecules” coming from the photodestruction or photoionization by the solar UV radiation of volatile stable molecules, the “parent molecules,” released from the sublimation of nucleus ices. Proposed parents were H₂O, NH₃, CH₄, CO, CO₂, HCN, etc., that could not be directly identified by the techniques available at that time.

Confirmation came with the advent of radio, infrared, and UV spectroscopy as well as in situ mass spectroscopy. We now have a confident knowledge of the main constituents of cometary ices (Bockelée-Morvan et al. 2004; Crovisier 2004; Crovisier et al. 2004; Mumma and Charnley 2011; Cochran et al. 2015; Bockelée-Morvan and Biver 2017; Altwegg et al. 1999, 2019; Fig. 2; Table 2). The main components are water (about 80% by number), followed by carbon monoxide and dioxide. Then come methanol, ammonia, methane and other hydrocarbons (C₂H₂, C₂H₆), hydrogen sulfide, and hydrogen cyanide. Other minor constituents are identified in small amounts and can only be observed in the most productive comets. For instance, the relatively complex organic molecules formic acid (HCOOH), methyl formate (HCOOCH₃), acetaldehyde (CH₃CHO), and ethylene glycol (CH₂OHCH₂OH) were first identified by their radio lines in C/1995 O1 (Hale-Bopp). They were retrieved in comet C/2014 Q2 (Lovejoy), where glycolaldehyde (CH₂OHCHO) and ethanol (C₂H₅OH) were additionally detected (Biver and Bockelée-Morvan 2019).

Indeed, the relationship between comets and spectroscopy is exemplary and dates back from the beginning of astrophysics in the second half of the nineteenth century. Many molecular species were observed in comets before they could be studied in the laboratory.

Mass spectroscopic measurements were performed in situ on 1P/Halley with Giotto

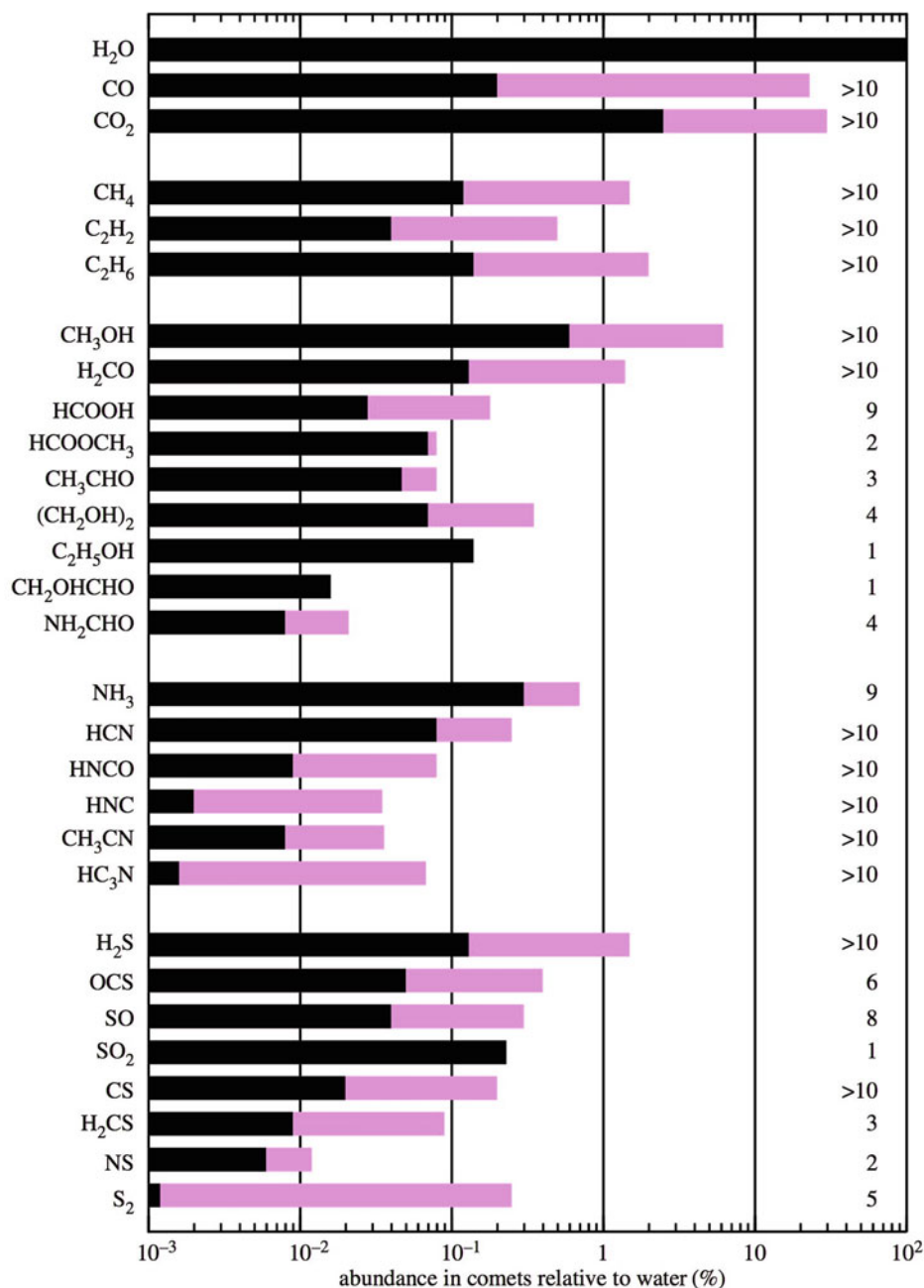
(Altwegg et al. 1999, and references therein). However, their interpretation was hampered by the limited mass resolution and the need for detailed chemical modeling to deduce neutral abundances from the mass spectra. This problem of mass ambiguity was resolved with the equipment of the Rosetta orbiter.

The ► [Stardust mission](#) returned samples from comet 81P/Wild 2. The collecting technique which was used (cometary grains were trapped by entering an aerogel substrate with a velocity of 6 km/s) could not preserve volatiles and favored refractory material. However, a careful analysis revealed the presence of methylamine (CH₃NH₂), ethylamine (CH₃CH₂NH₂), and possibly glycine (NH₂CH₂COOH) in the returned aerogel that could be of cometary origin (Elsila et al. 2009). These species could result from the degradation of carbonaceous cometary grains rather than from the sublimation of nucleus ices.

Many features detected in cometary spectra at all wavelengths are still unidentified, suggesting that new cometary species are still to be identified. This requires further theoretical and laboratory spectroscopic studies.

The investigation of comet ► [67P/Churyumov-Gerasimenko](#) by Rosetta, especially with the ROSINA instrument, really changed our view of cometary chemistry by doubling the number of identified parent molecules (Altwegg et al. 2019). One can note the observation of highly volatile species such as N₂, O₂, and noble gases; of saturated hydrocarbons up to heptane (C₇H₁₆), and also polycyclic aromatics such as benzene (C₆H₆) and possibly naphthalene (C₁₀H₈); the detection of many complex organic molecules, confirming the presence of glycine (NH₂CH₂COOH); and the presence of a phosphorus species, possibly PO.

Comets show a large diversity in their chemical composition (Fig. 2). For instance, the CO/H₂O, CH₃OH/H₂O, or H₂CO/H₂O production rate ratios vary greatly from one comet to another, whereas the HCN/H₂O ratio is fairly constant. It is important to assess whether this diversity is correlated with different sites of formation or to different evolutions of these bodies. Indeed, from the observations of daughter species, A'Hearn et al. (1995) have identified a class of carbon-



Comet, Fig. 2 Relative production rates of cometary volatiles and their comet-to-comet variations. These rates are believed to trace the relative abundances in cometary ices. The *pink* part of each *bar* indicates the range of

variation from comet to comet. The number of comets in which the species was detected until 2017 is indicated on the *right*. (Updated from Bockelée-Morvan et al. 2004)

poor comets, for which the C₂ radical is depleted. It appears that these carbon-poor comets are mostly present among Jupiter-family comets. However, how this carbon depletion could be

related to the abundance of bona fide parent molecules is still unclear. Clues from infrared and radio spectroscopy are yet inconclusive, perhaps because the sample of investigated comets at these

Comet, Table 2 The relative composition of volatiles observed in comet C/1995 O1 (Hale-Bopp), normalized to water

Water	H ₂ O	100	
Carbon monoxide	CO	12–23	^a
Carbon dioxide	CO ₂	6	
Methane	CH ₄	1.5	
Acetylene	C ₂ H ₂	0.1–0.3	
Ethane	C ₂ H ₆	0.6	
Methanol	CH ₃ OH	2.4	
Formaldehyde	H ₂ CO	1.1	^a
Formic acid	HCOOH	0.09	
Methyl formate	HCOOCH ₃	0.08	
Acetaldehyde	CH ₃ CHO	0.02	
Ethylene glycol	CH ₂ OHCH ₂ OH	0.25	
Formamide	NH ₂ CHO	0.015	
Ammonia	NH ₃	0.7	
Hydrogen cyanide	HCN	0.25	
Isocyanic acid	HNCO	0.10	
Hydrogen isocyanide	HNC	0.04	^a
Methyl cyanide	CH ₃ CN	0.02	
Cyanoacetylene	HC ₃ N	0.02	
Hydrogen sulfide	H ₂ S	1.5	
Carbonyl sulfide	OCS	0.4	^a
Sulfur dioxide	SO ₂	0.2	
Carbon disulfide	CS ₂	0.2	^b
Thioformaldehyde	H ₂ CS	0.05	
NS radical	NS	0.02	^c

Updated from Bockelée-Morvan et al. (2004)

Data derived from radio or infrared observations of comet Hale-Bopp made at heliocentric distances of about 1 AU

^aWith possibly an additional distributed source in the coma

^bFrom the observation of the CS radical

^cOf unknown origin

wavelengths is still sparse (Crovisier et al. 2009; Mumma and Charnley 2011; A’Hearn et al. 2012; Biver and Bockelée-Morvan 2016; Dello Russo et al. 2016).

Composition of Comets: Dust and (Semi-) Refractories

Knowledge of the composition of cometary dust stems from infrared spectroscopy (with ground-based telescopes and the ISO and Spitzer space observatories) and from the samples collected in the coma of the Jupiter-family comet 81P/Wild 2 by the ► [Stardust mission](#), providing ground truth for the remote-sensing investigations

(Hanner and Zolensky 2010). Additional information comes from the analysis of interplanetary dust particles (IDPs), collected in the upper Earth’s atmosphere, which could be of cometary origin. The analysis of the material excavated in the Jupiter-family comet 9P/Tempel 1 by the ► [Deep Impact](#) experiment revealed an inner nucleus composition similar to that observed in more active Oort-cloud comets, such as 1P/Halley or C/1995 O1 (Hale-Bopp).

Cometary dust appears to be heterogeneous, with silicates in both the amorphous (glassy) and crystalline forms, Fe and Ni sulfides, and other minerals in minor amounts. The presence of carbonates and phyllosilicates is subject to debate. Cometary silicates, which constitute the most abundant part of the refractory grains, show a large diversity, comprising forsterite (Mg₂SiO₄), enstatite (MgSiO₃), olivines, and pyroxenes with a wide range in Mg/Fe. Among the 81P/Wild 2 samples were found highly refractory calcium aluminum-rich inclusions (► [CAI](#)) and fragments of ► [chondrules](#), as is usually found in primitive meteorites.

A significant fraction of cometary dust is in the form of carbonaceous grains (also known as “CHON particles”), first found in the space exploration of comet Halley. They could be a potential source of molecules, an alternative to the sublimation of volatiles from nucleus ices. They have been invoked to explain the distributed sources of H₂CO, CO, OCS, HNC, CN, etc., through photo-degradation or, more likely, thermal degradation (Cottin and Fray 2008). Polyoxymethylene (H₂CO)_n (POM), hexamethylenetetramine C₆H₁₂N₄ (HMT), HCN polymers (HCN)_n, and carbon suboxide polymers (C₃O₂)_n have been proposed as cometary analogs, and their degradation was studied in the laboratory.

► [Polycyclic aromatic hydrocarbon](#) molecules (PAHs), which are ubiquitous in the interstellar medium, are also expected to be present in comets (see the review by Li 2009 and references therein). The identification of cometary PAHs from remote sensing, using near-ultraviolet or near-infrared spectroscopy (from features near 3.4, 6, 8, and 12 μm) is subject to debate. More compelling evidence of their presence comes from mass

Comet, Table 3 The relative compositions of interstellar and cometary ices

Species	Interstellar ices in high-mass YSO ^a	Interstellar ices in low-mass YSO ^b	Cometary volatiles ^c
H ₂ O	100	100	100
CO	9–16	6–25	1.7–23
CO ₂	14–20	15–22	6
CH ₄	2	<1.6	0.6
C ₂ H ₆	<0.4	–	0.6
CH ₃ OH	5–22	<4	0.9–6.2
H ₂ CO	1.7–7	–	0.13–1.3
HCOOH	0.4–3	–	0.09
NH ₃	13–15	<9	0.7
X-CN	1–3	<0.4	0.08–0.25
OCS, XCS	0.05–0.3	<0.08	0.4

From Despois and Cottin (2005)

^aHigh-mass Young Stellar Objects such as W33A and N753S

^bLow-mass Young Stellar Objects such as Elias 16 and Elias 26 (a category to which the protosun belonged)

^cFrom Table 2 and Fig. 2

Ground-based observations, confirmed by the results from the ► [Stardust and Rosetta missions](#), have shown that cometary matter includes ices as well as crystalline and amorphous silicates, originating from the cold and hot regions of the solar nebula. This points to an important turbulent mixing of the nebula. Thus, cometary silicates differ from interstellar silicates which are rather in the amorphous state. Cometary refractory grains could have both an interstellar and a nebular origin (Wooden 2008; A'Hearn 2011).

Comets and the Origin of Life

The possible role of comets as a vector for ► [panspermia](#) was advocated in several papers, especially by Hoyle and Wickramasinghe (e.g., 1981). The objections raised to this hypothesis are the hostile radiation environment and the easy destruction of organic material following the impact on Earth.

Could liquid water exist in comets, favoring the development of life in these bodies? As was suggested by Irvine et al. (1980) and studied in detail by Podolak and Prialnik (2006), a significant pressure together with a heating source is needed for this to be possible. The latter could be provided internally by ²⁶Al radioactivity or by amorphous crystalline water ice transition. However, this would only be imaginable inside huge cometary nuclei (>100 km) or large KBOs.

The hypothesized delivery of organic molecules to the Earth by the infall of small Solar System bodies was prompted by the discovery of carbonaceous matter in meteorites in the nineteenth century. The role of comets was pointed out by Chamberlin and Chamberlin (1908) and by Oró (1961). The important content of prebiotic molecules in cometary matter, which is now confirmed, brings a renewed interest in comets for elucidating the origin of life on Earth (Despois and Cottin 2005; Thomas et al. 2006).

Basic Methodology

Comets are usually observed from ground observatories, in wavelengths ranging from UV to radio domains. Most of the detections related to the composition of the coma have been achieved from the Earth. However, since the nucleus cannot be observed when the comet is active and surrounded by its coma, space missions are the only means to observe the nucleus and study the processes that govern the formation of the coma.

Future Directions

An inescapable further step for the study of comets will be to return to Earth a sample directly

taken from a comet nucleus. The challenge is to cool the sample to preserve cometary ices. Such missions are currently under study but are not yet firmly scheduled.

Short-period comets, which have predicted returns, are presently the only practicable targets. Flybys at low velocity and rendezvous are only possible for ecliptic (Jupiter-family) comets, due to energy limitations. Up to now, the only comet not belonging to the Jupiter family that was explored was 1P/Halley; this was done with a very high flyby velocity (about 70 km/s).

Although in situ cometary explorations are invaluable, they were (and will probably be for a long time) restricted to a very small number of targets. Thus, a study of the comet diversity, which needs a statistical approach, can only be achieved with remote-sensing long-term observing programs.

Cross-References

- [Carbonaceous Chondrite](#)
- [Centaur \(Asteroids\)](#)
- [Comet \(Nucleus\)](#)
- [Comet Halley](#)
- [Daughter Molecule, Comet](#)
- [Deep Impact](#)
- [Fluorescence](#)
- [Giotto Spacecraft](#)
- [Kuiper Belt](#)
- [Meteorites](#)
- [Molecular Cloud](#)
- [Oort Cloud](#)
- [Panspermia](#)
- [Parent Molecule, Comet](#)
- [Rosetta Spacecraft](#)
- [Stardust Mission](#)
- [Vega 1 and 2 Spacecraft](#)

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COMET (Experiment)

Michel Viso

Innovaxiom, Paris, CX, France

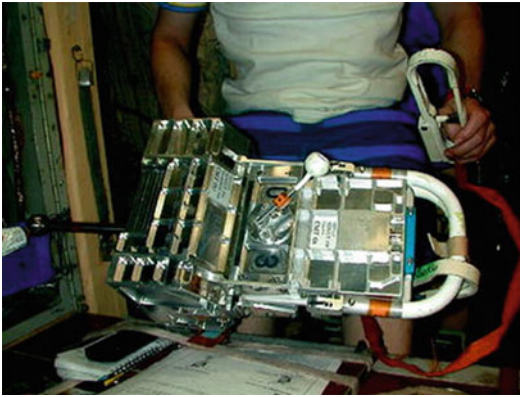
Synonyms

[Collection en Orbite de Matériel Extra Terrestre; European Space Exposure Facility \(ESEF\)](#)

Definition

The experiment “COMET” flew actually three times on board Soviet then Russian space stations. These experiments placed in 1985 (COMET-1), 1995 (European Space Exposure Facility), and 1999 (COMET-99) (Fig. 1) outside the stations aimed to collect interplanetary dust. This material is composed of grains with a size distribution dominated by particles in the micron range. Very long collection times are required to collect some grains with a reasonable size (10 μm or more). For instance, the experiment, Orbital Debris Collection Experiment (ODCE) sponsored by [NASA](#), was flown outside the MIR space station and collected for 18 months starting in March 1996.

Alternatively, during the crossing by the Earth of meteor streams, where the fluency can be enhanced by more than one order of magnitude, short collection times can be performed. Such collections were the aim of the COMET experiments and specially for COMET-99 performed outside the MIR station during the CNES-sponsored Perseus mission. It targeted



COMET (Experiment), Fig. 1 The COMET hardware before being placed outside the MIR space station. (Photo RKA/CNES)

more specifically the collection of grains from the swarm of Leonids originated from the Tempel-Tuttle comet.

The various collectors made of ultrapure metallic foil or aerogel, a transparent silicon dioxide material of very low density ($\sim 0.06 \text{ g/cm}^3$), came back to Earth by the end of the mission. On the metallic collectors, the incident particles sublime upon impact, leaving a crater, on the rims of which remnants of the particles can be found. The aerogel collectors are designed to avoid destroying the particles while impacting the surface. Penetrating inside the aerogel, they slow down and are trapped with little alteration. The metallic collectors show a very high density of large craters, due to particles larger than $20 \mu\text{m}$ attributed to the Leonid swarm. Chemical identification was possible in one case, the EDS spectrum showing identification of Mg, Si, Ca, and Fe.

Optical scanning of the aerogel collectors locates grains as small as a few microns and reveals their penetration track. In one of the two aerogel collectors of COMET-99, two populations of grains, with a mean diameter around $5 \mu\text{m}$, have been found, with penetration tracks in two main directions. A dozen of these grains have been extracted.

The experience gained during these experiments was used preparing for the ► [Stardust mission](#).

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Comet (Nucleus)

Jacques Crovisier

LESIA, Observatoire de Paris, Meudon, France

Keywords

Small body

Definition

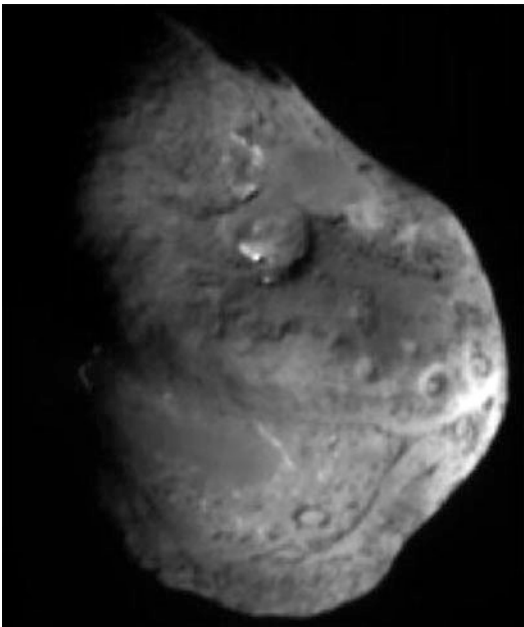
A cometary nucleus is the small-size (typically a few kilometers in diameter) solid body in the head of a comet whose activity provides the source of the comet's appearance.

Overview

With typical sizes from about 1 km to about 50 km (as for the giant comet C/1995 O1 (Hale-Bopp)), cometary nuclei are too small to be imaged by Earth-based telescopes. This can only be done with space probes that encounter or flyby these objects at small distances. This has been possible up to now only for a restricted number of objects. These observations confirmed that cometary nuclei are really solid bodies (Fig. 1 and Table 1).

The unresolved comet nucleus can be observed when the comet is far from the Sun and inactive or when the instrumental resolution allows us to separate the nucleus emission from that of the dust coma. It is then possible to evaluate the nucleus size and to investigate its rotation, using the same methods as those used for asteroids (Lamy et al. 2004). Radar studies are also possible for the nucleus of comets coming close to the Earth (Harmon et al. 2004).

Cometary nuclei are very dark, with ► **albedos** in the range 0.02–0.06, which makes them the darkest objects of the Solar System. Rotation



Comet (Nucleus), Fig. 1 The nucleus of 9P/Tempel 1 as seen by the Deep Impact probe. The nucleus average diameter is 6 km. (© NASA/JPL-Caltech/UMD)

periods range from a few hours to a few days. Some nuclei seem to be in an excited state of rotation (e.g., they are tumbling rather than rotating around a fixed axis).

The density of comet nuclei has long been an open issue due to the difficulty to estimate the nucleus mass. Indirect evaluations were performed using the effect of nongravitational forces, caused by nucleus outgassing, on cometary orbits (Weissman et al. 2004). They all point to small densities with a large error bar, in the range 0.5–1.2 g cm^{−3}. For comet 9P/Tempel 1 an evaluation was made from the trajectories of the ejecta following the Deep Impact experiment, leading to a density of about 0.35 g cm^{−3}. A precise evaluation comes from the measurement of the trajectory perturbation of a space probe in the small gravity field of the cometary nucleus. This could be performed by Rosetta for comet 67P/Churyumov–Gerasimenko. Its bulk density is 0.54 g cm^{−3} (Pätzold et al. 2019), confirming that cometary nuclei are indeed porous bodies.

Comet nuclei are frequently observed to split, showing that they are bodies with weak tensile strength, such as rubble piles.

Comet (Nucleus), Table 1 Space missions which were able to image cometary nuclei

Mission	Space agency	Launch date	Target	Encounter date	(a) (km)	(b) (km/s)
VEGA 1	IKI	15 December 1984	1P/Halley	6 March 1986 (flyby)	8890	79
VEGA 2	IKI	21 December 1984	1P/Halley	9 March 1986 (flyby)	8030	77
Giotto	ESA	2 July 1985	1P/Halley	14 March 1986 (flyby)	596	68
Deep Space 1	NASA	24 October 1998	19P/Borrelly	22 September 2001 (flyby)	2170	17
Stardust	NASA	7 February 1999	81p/Wild 2	2 January 2004 (flyby)	237	6
NeXT	”	”	9P/Tempel 1	14 February 2011 (flyby)	178	11
Rosetta	ESA	2 March 2004	67P/CG	2014–2016 (orb./land.)		
Deep Impact	NASA	12 January 2005	9P/Tempel 1	4 July 2005 (flyby/impact)	500	10
EPOXI	”	”	103P/Hartley 2	4 November 2010 (flyby)	700	12

For flybys are listed (a) the closest distance to the target and (b) the relative velocity. 67P/CG: Churyumov–Gerasimenko

See the ► [“Comet”](#) entry for a discussion of composition and other details on comet nuclei.

Cross-References

- [Albedo](#)
- [Comet](#)
- [Deep Impact](#)
- [EPOXI Mission](#)
- [Giotto Spacecraft](#)
- [Rosetta Spacecraft](#)
- [Stardust Mission](#)
- [Vega 1 and 2 Spacecraft](#)

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Comet Borrelly

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Comet 19/P Borrelly is a short-period comet, discovered in 1904. Its orbital period is 6.8 years. Its semimajor axis is 3.49 AU, and the aphelion and perihelion distances to the Sun are 5.83 and 1.35 AU, respectively. Comet Borrelly was visited on September 22, 2001, by the spacecraft Deep Space 1 that approached the comet at a distance of about 2200 km. The spacecraft returned high-quality images of the comet nucleus, revealing the presence of several jets. The comet is $8 \times 4 \times 4$ km in size, and its density is estimated as 0.3 g/cm^3 . Its albedo is 0.03, a typical value for comets.

Cross-References

- [Comets, History of](#)

Comet Encke

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

► [Comet](#) 2P/Encke was named after Johannes Encke who, in 1821, calculated its orbit on the basis of previous measurements made by Pons in 1818. He predicted its return in 1821 with an accuracy of 1 day. In 1823, he identified that comet Encke had already appeared in 1786, 1795, and 1805. Comet Encke was thus the second known periodic comet. Its period (3.3 years)

is the shortest reported until today. Its perihelion is 0.33 AU. After over 60 passages since its first discovery, comet Encke appears as a weak object that has lost most of its gas and dust.

Cross-References

► [Comet](#)

Comet Giacobini-Zinner

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

► [Comet](#) 21P/Giacobini-Zinner, discovered independently by Michel Giacobini in 1900 and Ernst Zinner in 1913, is a Jupiter-family comet with a period of 6.6 years; its perihelion is at 1.0 AU and its aphelion is at 6.0 AU. In September 1985, the comet was visited by the spacecraft ISEE 3, renamed International Cometary Explorer (ICE), which flew by the comet at a distance of 7,800 km. The spacecraft detected a shock front when the ionized cometary species came in contact with the solar wind. Six months before the encounter of comet Halley by five spacecraft, 21P/Giacobini-Zinner was the first comet to be investigated by a space mission.

Cross-References

► [Comet](#)

Comet Hale-Bopp

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Keywords

Comet

Definition

Comet C/1995 O1 (Hale-Bopp) was discovered simultaneously by Alan Hale and Thomas Bopp on July 23, 1995, at 7.1 AU from the Sun. It was soon realized that the comet, 100 times brighter than Halley at the same heliocentric distance, was abnormally big. Its 2,400-year period brought it to perihelion on April 1, 1997, at a distance of 0.91 AU from the Sun. It was a naked-eye object for over 2 months. As all long-period ► [comets](#), comet Hale-Bopp is an ► [Oort cloud](#) comet, one of the greatest of the twentieth century. Thanks to its early discovery and its exceptional size, comet Hale-Bopp is among the few objects which have allowed a major advance in our understanding of cometary physics.

Overview

A large international observing campaign was devoted to the comet in 1996 and 1997, using ground-based and space observatories at all wavelengths, from the X-ray to the radio range. Visible cameras (in particular aboard the Hubble Space Telescope) were used to determine the coma structure and the nucleus size and rotation. ► [Parent molecules](#) were mostly studied from infrared, millimeter, and submillimeter spectroscopy, including space observations from the Earth-orbiting Infrared Space Observatory (ISO).

With a diameter of 40–80 km, the nucleus of comet Hale-Bopp is the largest cometary nucleus ever measured. Its rotation period, determined from the evolution of the jets, is 11.4 h, a typical value for cometary nuclei. In addition to the dust and plasma tails usually visible on comets, a thin sodium-atom tail, observed in the visible range, was detected for the first time (Fig. 1).

Many parent molecules were detected through infrared and millimeter spectroscopy. In addition to previously detected species (H_2O , CO, CO_2 , CH_3OH , H_2CO , HCN, H_2S , NH_3 , HNC, CH_3CN , HNC, and OCS), new molecules were found in the radio range: HCOOH , CH_3CHO , HCOOCH_3 , NH_2CHO , HC_3N , H_2CS , SO, SO_2 , and NS. The detection of HDO in the



Comet Hale–Bopp, Fig. 1 Comet Hale–Bopp, observed from Earth during its 1997 passage. (© M. Jourdain de Muizon 1997)

submillimeter range, in complement with the estimate of H_2O inferred from the radio monitoring, led to the determination of D/H. As for comets Halley and Hyakutake, the D/H was found to be 3×10^{-4} , i.e., twice its value in the terrestrial oceans; this result is important as it leads to the conclusion that only a minor fraction of water on Earth probably has a cometary origin. Ground-based observations in the near-infrared range led to the detection of H_2O , CO, CH_4 , C_2H_2 , C_2H_6 , OCS, NH_3 , as well as several radicals.

Another important result is the determination of the nature of the cometary dust, inferred from ► [Infrared Space Observatory](#) measurements. In addition to already known silicate signatures, the spectrum of Hale–Bopp, recorded over the whole infrared range, exhibited specific signatures which were attributed to forsterite, a magnesium-rich olivine (Mg_2SiO_4). This spectrum is remarkably similar to those of dust disks surrounding young or evolved stars, showing a close similarity between interstellar and cometary dust.

Cross-References

- [Comet](#)
- [Oort Cloud](#)
- [Parent Molecule, Comet](#)

Comet Halley

Therese Encrenaz¹ and Hervé Cottin²

¹Observatoire de Paris, PSL Université, CNRS, Sorbonne Université, Université de Paris, Section de Meudon, LESIA, Meudon, France

²Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, Créteil, France

Keywords

Comet

Definition

Known since antiquity, comet Halley is probably the most famous comet in the world. With its 76-year period, it is the only bright and out of the ecliptic plane comet whose trajectory is predictable enough for space exploration to be planned. It is also the comet that allowed the astronomer Edmund Halley to demonstrate the nature and the periodic appearance of these objects: in 1705, on the basis of previous observations, he predicted the comet's return in 1758. The comet's apparition was actually observed in December 1758, 16 years after Halley's death. The apparition of comet Halley was decisive in confirming Newton's laws of universal gravitation.

Overview

Early apparitions of comet Halley go back to antiquity. Its 1066 CE apparition was recorded in the Bayeux tapestry showing King Harold's fear shortly before the Hasting battle and the victory of William the Conqueror. In 1301, the famous Italian painter Giotto di Bondone represented the comet as the Bethlehem star in his fresco "Adoration of the Magi" in Padua.

The 1835 comet Halley apparition led to the first observations of physical phenomena such as gas and dust ejection in the form of jets and fans around the nucleus, represented, in particular, in Bessel's drawings. His "fountain model" gave the first interpretation of the motion of cometary material ejected sunward and being repelled away from the Sun. This was the first confirmation of Laplace's predictions, in 1803, about a frozen nucleus. The next apparition, 1910, was especially favorable in terms of geometrical configuration: photographs and spectra of the comet were recorded, showing emissions from several radicals and ions. At that time, secondary products (coming from the photolysis and ionization of parent molecules), observed in the visible range, were much better known than the parent molecules themselves, which are better probed at infrared and millimeter wavelengths. In 1950, based on the H and OH production rates, the astronomer Fred Whipple proposed his "dirty snowball model," which predicted that the ► [comets](#) are mainly composed of water ice together with minor amounts of dust.

The next apparition, in 1986, was not favorable in terms of geometry: with respect to the Earth, the comet was behind the Sun at the time of perihelion, on February 9, 1986. Ground-based monitoring was thus much more difficult than at the time of the 1910 apparition, and the images of the comet were much less spectacular; the best observations were performed when the geocentric distance of the comet was minimum in November 1985 and in April 1986. Despite the poor observational conditions, the development of new technologies, both for ground-based and space explorations, allowed astronomers to get an

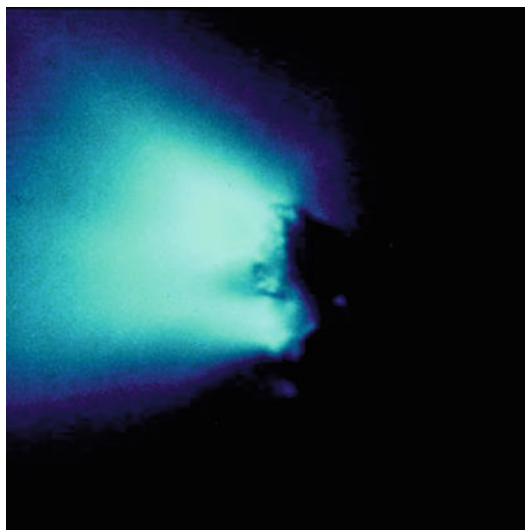
excellent scientific return from this event. The apparition was prepared long in advance by an impressive worldwide observing campaign, including five spacecraft- and ground-based observations at all wavelengths, from the UV to the radio range, coordinated by the "International Halley Watch." The five space missions included the European Giotto mission, launched by the ESA, the two Vega missions led by the Soviet Union, and two Japanese spacecraft, Suisei and Sakigake. For the first time, images of the nucleus were obtained; in situ measurements of the cometary gas and dust were recorded; and from space and ground-based experiments, parent molecules were actually detected, thanks to the development of infrared spectrometers and millimeter heterodyne spectroscopy.

Comet Halley was recovered in October 1982, at a heliocentric distance of 11 AU, with an angular distance of only 9 arcsec from its predicted position. The observation was made at Mount Palomar Observatory (California, USA), and its recovery illustrated the growing success of ► [CCD](#) cameras in astronomy.

The Nucleus

The first images of a cometary nucleus were those of comet Halley, taken by the Vega 2 and Giotto spacecraft in 1986. They were surprising at least in two aspects: the nucleus had an elongated shape, with dimensions of $15 \times 8 \times 7$ km in size, and its mean albedo was very low (0.04). The nucleus surface was mostly covered with dark material, probably due to a carbonaceous deposit, with a surface temperature as high as 300 K; water vapor, together with dust, was outgassed through a few discrete active areas, at temperatures of about 200–220 K (Fig. 1).

The presence of carbonaceous material at the nucleus' surface was also inferred by another discovery. The mass spectrometers of the Giotto and Vega spacecraft detected unexpectedly large abundances of light elements (H, C, N, O), especially in dust particles rich under the form of complex organic compounds. This result was independently derived from the analysis of the near-infrared spectrum of Halley recorded



Comet Halley, Fig. 1 The nucleus of comet Halley, as observed by the camera of the European Giotto mission on March 13, 1986, as the spacecraft flew over the comet at a distance of 500 km. Active areas showing jets of water and dust appear on the object's left side. The dimensions of the nucleus are $15 \times 8 \times 7$ km (© ESA)

by Vega, which revealed a broad emission attributed to both saturated and unsaturated hydrocarbons. Such spectral signatures have been observed under other circumstances in interstellar spectra and also in laboratory spectra of ice mixtures irradiated by solar UV or high-energy particles.

Long-period ground-based photometric monitoring has been used to determine the rotation period of Halley's nucleus. A two-component model has been favored with a slow precession (with a period of at least 7 days) and a 2-day rotation period.

The Coma

As a first result, Whipple's "dirty snowball model" was confirmed. Water, identified by its near-infrared vibration bands, was unambiguously detected, both from the Kuiper Airborne Observatory and from the Vega IKS spectrometer. The relative water content, in number of atoms, was found to be close to 80%. In addition to water and hydrocarbons, other molecules were detected by IKS aboard Vega: CO_2 , H_2CO , and CO were

also detected in the UV range. Hydrogen cyanide HCN was detected for the first time in a comet from ground-based millimeter heterodyne spectroscopy. Some molecules are outgassed from the nucleus, but some also from the dust particles in the coma. This is the case for CO and H_2CO , which density distribution in the coma shows they are released from the dust particles, possibly from the degradation of large macromolecules and polymers (for instance, H_2CO could be released from polyoxymethylene, the polymeric form of H_2CO). Another interesting result was the reported tentative detection, by the UV spectrometer of Vega, of some polycyclic aromatic hydrocarbons (PAHs), probably naphthalene C_{10}H_8 and phenanthrene $\text{C}_{14}\text{H}_{10}$, in the close vicinity of the nucleus. Similar species have been also identified in interstellar spectra. It is in fact striking to note that all parent molecules found in comet Halley have been also detected in the interstellar medium. These results strongly suggest a link between interstellar and cometary matter.

Radio observations of the OH radical at wavelength of 18 cm were used to monitor the water production of the comet as a function of its heliocentric distance.

An important parameter measured by mass spectroscopy was the D/H ratio inferred from $\text{HDO}/\text{H}_2\text{O}$ in the coma. This ratio is diagnostic of the early conditions of the comet's formation: at low temperatures, the D/H ratio is enriched in ices due to ion-molecule and molecule-molecule reactions. D/H in comet Halley was found to be 3×10^{-4} , i.e., twice its value in the terrestrial oceans. Further observations of comets have shown that this D/H ratio in water can range from terrestrial values in some comets (e.g., comet 103P/Hartley 2) to values even higher than the one measured in comet Halley (e.g., $\text{D}/\text{H} = 5.3 \pm 0.7 \times 10^{-4}$ in comet 67P/Churyumov-Gerasimenko).

Origin and Fate of Comet Halley

As shown by its retrograde orbit, comet Halley is most likely a captured object from the Oort cloud. The [Oort cloud](#) is the reservoir to which many planetesimals were ejected by gravity

perturbations due to the ► [giant planets](#). This explains why, after so many apparitions, comet Halley is still an active body: its long period allowed it to keep a significant fraction of its icy reservoir. At each perihelion passage, the surface of comet Halley is eroded and loses about 1 m depth of ice and dust. In the future, the icy content of comet Halley will slowly decrease.

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Comet](#)
- [Comet \(Nucleus\)](#)
- [Comet Hartley 2](#)
- [Daughter Molecule, Comet](#)
- [Deuterium/Hydrogen Ratio](#)
- [Giotto Spacecraft](#)
- [Parent Molecule, Comet](#)
- [Rosetta Spacecraft](#)
- [Vega 1 and 2 Spacecraft](#)

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Comet Hartley 2

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Comet 103 P/Hartley 2, discovered in 1986, is a Jupiter-family comet with an orbital period of 6.46 years and a semimajor axis of 3.46 AU. Its perihelion distance to the Sun is 1.05 AU, close to Earth's orbit. In 2010, the comet approached the Earth to a distance of 0.12 AU. Radar

observations revealed an elongated shape and measured a rotation period of 18 h. On November 2010, the comet was visited by the ► [Deep Impact](#) spacecraft, renamed Epoxi, after its flyby of comet Tempel 1. Epoxi approached the comet at a distance of 700 km, measured its maximum size (2.25 km), and revealed an unexpected activity. In 2011, the Herschel space observatory measured heavy water HDO in the coma and inferred a D/H ratio close to the terrestrial value. This result suggests that the ocean water might come, at least partly, from Jupiter-family comets.

Cross-References

- [Comet](#)

Comet Hyakutake

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Comet C/1996 B2 Hyakutake was discovered in January 1996 and it approached the Earth in March 1996 to a distance of only 0.10 AU. It passed perihelion in May 1996 at a distance of 0.23 AU. It is a long-period comet (about 9,000 years) which presumably comes from the ► [Oort cloud](#). A campaign of astronomical observations was set up, taking advantage of its proximity to Earth. The comet nucleus is 2–3 km in diameter and its rotation period is 6.3 h. Many parent molecules were detected from infrared and millimeter ground-based spectroscopy (H₂O, CO, CO₂, CH₃OH, H₂CO, HCN, and H₂S).

Cross-References

- [Comet](#)
- [Oort Cloud](#)

Comet Interceptor Mission

Geraint H. Jones¹, Colin Snodgrass², Cecilia Tubiana³ and Michael Küppers⁴

¹Mullard Space Science Laboratory, University College London, Surrey, UK

²University of Edinburgh, Edinburgh, UK

³Istituto di Astrofisica e Planetologia Spaziali – IAPS/INAF, Via del Fosso del Cavaliere, 100, Roma, Italy

⁴European Space Agency (ESA), European Space Astronomy Centre (ESAC), Madrid, Spain

Keywords

Comets · Missions · Small bodies

Definition

Comet Interceptor is a mission designed to characterize a long period comet (LPC), which could potentially be a dynamically new comet (DNC), or an Interstellar Object (IO). This will broaden our understanding of comet morphology, composition, and plasma environment. Most importantly, such a comet would offer a unique new viewpoint along the evolutionary path of comets from their formation to migration into the inner Solar System, as a relatively unprocessed object that will have been active for only the past few years or less, rather than a returning comet that has experienced many close approaches to the Sun.

History

The Comet Interceptor mission was selected by ESA in June 2019 as ESA's new fast-class mission in its Cosmic Vision Programme. The mission was formally adopted by ESA in June 2022.

Overview

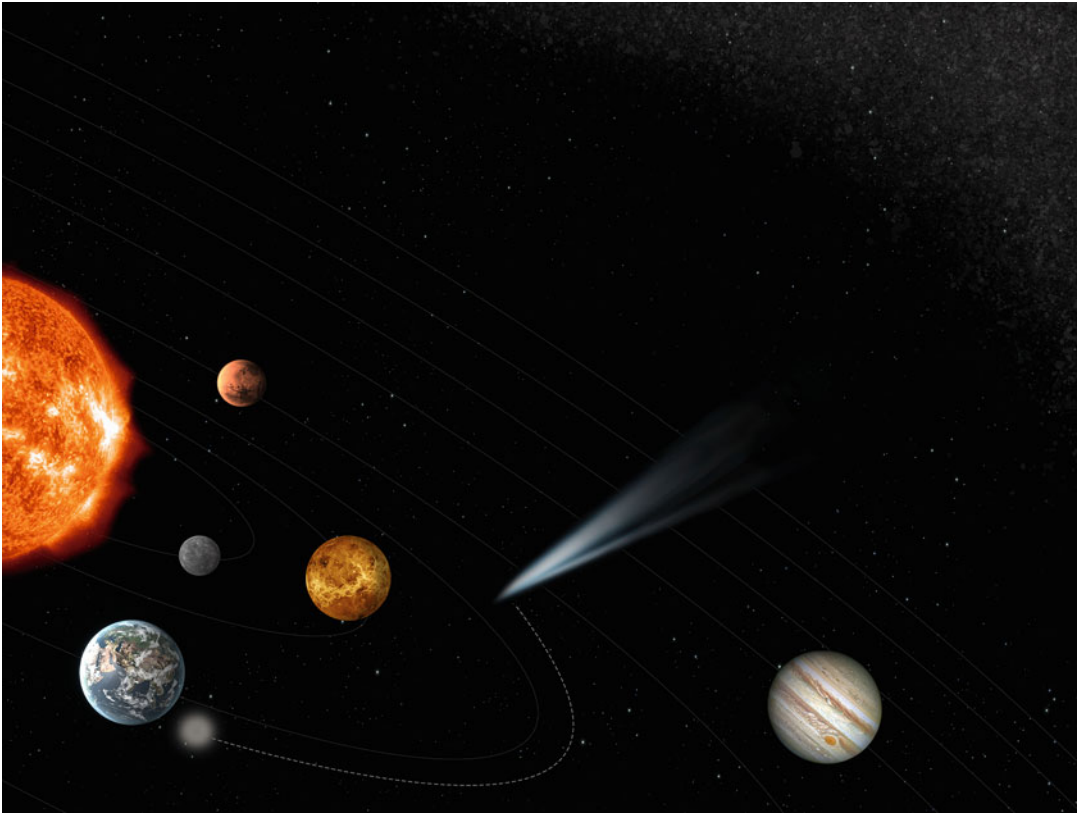
Comet Interceptor is planned to be launched with the ESA ARIEL spacecraft in 2029 and delivered to the Sun-Earth Lagrange Point L2. It will be a

multielement spacecraft comprising a primary platform which also acts as the communications hub and two probes, one from ESA and one from JAXA, allowing multipoint observations around the target. All spacecraft will be solar powered. The spacecraft and probes will remain connected to each other at L2, where they will reside until directed to their target. The mission cruise phase will last months to years. Before the encounter, the spacecraft will detach into its separate elements, probably a few days preflyby. For very active comets, separation will be earlier, to maximize separation of the spacecraft elements, while for low activity targets, separation will occur only a few hours before the encounter takes place.

Comet Interceptor's main spacecraft and two probes will be equipped with a complementary science payload, providing different perspectives of the comet's nucleus and its gas, dust, and plasma environment. Such "multipoint" measurements will greatly improve the 3D information needed to understand the dynamic nature of a pristine comet while it is interacting with the constantly changing solar wind environment.

Previous comet missions, including ESA's pioneering spacecraft Giotto and Rosetta, encountered short-period comets. These are comets with orbital periods of less than 200 years that have approached the Sun many times along their orbits in relatively recent times and as a consequence have undergone significant changes: e.g. Rosetta's comet, 67P/Churyumov-Gerasimenko orbits the Sun once every 6.5 years while Comet 1P/Halley, visited by Giotto and other spacecraft in 1986, returns to our skies every 76 years.

Comet Interceptor is different because it will target a comet visiting the inner Solar System for the first time – perhaps from the vast Oort cloud that is thought to surround the outer reaches of the Sun's realm. As such, the comet will contain material that has not undergone much processing since the dawn of the Solar System. The mission will therefore offer a new insight into the evolution of comets as they migrate inwards from the periphery of the Solar System.



Comet Interceptor Mission, Fig. 1 Comet Interceptor has been selected as ESA's new fast-class mission. It will be the first spacecraft to visit a truly pristine comet or other

interstellar object that is only just starting its journey into the inner Solar System.

The only way to encounter dynamically new comets or interstellar objects is to discover them inbound with enough warning to direct a spacecraft to them. The time between their discovery, perihelion, and departure from the inner Solar System has until recently been very short, historically months to a year: far too little time to prepare and launch a spacecraft. This timescale is, however, lengthening rapidly, with recent advances allowing observational surveys to cover the sky more deeply, coherently, and rapidly, such as the current Pan-STARRS and ATLAS surveys, and the **Vera C. Rubin Legacy Survey of Space and Time (LSST)** under construction in Chile (www.lsst.org).]

Cross-References

- [Comets, History of](#)
- [European Space Agency](#)
- [Comet](#)
- [Comet \(Nucleus\)](#)
- [Oort Cloud](#)
- [Rosetta Spacecraft](#)

References and Further Reading

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Comet Mc Naught

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Over 50 comets have been discovered by Robert H. McNaught since 1987. Comet C/2006 P1 McNaught is a special comet which crossed perihelion at 0.17 AU from the Sun in December 2006 and became, in January 2007, the brightest and largest comet observed from Earth for 40 years. Infrared observations from Earth led to the identification of a large number of parent molecules. The unusually large size of the ionized comet's tail was explored as the Ulysses spacecraft passed through it in 2007. The comet is a dynamically active ► [Oort cloud](#) comet, and its material is expected to be pristine, reflecting early conditions of the solar system's history.

Cross-References

► [Comet](#)

Comet Shoemaker-Levy 9

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Keywords

Comets

Definition

Comet Shoemaker-Levy 9 (SL9) was discovered in March 1993 by Eugene and Carolyn Shoemaker and by David Levy. At that time, it

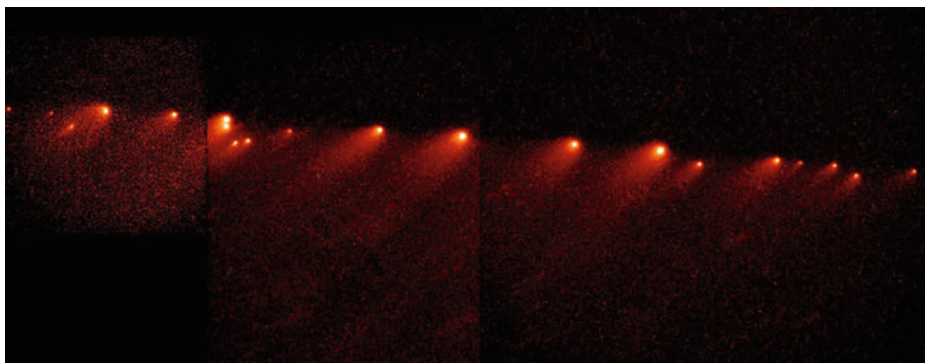
appeared as a trail of about 20 fragments. The study of their trajectories showed that it was a Jupiter-family comet which was disrupted by tidal forces at its previous closest (perijove) passage, in July 1992. It was soon predicted that the fragments would collide with ► [Jupiter](#) at its next closest passage, in July 1994 (Fig. 1).

Overview

A collision of a comet with Jupiter is very rare: according to dynamical models, it could be expected only once every few centuries. Actually, a similar event was reported by ► [Cassini](#) at the end of the seventeenth century. As a consequence, at the time of the SL9 collision, a huge international campaign took place in order to monitor the event using all possible ground-based and space means, covering the whole spectral range, from the X-ray to the radio range. Among the spacecraft were the Galileo spacecraft (en route to Jupiter for an approach in 1995), the Hubble Space Observatory (HST), the International Ultraviolet Explorer (IUE), and the X-ray satellite ROSAT. Among the objectives were the determination of the impact altitude, the temperature rise and decay, the monitoring of the impact craters, and the search for new molecules formed by shock chemistry.

The fragments of SL9 entered the Jovian atmosphere at a latitude of 44° south (44S). Between July 16 and July 22, 1994, the impacts spread along the 44S parallel as the planet was rotating; the collisional events took place within a few minutes of the predicted impact times. As seen from Earth, the impacts took place just behind the limb and came to direct view only about 10 min later. The Galileo spacecraft, still at a distance of 1.6 AU from Jupiter, was the only observatory which could see the whole event in direct view.

The successive events were recorded with three types of data: light curves, images, and spectra. Light curves, measuring the brightness versus time at different wavelengths, allowed astronomers to determine the temperature evolution and



Comet Shoemaker-Levy 9, Fig. 1 Image of the comet Shoemaker-Levy 9 before its impact with Jupiter (© NASA)

gave an estimate of the energy budget. Images, taken from Galileo, the HST, and ground-based telescopes, recorded the meteor (cometary fragment) entry (Galileo), the ejecta trajectories (limb images from the HST), and the crater evolution (HST and ground-based telescopes). Spectra, recorded in the UV (IUE, HST), the visible, infrared, and radio range, have detected new molecular species and monitored their evolution.

Temporal Sequence of the Impacts

The collisions of each individual fragment were remarkably similar, although of different intensities, depending on the impactor size. In all cases, the light curves showed a sequence of three phases:

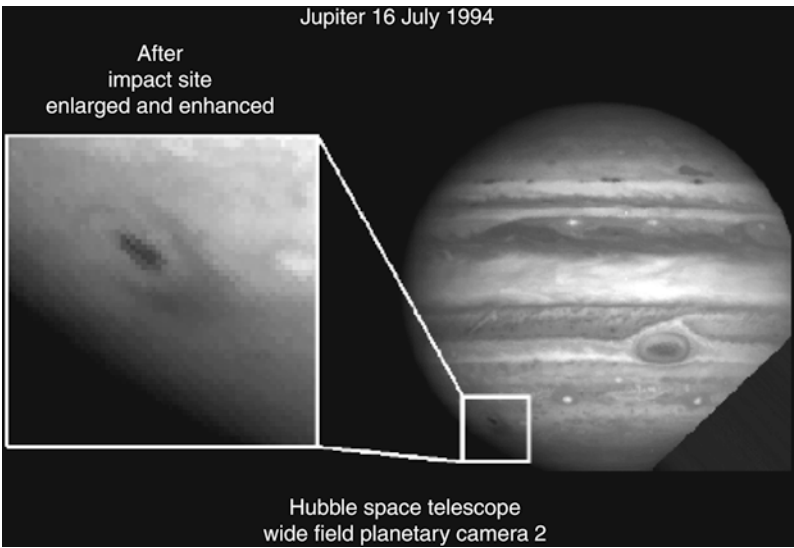
- The entry phase was observed as a flash by the camera and the photometer of the Galileo spacecraft.
- The explosion phase occurred 1 min later; it corresponded to the explosion of the impactor within the atmosphere and to the ascent of a fireball; HST images taken at Jupiter's limb showed ejecta up to an altitude of 3,000 km for all fragments (the smaller exploding at a higher altitude than the larger ones). The fireball increased in size adiabatically from 15 km, 10 s after the impact, to 100 km after 40 s. Explosions took place at a pressure level ranging between 0.1 and 1 bar. For the largest impacts, the temperature was over 10,000 K at the early beginning and decreased to 2,000 K after about 15 s.
- The “splash phase” was studied from the light curves, the images, and the evolution of the spectra. In particular, the monitoring of methane emissions in the near-infrared range showed a decrease of the temperature from 1,000 K at $t = 10$ min to 600 K at $t = 25$ min. HST images showed the formation of dark craters surrounded by crescent-shaped areas resulting from infalling ejecta, indicating the formation of dust, possibly including carbonaceous and silicate material (Fig. 2).

New Molecules

Several species new to Jupiter have been detected in the stratosphere during the splash phase:

- The most abundant was CO, detected both in the infrared and in the millimeter range. In particular, infrared spectra of CO showed a high excitation temperature of a few thousand K at the beginning of the splash phase.
- Water was detected in the near infrared by the (NIMS) Near Infrared Mapping Spectrometer instrument aboard Galileo and by the Kuiper Airborne Observatory, with an excitation temperature of 1,000 K.
- Sulfur species were identified by the UV spectrometer of the HST: S₂, CS₂, CS, and possibly H₂S.
- From mid-infrared spectra (10–13 μ m), NH₃, HCN, and C₂H₄ were identified.
- Ground-based millimeter heterodyne spectroscopy allowed the detection and long-term monitoring of CO, CS, OCS, and HCN.

Comet Shoemaker-Levy 9, Fig. 2 One of the first impact sites of the SL9 collision as observed by the HST. All impacts occurred at latitude 44S. The enlargement on the *left* side shows the crescent-shaped structure surrounding the main impact crater in the atmosphere (© NASA)



Comet Shoemaker-Levy 9, Table 1 New molecules formed in Jupiter atmosphere by shock chemistry

Molecule	Observations	Molecular mass in SL9 impact (g)	Elemental mass in SL9 impact	Elemental mass in a 10 ¹⁵ g fragment (comet)
H ₂ O	IR, (radio)	>2 × 10 ¹²	>1.5 × 10 ¹⁴ [O]	5 × 10 ¹⁴ [O]
CO	(IR), radio	2.5 × 10 ¹⁴		
NH ₃	(UV), IR	1 × 10 ¹³	1 × 10 ¹³ [N]	2 × 10 ¹³ [N]
HCN	IR, radio	6 × 10 ¹¹		
S ₂	UV	1.5 × 10 ¹²		
CS ₂	UV	1.5 × 10 ¹¹		
CS	(UV), radio	5 × 10 ¹¹	5 × 10 ¹² [S]	4 × 10 ¹³ [S]
H ₂ S	UV	Marginal		
OCS	Radio	3 × 10 ¹²	1 × 10 ¹⁴ [C]	2 × 10 ¹⁴ [C]
Silicate	IR	6 × 10 ¹²	8 × 10 ¹³ [Si] 4 × 10 ¹³ [Mg]	1 × 10 ¹⁴ [Si] 4 × 10 ¹³ [Mg]

The relative abundances of the newly formed species are indicated in Table 1.

Long-Term Evolution of Impact Phenomena

The new molecules formed by shock chemistry had very contrasting lifetimes. Water was the first molecule to disappear, after a few hours. Still, the water from the SL9 collision is believed to be at least partly responsible for the traces of stratospheric water discovered in 1997 by the Infrared Space Observatory and later observed by other submillimeter satellites. OCS, NH₃, and S₂ were detected during a few weeks. CO and CS₂ were observed during several months, and HCS and

CN were detectable over several years. The observed lifetimes were found to be in good overall agreement with the predictions inferred from photochemical models.

The dust observed in the impact craters could be monitored during the weeks and months following the collision. The clouds first extended in longitude as an effect of Jupiter’s fast rotation and, after a couple of weeks, formed a continuous band at latitude 44S. During about a year, the clouds extended in latitude between 20S and 80S. Aerosols, first formed in the stratosphere, moved downward, contributing to the atmospheric profile cooling, to reach tropospheric levels after about a year.

Magnetospheric Effects

The Jovian ► [magnetosphere](#) was also affected by the collision. The synchrotron radiation, monitored at centimeter wavelengths, showed an enhancement of a few tens of percent during the week of impacts. The emission was mostly observed at localized longitudes, between 100 and 240°, showing evidence for a new population of excited electrons. This region correlates with the side where the magnetic field lines cross the radiation belts, intercepting the disk of Jupiter around latitude 44S.

Auroral phenomena were also recorded, in some cases, prior to the impacts, implying a strong heating of the upper stratosphere, in particular UV emissions of H and H₂, and H₃⁺ in the infrared. Often, auroral emissions were detected at the location of the northern counterparts of the impact sites, corresponding to the footprints of the connecting magnetic field lines: X-ray emissions were recorded by the ROSAT satellite at the time of two impacts; UV emissions were observed by the HST; and H₃⁺ near-IR emissions were detected from the terrestrial ground-based facilities.

About the SL9 Comet

All astrometric measurements performed before and during the collision were used to retrieve the best orbital fits ever obtained for a comet. The progenitor of comet SL9 had been captured by Jupiter nearly in the year 1930. Before its capture, the comet's orbit was probably within Jupiter's orbit, with a low eccentricity and a low inclination.

From the disruption of the comet's nucleus in 1992, its tensile strength was inferred. The very low value, 100 Pa, is consistent with a fluffy aggregate of submicron particles. Models of the swarm elongation are consistent with a progenitor of 1.5 km in size, with a density of 0.5 g/cm³. These numbers are consistent with the estimates inferred for the impactors on the basis of the impact dynamical models. The comet's activity was measured in 1993 and 1994 before the impact. Very low dust production rates were estimated (1–5 kg/s for the different impacts). No gaseous activity was

detected; an upper limit of 10²⁷ mol/s was retrieved for the OH production rate.

Information about the comet's composition was obtained from visible spectra taken during some impacts that showed a variety of atomic lines (Fe, K, Ca, H, Na, Mg, Mn, Cr, and for the first time, Li). UV spectra taken by the HST also showed atomic and ionic transitions: H, He, S, Si, Mg⁺, Fe⁺, Si⁺, and Al⁺. All these species, absent from Jupiter's spectrum, belong to the impactor; they are frequently observed in the spectra of sun-grazing ► [comets](#).

The composition of SL9 is difficult to retrieve from the new molecules formed during the impacts because they result from a recombination of products partly possibly having a planetary origin. Still, the oxygen and sulfur-bearing molecules, absent from Jupiter's stratosphere, can be used to infer the O and S content of the impactor. The inferred O/S is consistent with cometary values. The carbon content of the impactor cannot be inferred as the new molecules may have been formed from Jovian methane. Assuming that all the nitrogen of the new molecules is coming from the impactor, the inferred N/O ratio is consistent with a cometary origin. The Si/O ratio inferred from the silicate signature at 10 μm is also in agreement with typical cometary values. In conclusion, several facts support a cometary rather than asteroidal origin for the impactor: the small size, the weak but real level of activity, the low density, the very low tensile strength, the chemical composition, and the presence of silicates. Comet SL9 was actually a very small and very common Jupiter-family comet.

In summary, the collision of comet SL9 with Jupiter has not allowed astronomers to fully understand the nature and the composition of the comet; however, it provided a real-time observation of the response of a planetary atmosphere to a large meteoritic impact.

Cross-References

- [Comet](#)
- [Jupiter](#)

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Comet Shower

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

A comet shower is a short-lived burst in the flux of comets entering the inner Solar System from the ► [Oort cloud](#). Comet showers are thought to be triggered primarily by relatively close passages of nearby stars with the Solar System. Comet showers are not considered an impact threat on Earth.

Cross-References

► [Oort Cloud](#)

Comet Tempel 1

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Comet 9/P Tempel 1 was discovered in 1867 at the Observatoire de Marseille by the astronomer Ernst

Wilhelm Tempel. Its orbit, very close to the ► [ecliptic](#), has a period of 5.5 years around the Sun and lies between the orbits of Mars and Jupiter. The diameter of the comet is 6.5 km and its rotation period is 41 h. Comet Tempel 1 has been explored in detail by the NASA probe ► [Deep Impact](#) which sent an impactor to its surface on July 4, 2005. The impact led to the formation of a 30-m large crater and the massive ejection of dust, water, and HCN. Following the success of another cometary mission, the ► [Stardust](#) encounter of comet Wild 2 in 2004, NASA decided in 2007 to reorient the Deep Impact spacecraft for a new flyby of comet Tempel 1. The flyby successfully took place on February 15, 2011, with a closest approach of less than 200 km, and the spacecraft recorded several tens of images of the surface, including the impact crater site.

Cross-References

► [Comet](#)

Comet Wild 2

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

► [Comet](#) 81 P/Wild, also named Wild 2, was discovered in 1978. After a passage close to Jupiter in 1974, its orbit moved toward the inner solar system, with a high ellipticity and a short period (6.4 years). Its perihelion is close to 1 AU. In January 2004, comet Wild 2 was approached by the Stardust spacecraft which collected cometary grains from its tail and brought them back to Earth in 2006. This cometary matter included material originating from different regions of the solar system before being incorporated into the comet nucleus. The presence of glycine, the simplest amino acid, has been reported in the cometary

samples. Comet Wild 2 is the only comet for which samples have been brought back to Earth and analyzed.

Cross-References

- [Comet](#)
- [Stardust Mission](#)

Comets, History of

Stéphane Le Gars

Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Astronomy · Comets · Gravitation · Halley ·
History · Meteorites · Oort · Physics

History

Since ancient times, ► [comets](#) have raised questions and polemics. Visual observations of comets date back to the eleventh century BCE, when Chinese chronicles related a cometary apparition to war between two kings. There are many references in classical literature, including Pliny's report of a comet during the Battle of Salamis (480 BCE). During the Middle Ages in Europe, comets were seen as portents, of the Norman conquest of England in 1066 in the Bayeux Tapestry and of the birth of Jesus as depicted by Giotto in 1304. The New World also linked comets and important events, including that observed by the Aztec emperor Moctezuma, prior to the conquest of Mexico by Cortes. If the Chaldean considered them as planets, some Greek philosophers such as Aristotle situated them in the area between the Earth and the Moon. From the sixteenth century, comets were being studied more systematically. Their movements were described through the constellations; an interest is taken in their tail's orientation with regard to the Sun, and an estimation of their parallax puts them definitely beyond the Moon (the turning point in

the study of comets was made with Tycho Brahe's observations of the parallax of the comet of 1577).

It is since the universal gravitation law, proposed by Newton in 1687 in his *Philosophiae Naturalis Principia Mathematica*, that the astronomer Edmund Halley identified the 1682 comet with those of 1607 and 1531 and predicted its return for 1759: at this moment, it was proved that those celestial bodies were bound, like planets, by gravitation, describing on the other hand elliptical (in that case they are periodical), parabolic, or hyperbolic orbits about the Sun. Then, in the nineteenth century, attention turned to the origin and the composition of those heavenly bodies. Analysis of the spectrum and polarization of light permitted astronomers at this time to identify in the comet's coma (atmosphere; from the Latin word for "hair") and tail both dust and atoms and small molecules (typically photodissociation products). It is only in 1950 that the American astronomer Fred Whipple described the comets as "dirty snowballs," speculating that their nucleus is essentially constituted of watered ice mixed with carbonic ice, silicates, and organic compounds. It is also in 1950 that Dutch astronomer Jan Oort calculated that long-period comets came from a gigantic spherical reservoir, containing thousands of millions of those little bodies, and located them at 1 or 2 light years from the Sun. Starting with the return of Comet Halley in 1986, radio and infrared astronomers have identified many molecular constituents of comets by observing their emission at millimeter wavelengths. In 2006, the Stardust space probe brought back to Earth dust from the Wild-2 comet, out of which analysis led to new knowledge on the solar system.

Cross-References

- [Kuiper Belt](#)
- [Oort Cloud](#)

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Commercial Use of Space

Klara Anna Capova

Department of Anthropology, Durham University, Durham, UK

Synonyms

[Privatization of space](#); [Space tourism](#)

Acronyms

EU	European Union
OECD	Organisation for Economic Co-operation and Development

Overview

The Space Economy is defined by the OECD as the full range of activities and the use of resources that create value and benefits for human beings in the course of exploring, researching, understanding, managing, and utilizing space. The commercial use of space involves currently mostly satellite technologies (navigation, communication), with the prospect of new fields such as recovery of space resources (space mining), space tourism, and other private undertakings.

In 2015, the US Commercial Space Launch Competitiveness Act was signed, encouraging commercial exploration and resource utilization

activities. In 2020, the European Council adopted a set of conclusions related to the key principles for the global space economy. The Council noted the emergence of a highly competitive European space industry and supply chains, which enabled Europe to participate in (and contribute to) the global growth of the space economy. The 2021 Space Economy Report estimated that the consolidated space economy, including both government space investments and commercial space, valued at \$385 billion in 2020, with commercial space revenues totaling over \$310 billion.

With the anticipated growth of the space economy that also includes commercial activities such as private spaceflight (also referred to as space tourism), a number of implications for scientific pursuit have emerged. Of importance to astrobiology is the potential future privatization and commodification of space resources and commercial exploration of celestial bodies. While sites of special scientific, astrobiological, or cultural significance (e.g., rover landing sites on Mars, first-landing sites on the Moon) may need comprehensive protection from commercial use, other locations may also be candidates for both scientific examination and commercial activity. This may lead to potential conflicts of interest between conduct of science and commercial use of space.

The questions of whether astronomical objects are regarded to be exploitable natural resources (Olson 2012) or whether celestial bodies can even be owned (Milligan 2014) are being discussed. Protocols for site evaluation may need to be developed, together with a code of conduct of commercial activities as related to space science, and multilateral agreements for sustainable use of space.

Cross-References

- [Astrobioethics](#)
- [Geoethics](#)

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Common Ancestor

Luis Delaye
Departamento de Ingeniería Genética,
CINVESTAV-Irapuato, Irapuato, Gto, Mexico

Synonyms

[Concestor](#); [Most recent common ancestor](#); [MRCA](#)

Definition

A common ancestor is the ancestral biological entity from which a group of other biological entities have evolved. Examples of biological entities are species, biological structures, or molecular [▶ sequences](#). One of the main ideas of Charles Darwin in *The Origin of Species* (1872) is that species are related by common ancestry, i.e., that species have evolved by divergence from a common ancestral specie. As a result of evolution by divergence from a common ancestor, the phylogenetic relationships among species or other biological entities can be described using a treelike structure. The related concept of most recent common ancestor (MRCA) specifies the least ancient common ancestor.

Cross-References

- ▶ [Cenancestor](#)
- ▶ [Darwin's Conception of the Origins of Life](#)
- ▶ [Endosymbiosis](#)
- ▶ [Evolution, Biological](#)
- ▶ [Homology](#)
- ▶ [Last Universal Common Ancestor](#)
- ▶ [Phylogenetic Tree](#)
- ▶ [Phylogeny](#)
- ▶ [Sequence](#)

Community Genome

- ▶ [Metagenome](#)

Compatible Solute

Josefa Anton
Department of Physiology, Genetics and
Microbiology, University of Alicante, Alicante,
Spain

Keywords

Haloadaptation · Halophile · Halotolerant

Definition

A compatible solute is a substance compatible with the cellular metabolism that accumulates in the cytoplasm to balance external osmotic pressure. This accumulation can be due to either transport from the medium or de novo synthesis and helps maintain turgor pressure, cell volume, and concentration of electrolytes, all needed for cell viability and proliferation.

Overview

Microorganisms cope with osmotic stress (due to high salt, freezing, and/or desiccation) by using

Word range of Entry: approx. 1200 words excl. references, as agreed with the Editors-in-Chief

two different types of strategies. *Archaea* of the order *Halobacteriales*, anaerobic *Bacteria* belonging to the order *Haloanaerobiales*, and some members of the *Bacteroidetes* (i.e., *Salinibacter ruber*) accumulate high concentrations of inorganic ions (mostly potassium) in the cytoplasm. This is known as the “salt-in” strategy and requires the adaptation of the entire intracellular machinery in order to function in this highly saline environment. The second strategy relies on intracellular accumulation, either by uptake or de novo synthesis, of low-molecular-weight organic-compatible solutes (also called osmolytes) to balance the external osmotic pressure. The accumulation of such solutes is very widespread in nature since the cytoplasm of most organisms does not tolerate salt. In addition, this is a very versatile strategy that allows for rapid response to changing environments since organisms can regulate their intracellular concentration according to the surrounding salinity.

Compatible solutes are small organic molecules that act as osmoprotectants, thanks to their ability to stabilize cellular proteins, providing a hydration shell and stabilizing their tertiary structures without interfering in cell metabolism (this is why they are called “compatible”). Indeed, compatible solutes not only provide protection from osmotic stress but some can also act as thermostabilizers, a property that has been exploited for biotechnological purposes.

There is a wide range of compatible solutes, but they can be classified into a few chemical categories (Empadinhas and da Costa 2008), such as amino acids and derivatives (including ectoines and hydroxyectoines), sugars and derivatives, phosphodiesteres, and polyols. Some of them, such as glycine betaine, are universally compatible solutes, while others are restricted to a specific group of microorganisms. For a detailed description of the chemical nature and occurrence of organic-compatible solutes within halophilic and halotolerant organisms, see Roberts (2005).

Recent work indicates that some microorganisms are able to combine the salt-in and compatible solute accumulation strategies depending on the environmental conditions (Deole and Hoff 2020).

Cross-References

- [Halophile](#)
- [Halotolerance](#)

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Complex Organic Molecules

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

In astronomy, complex organic molecules are defined as molecules with several carbon atoms such as benzene or acetic acid. These molecules have been detected in interstellar space using radio telescopes. A gas mixture of methane and nitrogen, for example, yields complex organic compounds upon UV irradiation or exposure to an electric discharge. These are sometimes referred to as ► [tholins](#), and they can be formed abiotically in the atmosphere of ► [Titan](#) (the largest satellite of Saturn).

In chemistry, “complex organic molecules” generally refer to much larger polymer-like molecules such as ► [proteins](#). Proteins are typical complex organic polymers, with well-defined three-dimensional structures, composed of 20 different amino acids. Given the immense possible variety of these polymers, they are indeed “complex.”

Cross-References

- ▶ [HCN Polymer](#)
- ▶ [Insoluble Organic Matter](#)
- ▶ [Protein](#)
- ▶ [Radio Astronomy](#)
- ▶ [Tholins](#)
- ▶ [Titan](#)

Complex Organic Product

- ▶ [Tholins](#)

Complex Organisms

- ▶ [Multicellular Organisms](#)

Complexity

Carlos Gershenson

Instituto de Investigaciones en Matemáticas
Aplicadas y en Sistemas & Centro de Ciencias de
la Complejidad, Universidad Nacional Autónoma
de México, México, CDMX, México

Keywords

Information · Computation · Complex
systems · Interactions · Non-reductionism ·
Scientific paradigm

Definition

There is no single definition of complexity (Edmonds 1999; De Domenico et al. 2019), as it acquires different meanings in different contexts. A general notion is the amount of information required to describe a phenomenon (Prokopenko et al. 2009), but it can also be understood as the length of the shortest program required to compute that description, as the time required to compute that description, as the minimal model to statistically describe a phenomenon, and more.

In general, complexity arises because of relevant interactions between the components of a system.

Overview

The study of complexity and complex systems is so broad and encompasses so many disciplines that it is difficult to define. There are different definitions suitable for different contexts and purposes. Etymologically, complexity comes from the Latin word *plexus*, which means interwoven. A complex system is one in which elements interact in such a way that it is difficult to separate their behavior. In other words, if one element affects the state of another element, the dynamics of the system cannot be *reduced* to the states of the elements, since interactions are relevant for the future state of the system. Interactions generate novel *information* that is not present in initial nor boundary conditions, so prediction is limited. Examples of complex systems include a cell, a brain, a city, the Internet, a market, a crowd, a pandemic, an ecosystem, a biosphere, and an atmosphere. A cell is composed of molecules, but the behavior and properties of a cell cannot be reduced to that of molecules. Their interactions generate constraints and information that is not present in molecules and determine the behavior of the cell.

Some approaches to complexity do not focus on its systemic aspect, but more on its probabilistic or algorithmic aspect. These are related to information theory, for example, how probable is a string of bits, how long is the shortest algorithm that produces a string of bits, what is the shortest time it can take an algorithm to produce a string of bits, or how compressible is a string of bits. Intuitively, in most of these descriptions, complexity represents a balance between order (stability) and chaos (variability) (Kauffman 1993), sometimes also described as criticality.

Since complexity can be found in almost any field, some people question its usefulness, while others defend it as a novel scientific paradigm that complements the traditional reductionist approach (Gershenson and Heylighen 2005; Morin 2006).

Basic Methodology

There have been several methods developed within the study of complexity that have proven to be useful, since they are able to take into account the interactions of the elements of a complex system (Sayama 2015). Tools include network science (Barabási 2016), agent-based modeling, cellular automata, genetic algorithms, and swarm intelligence.

Most of the complexity research is based on computer simulations. On the one hand, complex models tend to involve a large number of elements and/or interactions, which are difficult to handle without computer aid. On the other hand, interactions generate novel and relevant information that is not present in initial or boundary conditions. This makes it difficult to know *a priori* a final state of a system without computing all of its transitions, that is, predictability is limited. A model has to “run” before something definitive can be said about it. This is also known as *computational irreducibility*. Cellular automata provide a clear example of this. Thus, an equation-based approach is in many cases insufficient to explore the properties of a model.

There are many concepts that are related to the study of complexity, such as non-linearity, self-organization, adaptation, chaos, and emergence (De Domenico et al. 2019).

Key Research Findings

The scientific study of complexity has increased the understanding of phenomena in many different fields. Common examples include models of collective behavior, complex networks (molecular, metabolic, genetic, neural, trophic, ecologic, social, economic, organizational, political, geographical), non-linear dynamics, evolution, and distributed systems. Theoretically, complexity has also provided several concepts, formalisms, and tools. It has also contributed to emerging disciplines, such as digital epidemiology and computational social science.

The main difference between complexity-related and traditional techniques is that

complexity can easily include millions of variables into consideration, for example, with cellular automata, multi-agent systems, or networks. This is difficult to achieve with, for example, differential equations, which are more suitable for contexts where there are few variables considered and the state space or phase space does not change, that is, is stationary. The tools of complexity are suitable for studying non-stationary spaces, that is, those that change with time.

Applications

The scientific study of complexity and complex systems has found applications in physical, chemical, biological, computational/informational, social, economic, engineering, and other fields. In many cases, the concepts, tools, and methods of complexity have been applied to specific problems, for example, self-assembly, pattern formation, adaptive control, protein folding, ecological studies, robotics, evolution, etc. As such, many concepts from complexity have already been absorbed and used in several disciplines. In other cases, the study of complexity *per se* has also led to relevant research.

Complexity formalisms allow the study of phenomena at different scales and to relate them under the same framework. This is useful when multiple scales (spatial, temporal, functional, and dynamical) interact within a system, since the same language can be used to relate the scales. This is not feasible with a reductionist approach.

Future Directions

Some have speculated that complexity is a fad, and it will lose its popularity, following the steps of similar movements: cybernetics, catastrophe theory, and chaos theory. Nevertheless, complexity has been studied (under this name) since the 1980s, and everything indicates that the interest on it is growing. The concepts and methods that have been developed within the study of

complexity and complex systems are permeating into all disciplines. Maybe people will not use the term complexity, but this is not relevant. Complexity is helping shape a shift in the scientific worldview, from reductionist to “interactionist.” This is relevant since this shift is allowing us to expand the frontiers of our knowledge.

Cross-References

- ▶ [Artificial Life](#)
- ▶ [Cellular Automata](#)
- ▶ [Emergence of Life](#)
- ▶ [Scale-Free Networks](#)

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Composomes

Doron Lancet

Weizmann Institute of Science, Rehovot, Israel

Keywords

Prebiotic metabolism · Self-replication · Mutually catalytic sets · Selection · Evolution · Protocells · Vesicles

Definition

A composome is a quasistationary state in a dynamic description of compositional molecular assemblies (Segré et al. 2000). The term originated in the context of origin of life, in a monomer-world scenario (Shapiro 2007), proposed as an alternative to the RNA world. Composomes arise in an artificial chemistry description of early evolution, prior to the emergence of complex polymeric molecules such as RNA or proteins. This is a stage at which random assemblies of simple molecules might have acquired a prebiotic metabolism before exact polymeric replication existed. The dynamics of such molecular assemblies are thought to have been governed by processes such as catalytic closure, affording the emergence of mutually catalytic sets (Kauffman 1993) or a transition from a disordered to an ordered quasistationary state (Dyson 1999), both mimicking self-replication.

Overview

The specific computer-simulated model within which composomes have been invoked is the Graded Autocatalytic Replication Domain (GARD) model (Segré et al. 2000; Markovitch

and Lancet 2014). This model simulates assemblies of small molecules, typically lipids and other amphiphiles, that spontaneously accrete into discrete assemblies, much in line with Oparin's Conception of Origins of Life in a primordial soup environment. GARD is intimately linked to the concept of a Lipid World (Segré et al. 2001). This is an origin of life scenario that focuses on amphiphilic micelles and vesicles, in line with lipid protocells and other types of prebiotic protocells.

A key concept in GARD is that in a primordial soup, a huge diversity of amphiphiles has been available, so molecular assemblies could assume a large variety of compositions. The GARD chemical kinetics formalism shows that very specific compositions may breed true (with mutations), in a process of repeated accretion-driven growth followed by physical fission. Such favored compositions are defined as composomes, a name hinting at the idea that assemblies are capable of genome-like compositional information transmission from one generation to another. Composomes are a cornerstone of more recent studies that portray, among others, a route from metabolism-like composomes to genetic replication (Norris et al. 2012) and early ecology (Hunding et al. 2006; Markovitch and Lancet 2014). While some question the capacity of mutual catalysis-driven compositional assemblies devoid of informational biopolymer, to undergo selection and evolution (Vasas et al. 2010), solid evidence for the existence of such capacities has been reported (Markovitch and Lancet 2012).

The origin of life is ridden with a chicken or egg problem: present-day RNA and DNA are rather inert in the absence of catalytic proteins, and proteins cannot be formed without biopolymeric guidance. Composomes may be a clue as to where to look for a solution to this riddle (Shapiro 2007).

Cross-References

- Artificial Chemistries
- Chicken or Egg Problem
- Lipid
- Metabolism, Prebiotic

- Oparin's Conception of Origins of Life
- Origin of Life
- Primordial Soup
- Protocell
- RNA World

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Computational Biology

- Bioinformatics

CONAE, Argentina

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

Argentina space agency

Definition

The “Comisión Nacional de Actividades Espaciales” (CONAE) is the space agency for Argentina. Argentina’s first activities in the space field date back to 1961, when the National Commission for Space Research (Comisión Nacional de Investigaciones Espaciales, CNIE) was first established within the Argentine Air Force area. With other local and international organizations, CNIE carried out, by means of rockets and stratospheric balloons, the first Southern Hemisphere scientific atmospheric studies, which included wind measuring and assessment of neutral atmosphere dynamics using the alkaline clouds technique. Together with the Argentine Institute of Aeronautics and Space Research, CNIE designed and constructed a family of one- and two-stage sounding rockets.

In 1991, the Argentine government decreed the creation of this National Commission for Space Activities as a civil organization. Since 1996, this specialized agency accomplishes its mission governed by the Ministry of Foreign Affairs.

CONAE is involved, in particular, in the use of space data for telemedicine and tele-epidemiology and the use of space infrastructure for health emergencies during disaster management.

In January 26, 2016, CONAE was transferred to the scope of the Ministry of Science, Technology and Productive Innovation. The agency is working under a long term plan The national plan for Space 2016–2027.

Concentration Gradients

David Deamer
Department of Biomolecular Engineering,
UC Santa Cruz, Santa Cruz, CA, USA

Keywords

Membrane potential · Semipermeable membrane · Stored energy

Definition

Concentration is a measure of the amount of solute in a solvent, typically expressed in units of moles per liter. A 1.0 molar solution (abbreviated 1.0 M) contains 1 mole of a solute in 1 liter of total volume. A concentration gradient exists when a higher concentration of a solute is separated from a lower concentration, by a semipermeable membrane.

Overview

Concentration gradients of solutes are common in living cells and are essential sources of energy for all forms of life. Concentration gradients are generated and maintained across biological membranes by ion pump enzymes that transport ionic solutes such as sodium, potassium, hydrogen ions, and calcium across the membrane. Energy is required to produce a gradient, so the gradient is a form of stored energy. An important example is the sodium and potassium ion gradient across most cell membranes, which produces the resting potential and action potentials of excitable membranes like those of neurons. Hydrogen ion gradients are generated by the electron transport systems embedded in membranes, either as a pH gradient or a ► [membrane potential](#). For instance, a gradient equivalent to 210 mV or 3.5 pH units (~1000-fold gradient) is the source of energy driving ► [ATP](#) synthesis in mitochondria, chloroplasts, and bacterial membranes. Although concentration gradients are essential to life today, it is uncertain what role they may have played in the origin of life. Early membranes were likely to be relatively permeable to solute ions, so that primitive cells would be unable to use gradients as an energy source.

Cross-References

► [Membrane Potential](#)

Concestor

► [Common Ancestor](#)

Concretions (Mars)

Alessandro Airo

Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Definition

Concretions are postdepositionally cemented areas within sedimentary rocks that occur as spheres, disks, tubes, botryoidal aggregates, or have an irregular lumpy shape. The cement forms through precipitation from pore water and is usually composed of carbonate (e.g., calcite, siderite), sulphate (e.g., gypsum), silica (e.g., chert), or iron oxide (e.g., hematite). Nodules have a similar origin, but instead of cementing the pre-existing sediment in place, they substitute the particles through relocation or dissolution.

The Mars Exploration Rover Opportunity was the first to discover concretions on Mars, the so-called ‘blueberries’, which are cemented by hematite (Squyres et al. 2004). The Mars Science Laboratory Curiosity has discovered light-toned concretions within mudstones at Gale crater, which possibly are cemented by sulphates (Grotzinger et al. 2014). The occurrence of concretions on Mars is insofar of interest to astrobiologists as they indicate the former presence of groundwater.

Cross-References

- [Aquifer \(Mars\)](#)
- [Meridiani \(Mars\)](#)

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Condensate Layer

► [Clouds](#)

Condensation Sequence

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Cosmochemistry · Solar nebula

Definition

In planetary science, the condensation sequence refers to the order in which chemical compounds transition from gas to solid phase in a protoplanetary nebula (disk), based on the condensation temperature of each compound. The condensation sequence is important because the temperature of a protoplanetary nebula varies radially and temporally, and the chemical composition and mass of any bodies formed at a given place and time is defined by the materials that can condense at the local temperature.

Overview

Condensation is defined as the process by which chemical materials change phase from the gaseous or liquid phase to the solid phase. Chemical condensation occurs within a narrow range of temperature specific to each individual chemical compound (a few tens of degrees), defined by

the abundance of the elements in the nebular gas and the molecular structure and composition of the solid compound. Effective condensation temperatures depend on the local environment (i.e., pressure) and can be lowered by including catalytic reactions (i.e., grain growth reactions). A “condensation sequence” orders a specific list of chemical compounds of interest by their condensation temperatures, in order to determine which materials will condense in a medium of a specific temperature.

The Solar System is thought to have formed from a rotating disk of gas and dust called the ► “[solar nebula](#)” (this is true for other planetary systems as well; we call these disks “protoplanetary disks”). The temperature of the solar nebula varied both radially (from the inner regions of the disk to the outer regions) and vertically (from the midplane to the surface) due to heating from the Sun and viscous heating at the midplane. The temperature in different parts of the solar nebula also changed over time as the disk material was depleted due to accretion to the star and photo-evaporation. The material condensing out of the gaseous solar nebula into grains and larger bodies would therefore be a function of both location and of age, resulting in a changing chemical composition of bodies over space and time in the nebula. A typical condensation sequence of the nebular gas starts with refractory oxides and silicates (1,700–1,400 K), followed by iron and nickel which will eventually segregate into planetary cores and the silicates of their future mantle and crust (1,350–1,150 K). Alkali elements and sulfide-loving (chalcophile) elements such as Cu, Zn, and Pb and finally volatile elements such as S, C, N, and H₂O join between 600 and 100 K. The temperature at which condensation came to a halt for the material of a planetary body, therefore, defines its depletion in volatiles, among them water.

One of the most interesting consequences of the condensation sequence is therefore the proposed existence of a ► “[snow line](#)” in the solar nebula. The snow line is defined as the radial location in the solar nebula beyond which the local temperature of the nebula drops below the condensation temperature of water. Bodies formed beyond this boundary would contain

water, while bodies inside this boundary would be relatively waterpoor. In fact, Earth is thought to have formed inside the snow line, hence, the concept of “water delivery”. The existence of water ice beyond the snow line has increased the solid surface density at these locations and led to the rapid growth of the giant planets’ cores.

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Protoplanetary Disk](#)
- [Snow Line](#)
- [Solar Nebula](#)
- [Water, Delivery to Earth](#)

Condensation Temperature

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

The condensation temperature is that at which a given gas-phase constituent condenses into a liquid. This temperature depends on the physical and chemical state of the system.

Conjugation

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

In microbiology, conjugation is the process by which two individuals of the same – or even different – species exchange their genetic material during a temporary union. Among ► [bacteria](#), conjugation is a widespread mechanism that allows the transmission of one conjugative

► [plasmid](#) from one cell, called “donor,” to another, the “recipient,” through the physical contact between them. Conjugative plasmids carry genes that promote bacterial conjugation and are frequently involved in ► [lateral gene transfer](#) – also called horizontal gene transfer, HGT – between individuals of different species. For example, antibiotic resistance or the ability to metabolize a new organic molecule can be transmitted by conjugation among microorganisms. In the majority of bacteria, conjugation is not a standard mode of reproduction as it is the case in sexual organisms. In turn, in certain ► [protists](#) such as paramecia, although they usually reproduce asexually by fission, conjugation is a sexual process of reproduction between individuals of opposite mating types. Conjugation is also used as a genetic engineering technique in the lab.

Cross-References

- [Bacteria](#)
- [Domain \(Taxonomy\)](#)
- [Genetics](#)
- [Lateral Gene Transfer](#)
- [Plasmid](#)
- [Protists](#)
- [Transformation](#)

Constructive Biology

- [Synthetic Biology](#)

Contamination, Probability

Catharine A. Conley
NASA Ames Research Center, Moffett Field,
CA, USA

Definition

For purposes of ► [planetary protection](#), the probability of contamination may be determined, using a formulation of the ► [Coleman-Sagan equation](#)

that an Earth-originating organism might grow and propagate in another planetary environment.

Cross-References

- [Coleman-Sagan Equation](#)

Continental Accretion

- [Accretion](#)

Continental Crust

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

Continental crust is that portion of the Earth's ► [crust](#) composed mainly of low-density siliceous (granitoid) rocks. It represents about 70% (volume) and 40% (surface) of whole Earth crust and underlies most of emerged land. Its average thickness is ~30 km and varies from ≤10 km in rifts to up to 80 km beneath mountain belts. Dominant constituents are granitic rocks and their metamorphic equivalents (gneiss) and meta-sedimentary or metavolcanic sequences. Continental crust forms above ► [subduction](#) zones and contains a large proportion of the Earth's budget of incompatible trace elements and heat-producing elements. The presence of continental crust is a signature of ► [plate tectonics](#) that distinguishes ► [Earth](#) from other planets.

The continental crust is made of low-density material (granitoid $d \approx 2.7$) while the oceanic crust (basaltic $d \approx 3.0$) is denser. Consequently, the presence of continental crust in lithospheric segments confers to them more buoyancy, such that, due to Archimedes' principle, they float higher on the asthenosphere than those without it. Its average altitude above sea level is of 870 m, so that, liquid water usually only covers its margins

(“continental margins,” shelves). Such a situation allows there the biological colonization of regions covered by shallow water and within the photic zone. This gives rise to the “carbonate factory” on continental shelves.

Cross-References

- [Crust](#)
- [Earth](#)
- [Granite](#)
- [Plate Tectonics](#)

Continental Flood Basalt Provinces

- [Trapps](#)

Continental Lithosphere

- [Continents](#)

Continental Plate

- [Continents](#)

Continental Tectosphere

- [Continents](#)

Continents

Balz Samuel Kamber
School of Earth and Atmospheric Sciences,
Queensland University of Technology, Brisbane,
QLD, Australia

Keywords

Buoyancy · Gravity anomaly · Mechanical strength · Mountain belt · Plate motion ·

Radioactive heat · Sedimentary basin ·
Subcontinental lithospheric mantle ·
Subduction

Synonyms

[Continental lithosphere](#); [Continental plate](#); [Continental tectosphere](#)

Definition

On a planet with ► [plate tectonics](#), continents are the topographic expression of emergent, buoyant, strong, and cool plates, contrasting with thinner, denser and hotter oceanic plates covered by water. A relatively thin crust (mostly 25–45 km) and an underlying much thicker subcontinental ► [mantle](#) (150–250 km) together form the continental lithosphere that moves as a coherent unit. Together they have the capacity to withstand destructive convective forces for billions of years. The uppermost crust is highly enriched in many incompatible trace elements, including the sources of radioactive heat (i.e.; ^{238}U , ^{235}U , ^{232}Th , ^{40}K). Where continents collide with other plates, their edges thicken to form mountain belts, which eventually erode to fill sedimentary basins.

Overview

From a geological perspective, large expanses of land – continents – are an expression of the greater buoyancy of continental plates compared to oceanic plates. Continental plates consist of an upper layer, the ► [continental crust](#), which on Earth is typically 35 km thick, and a lower layer, called the subcontinental lithospheric mantle, which on Earth can reach as deep as 250 km. The density of both layers is lower than that of typical convecting upper mantle, resulting in a negative gravity anomaly over continents (Barrell 1914).

► [Radiogenic isotopes](#) demonstrate that the two layers are formed contemporaneously during subduction of oceanic plates (e.g., Nägler et al. 1997).

At depth, where subducted ► [oceanic crust](#) experiences ► [metamorphism](#), hydrous fluids are released and rise up into the overlying mantle, allowing a partial melt to form, which preferentially consumes the denser mantle minerals and also incorporates many (incompatible) chemical elements that are not favored by mantle minerals. This leaves behind a less dense residue that is depleted in many trace elements, among others, in the radioactive heat producers (U, Th, K). Such subcontinental lithospheric mantle acts as a buoyant, strong, cool protective root for continental crust (e.g., Kamber and Tomlinson 2019). The melt itself rises to the ► [Moho](#) (the boundary between the Earth's crust and mantle) and differentiates into the continental crust, which is also buoyant and chemically very different from the bulk planet (Taylor and McLennan 1985). The buildup of radioactive heat in the crust leads to chemical stratification, typically culminating in an event of widespread granite emplacement (cratonization) after which the new crust achieves full mechanical stability (Sandiford and McLaren 2002).

On Earth, continents have an average age of ca. 2.2 billion years; the oldest continental fragments are about 3.85 billion years old. Such antiquity is testimony to the thermal and mechanical stability of continents (e.g., Peslier et al. 2010).

The familiar concept of continents surrounded by ocean basins may only be valid on planets whose interiors cool via the plate tectonic process. Furthermore, as a result of relative plate motion, the continental plates (which cannot be destroyed by subduction processes) can thicken and deform along their edges, leading to the formation of mountain belts. Continents on young planets with higher crustal heat production have less mechanical strength and lower topography, whereas mid-aged planets, like Earth, have continents capable of supporting rapid vertical movement. Amalgamation of several continental plates produces ► [supercontinents](#), whose breakup is typically triggered by thermal erosion of the subcontinental lithospheric mantle by heat upwellings from the deeper mantle (mantle plumes; McKenzie and Bickle 1988).

Large sedimentary basins that accommodate erosion products of mountain belts either express the thinning of the underlying continental lithosphere (rift basins and passive margins), thermal doming followed by erosion and subsequent cooling (intraplate basin), or flexural loading of lithospheric margins (e.g., foreland basins).

Cross-References

- [Continental Crust](#)
- [Greenstone Belt](#)
- [Heat Flow, Planetary](#)
- [Lithosphere, Planetary](#)
- [Mantle](#)
- [Mantle Plume, Planetary](#)
- [Metamorphism](#)
- [Moho](#)
- [Oceanic Crust](#)
- [Plate Tectonics](#)
- [Plate, Lithospheric](#)
- [Radioactive Heating](#)
- [Radiogenic Isotopes](#)

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Continuum

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The continuum is the smooth, continuously varying portion of an ► [electromagnetic spectrum](#), with no spectral features such as atomic or molecular lines or bands. It may be produced by different physical processes: radiative recombination of electrons previously in free states, two-photon decays of metastable levels, thermal bremsstrahlung, ► [blackbody](#) radiation, and synchrotron emission.

Cross-References

- [Background](#)
- [Blackbody](#)
- [Bremsstrahlung Radiation](#)
- [Electromagnetic Spectrum](#)
- [Radiative Processes](#)

Contribution of Science to Society

- [Socioeconomic Benefits of Space](#)

Convection, Stellar

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

Convection is the transport of heat by turbulent motion of gas. Within stars, this thermal energy

is supplied either by nuclear fusion or bulk gravitational contraction. The luminosity of the Sun is carried outward by convection in the outer third of its radius. The shifting pattern of granulation visible on the solar surface represents rising and falling gas cells in the convection zone. The upwelling of gas in this zone, together with the Sun's rotation, amplifies and maintains the solar magnetic field. When the Sun was a ► [pre-main-sequence star](#), its relatively high surface cooling drove convection throughout its interior.

Overview

Stars generate energy by nuclear fusion or gravitational contraction. This energy is transported through the interior, eventually streaming outward as radiation from the surface. The transport occurs either through the diffusion of radiation or convection. In the Sun, whose luminosity stems entirely from fusion, convection operates in the outer third of the radius. This zone is a remnant from the Sun's pre-main-sequence epoch, when it was entirely convective.

Convection occurs through upwelling of gas cells. The hot cells are buoyant and rise toward the surface, expanding and releasing energy by radiation. The cooled cell, now denser, falls back down, where it is reheated by the star's energy source. The cycle then repeats itself in a circulating pattern of motion. Convection only occurs if the specific entropy (entropy per unit mass) of the gas declines toward the surface. In regions where the entropy rises, fluid cells can rise temporarily, but then quickly fall back down and thereafter oscillate. Net energy transport in such regions occurs through radiative diffusion.

The specific entropy inside a star falls if the object is either heated from below or cooled from above. The first mechanism operates in main-sequence stars, where hydrogen fusion generates energy in the central region. The second mechanism operates in pre-main-sequence stars. These stars have such large radii that surface cooling alone drives convection throughout the interior.

The upwelling of convective eddies in the Sun is visible directly in the ever-changing pattern of granulation near the surface. It is a combination of this upward motion and the Sun's internal rotation that creates the star's magnetic field. This field, in turn, channels the solar wind and provides a braking mechanism for the star's rotation. This general idea is confirmed by observations of other main-sequence stars. Those with outer convection zones rotate much more slowly than stars lacking them.

The rise and fall of cells, while it has an overall order, is also a somewhat chaotic process. In this regard, convection is similar to other forms of fluid turbulence, all of which are difficult to treat in a quantitative manner. The most successful approach is the *mixing-length theory*. Models of stellar interiors that use the mixing-length theory accurately reproduce the chief properties of main-sequence stars, including the depth of the convection zone itself.

Cross-References

- [Main Sequence, Star](#)
- [Pre-main-Sequence Star](#)
- [Protostars](#)
- [Stellar Winds](#)

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Cool Early Earth

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Synonyms

[Early Earth](#)

Definition

The term “Cool Early Earth” refers to the new vision of the ► [Hadean](#)-early Archean Earth characterized by much more temperate surface conditions than believed before. The term was coined by the American geochemist John Valley in 2002. A popular image of the early Earth is indeed, that of a planet covered by hot magma and subjected to an intense meteoritic bombardment. This image is at the origin of the term Hadean (from the Greek god of the underworld, Ἅδης = *Hades*) for the first eon. The fractionated oxygen isotopic compositions of 4.4–4.3 Ga-old Jack Hills zircons indicate, however, that they crystallized from magma that had been in contact with water or sediments; thus, surface temperatures may have been low enough to permit liquid water on the Earth's surface. It is therefore possible that liquid water was present at the surface of the Hadean Earth and that Earth cooled rapidly from its “hot phase” during and soon after core formation.

Overview

The chemical composition of the 4.4–4.3 Ga Jack Hills zircon crystals implies that they crystallized from granitic magma. Consequently, as granitoids are the main components of continental crust, it can be concluded that this later existed as early as 4.4 Ga ago (Wilde et al. 2001). However, the existence of continental crust does not necessarily imply that continents emerged above sea level. The genesis of granites requires that water was transported into the mantle, perhaps by subduction of hydrated oceanic crust. This implies that oceans were present at the surface and that ► [plate tectonics](#) operated. The presence of oceans, in turn, allows speculation that life could have been present at that time. Metamorphosed sedimentary rocks and ► [pillow lavas](#) in 3.8 Ga-old strata from the ► [Isua Supracrustal Belt](#) (West Greenland) provide evidence of liquid water and temperate conditions in the early Archean.

It is commonly accepted that the Sun was less luminous in the first part of Earth history, 25–30% less than today during the Hadean and early

Archean (Sagan and Mullen 1972; Goldblatt and Zahnle 2011). This should have resulted in extremely cold conditions at the surface of the Earth and other terrestrial planets. The probable mechanism to generate temperate surface conditions is the atmospheric presence of a high proportion of greenhouse gases such as CO₂ and CH₄, combined with some sort of internal regulation that maintained their concentrations at the levels needed to preserve clement conditions at the surface (the so-called Faint Young Sun Paradox).

Cross-References

- [Earth, Formation, and Early Evolution](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Faint Young Sun Paradox](#)
- [Hadean](#)
- [Isua Supracrustal Belt](#)
- [Jack Hills \(Yilgarn Craton, Western Australia\)](#)
- [Oceans, Origin of](#)
- [Water, Delivery to Earth](#)

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Coonterunah Subgroup, Australia

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The Coonterunah Subgroup is one of the oldest well-preserved supracrustal sequences known on

Earth. Located in the ► [Pilbara Craton](#), Western Australia, the sequence is about 5 km in stratigraphic thickness and exposed over about 75 km strike length. It consists mainly of tholeiitic and minor komatiitic basalt, some felsic lava with intercalated carbonate, and ► [chert](#) beds. It is 3.52 Ga old and its metamorphic grade is only mid-greenschist to lower amphibolite facies. It contains sedimentary carbonate and ► [kerogen](#) that may represent some of the oldest traces of life on Earth.

Cross-References

- [Archaean Traces of Life](#)
- [Basalt](#)
- [Chert](#)
- [Kerogen](#)
- [Komatiite](#)
- [Mafic and Felsic](#)
- [Pilbara Craton](#)

Coordinate Systems

François Mignard
CNRS, Observatoire de la Côte d'Azur,
University of Nice Sophia-Antipolis, Nice, France

Keywords

Astrometry · Declination · Fundamental astronomy · Hipparcos · ICRF · ICRS · Right ascension · VLBI

Synonyms

[Reference frame](#)

Definition

An astronomical coordinate system is a set of three orthogonal directions, an origin, and a choice of mathematical coordinates within this system, with respect to which the position and motion of celestial bodies are referred.

Overview

Motion and position are not absolute concepts and must be described with respect to some reference. In astronomy, this is a reference frame, that is to say the realization of a set of axes with the means to assign coordinates to an object. Since these axes are not given a priori on the celestial sphere, one must use existing celestial bodies or directions to define the coordinate system. In this context, it is important to draw attention to the difference between a reference system and a reference frame. A reference system is the set of prescriptions stating how a celestial coordinate system is to be formed. It defines the origin and fundamental planes (or axes) of the coordinate system, together with the constants and models necessary to fully define the system. A reference frame consists of a set of identifiable points on the sky, together with their coordinates, which serves as the practical realization of a reference system.

A system of axis is determined by the choice of an origin and of three mutually orthogonal directions labeled by the unit vectors e_1 , e_2 , and e_3 . With the underlying assumptions of absolute Euclidean space, the orientation of the system does not change when translated between two origins, meaning that the choice of the origin and directions are independent of each other. The commonest origins are the location of the observer (topocentric frame), the center of the Earth (geocentric frame), the barycenter of the solar system (barycentric frame), and the center of the Galaxy (the galactic frame). The center of a planet or a satellite can be used as well for specific purposes. The set of three directions is constructed by selecting the polar direction e_3 , or equivalently by selecting a fundamental plane going through the origin, and a direction e_1 in this plane for the x -axis. A point M is then represented by the Cartesian coordinates in this frame or by spherical coordinates. The latter are more convenient to represent directions on the celestial sphere and are widely used in observational astronomy or to construct stellar catalogues and ephemerides of low accuracy. Cartesian coordinates are preferred to model motions in the solar system and to produce accurate ephemerides with position and velocity vectors. The choice of the

fundamental directions is dictated by the necessity to make them accessible to observation, so that the system is materialized in space. This leads to the following usual systems, appearing in most astronomical work.

- The horizon coordinate system uses the observer's local vertical as a fundamental direction or equivalently the local horizon as a fundamental plane. This is a physical definition that can be accessed with a plumb line or a spirit level. The pole overhead is the zenith, and the one diametrically opposite is the nadir. The two angles that specify the spherical coordinates are the azimuth angle (A) and the altitude (h). The azimuth is measured in the horizontal plane from one of the two points of intersection of the celestial meridian with the horizon. The altitude is the angular height of a point with respect to the horizon, counted positively above the horizon and negatively below. Instead of altitude h , its complement measured from the zenith, the zenith distance z , is also frequently used.
- In the equatorial coordinate system, the primary direction is defined by the Earth's spin axis, giving the ► [celestial equator](#) (the projection on the sky of the Earth's equator) as fundamental plane. The reference point on the celestial equator is the vernal equinox, the direction on the celestial sphere at which the Sun, in its yearly path around the celestial sphere, crosses the equatorial plane moving from south to north. The ► [declination](#) (δ) of a body is its angular distance north or south of the equator, and the ► [right ascension](#) (α) is its angular distance measured eastward along the equator from the equinox. Because both the celestial equator and the ► [ecliptic](#) are moving (precession of the equinoxes), the coordinate systems that they define must be specified at a particular date. In contrast, the ICRF (International Celestial Reference Frame) has fixed directions determined by the positions of a set of extragalactic sources observed in radio interferometry, with an origin at the barycenter of the solar system. However, these axes correspond closely to what would conventionally be described as the equator and equinox of

J2000.0 and therefore to the equatorial system at this epoch. For application with accuracy requirement less than 0.1 arcsec, the distinctions between ICRS and the conventional definition are not significant. The subset of the single stars of the Hipparcos Catalogue is a secondary realization at optical wavelengths and is designated as the HCRF (Hipparcos Celestial Reference Frame).

- Of less importance are the ecliptic system, using the mean orbital plane of the Sun as fundamental plane with origin at the vernal equinox, and the galactic coordinate system defined by arbitrarily assigning equatorial coordinates for the pole and the origin in the galactic equator, nominally close to the galactic center. In the ICRF, the galactic pole is near $\alpha_p = 192.75^\circ$, $\delta_p = 27.13^\circ$, and the galactic center is located at about $\alpha_p = 266.40^\circ$, $\delta_p = -28.93^\circ$.

Cross-References

- ▶ [Astrometry](#)
- ▶ [Celestial Equator](#)
- ▶ [Declination](#)
- ▶ [Ecliptic](#)
- ▶ [Right Ascension](#)

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Copernican Principle

David Dunér
Lund University, Lund, Sweden

Keywords

Cosmology · Heliocentric Worldview · History of Science · Philosophy of Science

Synonyms

[Cosmological principle](#); [Mediocrity principle](#)

Definition

The Copernican principle states that Earth has not any privileged position in the universe. In astrobiological terms, it means that terrestrial life, including the human beings, has not any particularly privileged, special, or unique position in the universe, which leads to the assumption that, given the presence of life on Earth, life will exist also in other places in the universe.

History

The term Copernican principle was first coined by the cosmologist Hermann Bondi in 1952. The principle refers to the Polish astronomer Nicolaus Copernicus (1473–1543), who, in his book *De revolutionibus orbium coelestium* (On the Revolutions of the Celestial Spheres) from 1543, proposed a heliocentric model for the explanation of the movements of the planets. The consequence of placing the Sun instead of the Earth in the center of our planetary system was that Earth no longer had any particularly privileged position within this planetary system. Earth became a planet among other planets. There was not any fundamental difference between Earth and the Heavens, the sublunar world, and the supralunar world as the Aristotelian-Scholastic philosophy maintained. This opened up the possibility of life on other planets. According to the Ptolemaic geocentric model and Aristotelian physics extraterrestrial life was unlikely, due to Earth's privileged position in the center of the universe and the physical laws of the elements. But, if Earth is just a planet among other planets, and as Giordano Bruno claimed, that every star has its own planetary system, there might be countless other living planets out there. If the living Earth is a rather common, mediocre place in universe, why should not also other planets harbor life? In the seventeenth and eighteenth century, many leading astronomers and philosophers have relied their

arguments on the Copernican principle, for example, Bernard le Bovier de Fontenelle and Christiaan Huygens. The presumed existence of extraterrestrial life was very much a question of how similar those potential life-bearing places must be to Earth. The answers varied, for some interpreters it was just enough that it was a planet orbiting a star, but others added a number of considerations such as temperature, presence of water, atmosphere, rocky surface, etc.

Overview

In astrobiology, the Copernican principle has been extended to the biological realm, to the question of the existence of life elsewhere in the universe. Given the existence of planets similar to ours, the mediocrity claims of the Copernican principle fuel expectations of finding life beyond Earth. In that sense, the Copernican principle lies historically behind much of the astrobiological endeavor.

The Copernican principle is sometimes used interchangeably with the related principles, the Mediocrity principle and the Cosmological principle. The Mediocrity principle suggests that there is nothing special or unusual with the evolution of the solar system and the formation of Earth, as well as the evolution of life on Earth. This means, given the existence of life on Earth, and that there are many such mediocre Earth-like planets out there, it would not be unlikely if these or some of these planets also harbor life. The Cosmological principle, on the other hand, states that humans are not privileged observers in the universe. Universe is isotropic and homogeneous, and then would look pretty much the same irrespectively from where one observes it. Contrary to the Copernican principle stands the trend of explaining the rarity and specialness of our place and our existence, the fine-tuned universe, that the existence of life rests on the exact value of certain physical constants. If the value of these constants had differed only slightly from the present ones, the evolution of the universe would have taken another path and life as we know it would not have emerged.

The Copernican heliocentric worldview had far-reaching consequences for the view of the

human being and its place in the creation. The human being was not the center of the universe, everything was not orbiting around her, which challenged the teachings of the Scripture. The Copernican principle thus leads to a retreat of an anthropocentric view of the universe. It could be extended further from the Earth. Our solar system has no particularly unique location in the Milky Way, it moves around the center of the galaxy along with many other stars and their planets. Our galaxy itself is, as Edwin Hubble showed, just one among many other galaxies in the universe. Even the entire universe may be only one among many others in a multiuniverse. Carl Sagan sums up this dethronement of the human being from the center of the universe, in *Cosmos* (1980) he says: “We find that we live on an insignificant planet of a humdrum star lost in a galaxy tucked away in some forgotten corner of a universe in which there are far more galaxies than people.” The Copernican principle can not only be used for our spatial position, but also to our temporal position. Bondi himself coined the term in order to support his steady-state cosmology. We, who now observe the universe, do not live in any special or unique moment in time, in the history of the universe, neither in the beginning nor at the end of time. We humans are also rather mediocre in magnitude, far smaller than galaxies and far larger than atoms. But we human beings are the only ones, so far we know, who are aware of this mediocrity – that is, one might say, the paradox of the Copernican principle.

Cross-References

- [Heliocentric Worldview](#)
- [Huygens](#)
- [Principle of Plenitude](#)

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Copper Isotopes

Ernest Chi Fru

Centre for Geobiology and Geochemistry, School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK

Keywords

Copper and life · Copper and proteins: copper isotopes and atmospheric evolution · Copper isotopes and environmental redox chemistry

Definition

Copper (Cu) has two isotopes: ^{63}Cu and ^{65}Cu . Both are stable, with natural abundances of 69.174% and 30.826%, respectively (Albarède 2004). The distribution of these Cu isotopes in nature is defined by the equation: $\delta^{65}\text{Cu} = [(^{65}\text{Cu}/^{63}\text{Cu})_{\text{sample}} / (^{65}\text{Cu}/^{63}\text{Cu})_{\text{standard}} - 1] \times 1000$.

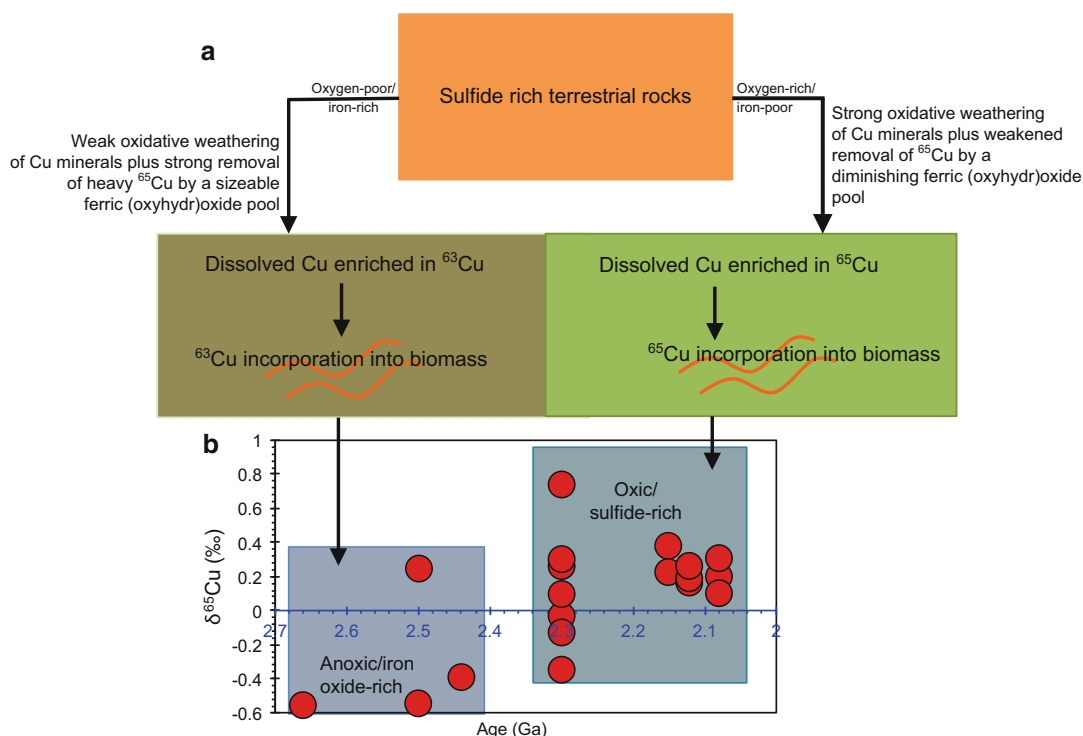
Overview

Cu is a transition metal that rarely occurs in its native form (Cu^0) (Dekov et al. 2013). It is, however,

abundant in oxygen-poor environments as Cu^+ and Cu^{2+} when conditions are partially to fully oxygenated (Chi Fru 2011; Dekov et al. 2013; Moynier et al. 2017). The oxygen-driven transformation of Cu results in isotopic fractionation between precipitated minerals and the solutions from which they formed (Zhu et al. 2002; Ehrlich et al. 2004; Dekov et al. 2013; Moynier et al. 2017). Cu readily binds to sulfide, leading to Cu being hosted by sulfide minerals in differentiated magmas and volcanic rocks, but rarely in the silicate mineral phases that make up a bulk of volcanic rocks (Albarède 2004).

The Cu minerals in volcanic rocks weather as a function of oxygen availability to form soils and sediment minerals. This quantifiable relationship between rock Cu minerals and oxygen-driven weathering has been used to link Cu to the permanent rise of oxygen in Earth's atmosphere during the so-called Great Oxidation Event (GOE) that occurred ~2.45 billion years ago (Chi Fru et al. 2016). At this time, atmospheric oxygen rose from below 10^{-5} present-day levels and climbed to at least 10% of the modern value (Lyons et al. 2014). It is thought that the replacement of terrestrial detrital iron sulfide-rich beds by iron (oxyhydr) oxide-rich layers after this time was a result of the progressive oxidation of the sulfide minerals as appreciable amounts of oxygen became a permanent fixture of the atmosphere (Holland 2006). The evidence shows that the oxygen weathered and transformed a major sulfide reservoir that had accumulated on the continents in the absence of oxygen in the atmosphere before 2.45 billion years ago (Canfield 1998; Konhauser et al. 2011).

As a corollary, the weathering of Cu sulfides on land discharges fluids enriched in heavy ^{65}Cu (Moynier et al. 2017). This is consistent with the enrichment of ^{65}Cu in modern, sulfate-rich seawater and sediments (Dekov et al. 2013; Takano et al. 2014; Moynier et al. 2017). In addition, the binding of Cu by iron (oxyhydr)oxide minerals precipitating from the water column removes heavy ^{65}Cu from solution (Pokrovsky et al. 2008; Balistrieri et al. 2008). It is, therefore, believed that a change in the isotopic signature of Cu in marine, organic carbon-rich sediments following the GOE was impacted by the weathering of continental sulfide minerals and the difference in the volume of banded iron



Copper Isotopes, Fig. 1 (a) Conceptual model for the fractionation of Cu isotopes in anoxic and oxic atmospheres linked to the weathering of continental sulfide minerals, adsorption by iron (oxyhydr)oxides and biological

incorporation into biomass. (b) Cu isotope fractionation and preservation in organic carbon-rich sediments deposited under oxygen-poor and oxygen-rich atmospheres before and after 2.5 billion years ago (Chi Fru et al. 2016)

formation (BIF) that was precipitated before and after the GOE (Fig. 1).

Living cells incorporate light ^{63}Cu into biomass (Zhu et al. 2002; Navarette et al. 2011). This has particular implications for biological complexes and enzymes that catalyze important biogeochemical processes, including aerobic methane, iron, and ammonia oxidation, the reduction of nitrate to nitrogen gas, and some aspects of photosynthesis (Zahn et al. 1996; Zumft 1997; Chi Fru 2011; Chi Fru et al. 2011; Ilbert and Bonnefoy 2013).

Taken together, the conceptual model presented in Fig. 1 suggests that the redox sensitivity of Cu makes it a robust biogeochemical tool for remotely identifying worlds with atmospheric compositions of the past, present, and future that can sustain Earthlike life forms. This important criterion arises from the ability of Cu isotopes preserved over long geological timescale in rocks that interacted with the atmosphere and biosphere to differentiate the oxygenation state

in which they formed. Because oxygenation is primarily a strong property of the *Oxyphotobacteria* that invented oxygen-producing photosynthesis, it is an expressed signature for Earthlike life conditions.

Cross-References

- [Anaerobic Photosynthesis](#)
- [Ammonia](#)
- [Archaean Traces of Life](#)
- [Archean Environmental Conditions](#)
- [Archean Eon](#)
- [Astrobiology](#)
- [Bacteria](#)
- [Banded Iron Formation](#)
- [Biogenicity](#)
- [Biogeochemical Cycles](#)
- [Biomarkers](#)
- [Biomarkers Atmospheric, Evolution over Geological Time](#)

- ▶ Biomineralization
- ▶ Bioprecipitation
- ▶ Biosphere
- ▶ Chemolithoautotroph
- ▶ Chemolithotroph
- ▶ Colonization, Biological
- ▶ Continental Crust
- ▶ Continents
- ▶ Cyanobacteria
- ▶ Denitrification
- ▶ Earth, Surface Evolution
- ▶ Earth's Atmosphere, History of the Origins
- ▶ Earth's Atmosphere, Origin and Evolution of
- ▶ Environment
- ▶ Evolution, Chemical
- ▶ Fractionation
- ▶ Fractionation, Mass Independent and Dependent
- ▶ Geomicrobiology
- ▶ Great Oxidation Event
- ▶ Iron Cycle
- ▶ Iron Oxides, Hydroxides, and Oxyhydroxides
- ▶ Isotope Biosignatures
- ▶ Isotopic Ratio
- ▶ Oceans, Chemical Evolution of
- ▶ Oxic
- ▶ Oxic Sediments
- ▶ Oxidation
- ▶ Oxidizing Atmosphere
- ▶ Oxygenation of the Earth's Atmosphere
- ▶ Precambrian
- ▶ Red Beds
- ▶ Sedimentary Rock
- ▶ Shale
- ▶ Sulfate Minerals
- ▶ Sulfate Reducers
- ▶ Sulfate Reduction
- ▶ Sulfidic Oceans
- ▶ Sulfur Cycle
- ▶ Terrestrial Analog
- ▶ Trace Elements
- ▶ Trace Metals

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Core Accretion, Model for Giant Planet Formation

Sean N. Raymond

Laboratoire d’Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Core accretion is the standard model for giant planet formation. The core accretion model proposes that the formation of ► [giant planets](#) starts with core formation followed by gas accretion. First, small bodies continually collide to form larger ones, eventually reaching the stage of protoplanetary cores, which are essentially large ► [planetary embryos](#) that form in the giant planet region. Cores that reach masses of a few Earth masses begin to accrete gas from the ► [protoplanetary disk](#), slowly at first, and then at a runaway rate when the gaseous envelope’s mass becomes comparable to the core mass. Cores, therefore, represent the “seeds” of gas giant and ice giant planets in this model. An alternative model for giant planet formation is disk instability that proposes that giant planets form via a local gravitational collapse in the disk, which can later be followed by core formation and accretion of solids.

Cross-References

- [Atmosphere, Primitive Envelope](#)
- [Giant Planets](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)
- [Runaway Gas Accretion](#)

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Core, Planetary

Tilman Spohn

International Space Science Institute, Bern,
Switzerland

Keywords

Planets · Satellites

Synonyms

[Planetary core](#)

Definition

The core is the central spherical region of a ► [planet](#). In a ► [terrestrial planet](#), it consists of an iron-rich alloy. In a satellite, the core may be composed of a mixture of iron, silicates, and ice depending on the degree to which the satellite interior is differentiated (see “► [Differentiation, Planetary](#)”). In a ► [giant planet](#), the core is made of a similar mixture of iron, ► [rock](#), and ice albeit at much larger pressures and temperatures.

Overview

The interiors of planets and satellites are differentiated to varying degrees with the heaviest materials at the center. The degree of differentiation in solid planets and satellites depends on their thermal histories since differentiation requires at least partial melting at some early epoch. Cosmochemical and physical models of the planets and satellites suggest the existence of cores and provide estimates of their sizes and masses. An iron-rich core has been proven beyond doubt for the ► [Earth](#) by the inversion of seismic and gravity data. The Earth's core is composed of a Fe-Ni alloy but also contains a small fraction (<10%) of lighter elements such as Si, O, or S and is layered with a liquid outer core and a solid inner core. (See Rabinowicz et al. (2015) for reviews on the interior structure of the Earth and Olsen and Schubert (2015) for reviews on the Earth's core dynamics.) It is widely agreed that the inner core is the result of core freezing and that it grows as the planet cools. It is also widely agreed that the energy liberated upon core freezing powers the generation of its ► [magnetic field](#) through a dynamo. ► [Mars'](#) core is inferred from gravity data and the chemistry of the ► [SNC meteorites](#) (Sohl and Schubert 2015 for a review). Its density, chemistry, and the absence of a present-day magnetic field suggest that the core is completely liquid (Schubert and Spohn 1990). The cores of ► [Venus](#) and ► [Mercury](#) are constrained by the average densities of these planets and cosmochemistry. Venus is thought to have a core approximately as large as the Earth's. The large average density of Mercury along with the recent gravity and libration data gathered by the Messenger mission suggests that the core is unusually large with a radius of about 0.8 planetary radii or about 1,800 km (Smith et al. 2012) and a solid inner core. Recent reanalysis of Apollo seismic data by Weber et al. (2011) suggests that the Moon has a solid inner core with a radius of 240 ± 10 km surrounded by a fluid, iron-rich outer core of 330 ± 20 km. The interpretation of the data suggests a partially molten zone in the rock mantle above the core of 480 ± 15 km. A solid mantle and a crust complete the lunar

interior structure. The gravity fields measured at the Galilean satellites of ► [Jupiter](#) suggest that ► [Io](#), ► [Europa](#), and ► [Ganymede](#) have iron-rich cores (e.g., Schubert et al. 2004). This is particularly true for Ganymede for which the magnetic field suggests a liquid iron-rich core with possibly a solid inner core. ► [Callisto](#) and ► [Titan](#) (Iess et al. 2010), as the data suggest, are incompletely differentiated and likely have large cores composed of ice, silicates, and possibly iron or iron oxides. The gravity fields of Jupiter and ► [Saturn](#) suggest cores consisting of ice, silicates, and iron, but their masses and, in particular, their radii are uncertain (Guillot and Gautier 2015 for a review). Estimates range from a few to about ten Earth masses. Uranus and ► [Neptune](#) may have similar cores, but interpretations of the gravity field suggest that the layering in the interiors of the latter two planets is less pronounced than in Jupiter and Saturn. Rather, density and composition change with depth more gradually (Podolak et al. 1995).

Cross-References

- [Callisto](#)
- [Differentiation, Planetary](#)
- [Dynamo, Planetary](#)
- [Earth](#)
- [Europa](#)
- [Ganymede](#)
- [Giant Planets](#)
- [Io](#)
- [Jupiter](#)
- [Magnetic Field](#)
- [Mars](#)
- [Mercury](#)
- [Neptune](#)
- [Planet](#)
- [Rock](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Silicate Minerals](#)
- [SNC Meteorites](#)
- [Terrestrial Planet](#)
- [Titan](#)
- [Uranus](#)
- [Venus](#)

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Corona Discharge

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A corona discharge is a positive or negative electrical discharge created by the ionization of a gas surrounding a conductor, for example, a mineral surface, which occurs when the strength of the

electric field exceeds a certain threshold value. A charged ► [plasma](#) is created around the surface generating ions, which dissipate their charge to proximal areas of lower potential or recombine to form neutral molecules. If the ionized region continues to grow instead of quenching, a momentary spark or a continuous arc may result. A neutral atom or molecule of the medium, in a region of strong electric field, may be ionized, for example, by the absorption of a photon, to create a positive ion and a free electron. The electric field around the surface may then separate these charged particles and prevent their recombination. As a result of the acceleration of the electrons, further electron/positive-ion pairs may be created when they collide with other neutral atoms. These then undergo the same processes creating a cascade of electrons.

Such energetic processes may have contributed to prebiotic synthesis, providing electrical energy similar to the electric discharge used in Miller-Urey-type experiments. Corona discharges are estimated by some to discharge some three times the energy of lightning strikes on the present Earth (Miller & Cleaves 2006), and this ratio may have been similar on the primitive Earth.

Cross-References

- [Miller, Stanley](#)
- [Plasma](#)

References

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Corona, Coroneae

Jörn Helbert
DLR, Institut für Planetenforschung, Berlin,
Germany

Definition

Coroneae are volcano-tectonic landforms only seen on the planet ► [Venus](#). They are oval to

circular features typically 100–300 km in diameter. A few of the coronae are even larger. They have a circular or nearly circular, tectonically deformed annulus, which usually stands a few hundred meters above the surrounding plains. The area inside the annulus is typically lower than the surrounding plains and has been flooded with plains-forming volcanic lava. Aprons of young lobate (tongue-shaped) volcanic flows are seen radiating from many coronae. At the center of some coronae one finds the corona core, an elevated and tectonically deformed area.

Cross-References

► [Venus](#)

Coronagraphy

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Coronagraphy designates the group of optical techniques that aim at suppressing or reducing the halo of light that surrounds the image of a star, in order to detect faint structures like a circumstellar disk or companions, especially exoplanets. It was invented in 1930 by the French astronomer Bernard Lyot (Fig. 1) to study the Sun's corona, the extremely faint emission from the region around the Sun, at times other than during a solar eclipse. The coronagraph is in its simplest form an occulting disk in the focal plane of a telescope combined with a mask in a plane optically conjugated to the entrance aperture, so that the image of the solar disk is blocked and the stray light reduced by a large factor. Since then, the term has been kept for research in areas other than the solar corona and designates now any optical system able to block as much as possible the glare of a star to allow detection of companions or disk structures in its immediate vicinity.



Coronagraphy, Fig. 1 Bernard Lyot, a French astronomer who invented the coronagraph, an optical instrument whose original purpose was to study the faint extended emission around the Sun, the so-called corona

Overview

The ability to directly image an extrasolar planet – that is, to separate the light emitted or reflected by its surface or atmosphere from that of the star it orbits – offers the greatest prospect for characterizing these objects. Direct ► [imaging](#) gives the possibility of determining the colors and spectra of planets, in a way independent of their orbital inclination. This information allows astronomers to distinguish between gas giants, ice giants, and Earth-like planets under a variety of circumstances such as distance from the star, age, etc. Direct imaging also allows astronomers to study the planet's atmosphere, possible cloud systems, etc., and may also become the successful way for establishing the habitability of an exoplanet.

Directly imaging extrasolar planets requires (a) angular resolution sufficient to spatially

separate the planet from its central star and (b) the means to suppress the diffracted light from the central star such that the planet's brightness becomes comparable to or greater than the residual diffracted star light.

Concerning the first point, at optical wavelengths a conventional telescope of several meters diameter is in principle sufficient to spatially resolve a planet on an orbit comparable to those observed in our solar system, around nearby stars. However, the telescope must be in space or equipped with an extremely efficient ► [adaptive optics](#) system; otherwise, the blurring due to atmospheric turbulences at ground level and at high altitude would degrade too severely the image quality.

As regards the second requirement, this is precisely the role of a coronagraph – to block the starlight as efficiently as possible, using optical elements within the telescope.

The main challenge of using an optical coronagraph for exoplanet imaging is the star-planet brightness contrast ratio. For an Earth-sized planet orbiting a star similar to our Sun, it is about 10^{10} –1 in the visible. Any successful starlight suppression technique must reduce this contrast ratio by a huge factor and must do so at a very small angle, typically equal to $\theta = 2\text{--}5 \lambda/D$, where λ is the wavelength of observation and D is the diameter of the telescope (this value corresponds to the fundamental limit imposed by the phenomenon of ► [diffraction](#)). An important parameter is thus the smallest star-planet angular separation at which this suppression level is achieved to avoid the need for primary mirror diameter larger than, say, 10 m.

There are other challenges albeit a little less stringent.

- The optical bandwidth of the light suppression technique – that is, the range of wavelengths over which the required light suppression can be maintained – should be as large as possible to enable either broadband photometry ($\Delta\lambda/\lambda = 10\%$) or the spectroscopic study of possible exoplanet atmospheric features at various different wavelengths.

- Imperfections in the telescope mirrors and coatings cause *speckles* in the image, that is, small spots of extra light intensity, after the coronagraphic mask; their intensity and variability can easily be high enough to obscure the extremely faint exoplanet image. It is possible to reduce these speckles using deformable mirrors (► [Adaptive Optics](#)), controlled thanks to smart algorithms, or to code them in order to recognize them from the planet image.
- Finally, the weak signal from an extrasolar planet requires substantial integration times (many hours) during which it is essential that the residual stellar leakage be kept extremely stable, which is especially challenging on the ground, considering atmospheric as well as thermal fluctuations. This stresses the need to conduct research of Earth-sized exoplanets from space, but, even then, drifts and vibrations in the telescope cause varying stellar “speckles” that can limit the ultimate sensitivity for planet detection.

Under the pressure of the *planet hunters*, coronagraphy is an area that has shown enormous progress in the past decade as presented below, with a flourishing of very new concepts and technical breakthroughs. Ground-based instruments are already capable of direct detection of exoplanets in the most favorable cases, and a first generation of coronagraphic instruments installed on the largest telescopes (8–10 m diameter) will soon extend by a large factor the population of directly detected exoplanets. It is rather likely that within another decade or so, a coronagraphic space mission will be able to obtain the first images of planets that are analogs to our Earth.

Basic Methodology

A star observed with a perfect telescope in space, thus unaffected by the aberrations of the Earth's atmosphere, will produce an image still surrounded by a halo of light diffracted from the edges of the telescope aperture. Known as the Airy pattern, this halo, which is structured with concentric rings of decreasing intensity (see



Coronagraphy, Fig. 2 The airy pattern is the appearance that the image of a star made by a perfect telescope in space would present. Because of the phenomenon of diffraction, it is not an extremely sharp spot but rather a central core surrounded by characteristic rings. The larger the diameter of the telescope and the smaller the wavelength, the sharper the diameter of the core

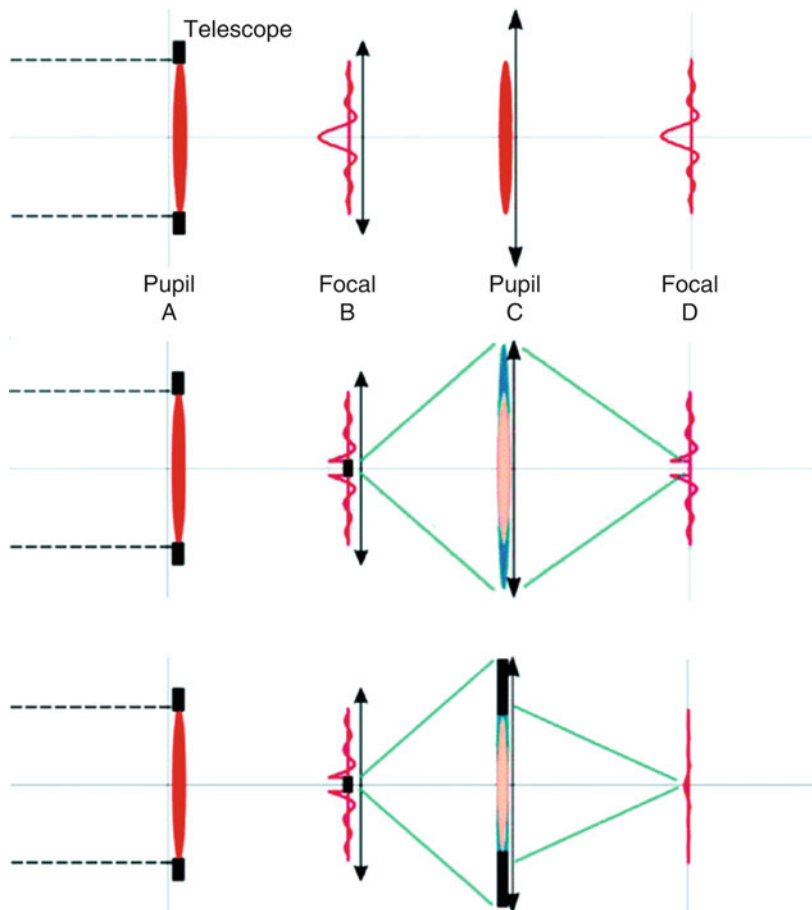
Fig. 2), is many orders of magnitude brighter than any extrasolar planet image that would be superimposed on it. Suppressing this halo is the role of a coronagraph.

The Basic Lyot's Coronagraph

The main finding of Bernard Lyot (1939) is that blocking the light with an opaque mask in the focal plane that follows the contour of the bright object (the Sun's surface in his case) is not sufficient at all, because light diffracted by the edge of the mask will spread far beyond the limits of the beam defined by geometric optics and finally will be able to refocus. This is illustrated in Fig. 3 (top and mid panels): the first mask in the focal plane blocks the core of the starlight but leaves residual diffracted light in the reimaged pupil (blue beam). Lyot realized that if a mask with a central circular

Coronagraphy,

Fig. 3 The principle of the Lyot's coronagraph. *Top:* optical scheme of an imaging system with relay optics. The image of a point-like object at infinity (star) is formed by a telescope (a) at its focal plane (b); a lens at this location forms the image of the telescope aperture in another plane (c) where a third lens re-images the star in plane D. The intensity of the light distribution is represented by the curve which is a cut of the image. *Middle:* An opaque mask is put at the focal plane and blocks a large part of the light; however, because of diffraction by the edges of the mask, a fraction of the light is spread beyond the geometrical beam and produces a significant intensity in the focal plane. *Bottom:* a ring mask placed in the pupil plane is efficient to block most of this spurious light



hole slightly smaller than the pupil image was installed, then it would block the essential part of this diffracted light as shown on the bottom panel of Fig. 3.

The New Coronagraphic Concepts

Over the past decade, coronagraphic concepts have proliferated far beyond Lyot's basic vision into a vast family of devices that can be broken down into various broad categories: amplitude or phase-mask coronagraphs, interferometric coronagraphs, and pupil apodization. A fifth family is the external occulter. Each one offers pros and cons that can be measured by a few key parameters. Four of those parameters are especially important:

- The inner working angle (IWA) is the angle of separation from the star below which the flux from the planet is rapidly attenuated and/or beyond which the flux from a resolved star rapidly increases. Currently, the most mature concepts feature an IWA of $\sim 4 \lambda/D$, and it is suggested that an IWA of $\sim 2 \lambda/D$ is achievable.
- The planet throughput, that is, the fraction of the planet's light that reaches the detector. Current throughputs of 8–30% are measured, but claims that a throughput of 80% or higher is reachable are made. In addition, several coronagraphs produce stellar halo suppression within only a fraction of the entire field of view, for instance, a sector or a ring, sometimes referred to as the “discovery space.”
- The sensitivity of the coronagraph to wavefront errors such as image position and focus. These defects arise due to drift and misalignment; even very small ones and their effects can hide or mimic a planetary signature.
- The chromaticity of the coronagraph, that is, its ability to suppress starlight across a broad wavelength range, thus allowing a lower total integration time. Typical useful bandwidth is $\Delta\lambda/\lambda \sim 20\%$ or less.

A thorough study on how each coronagraph design behaves with respect to those key parameters was done by Guyon et al. (2006).

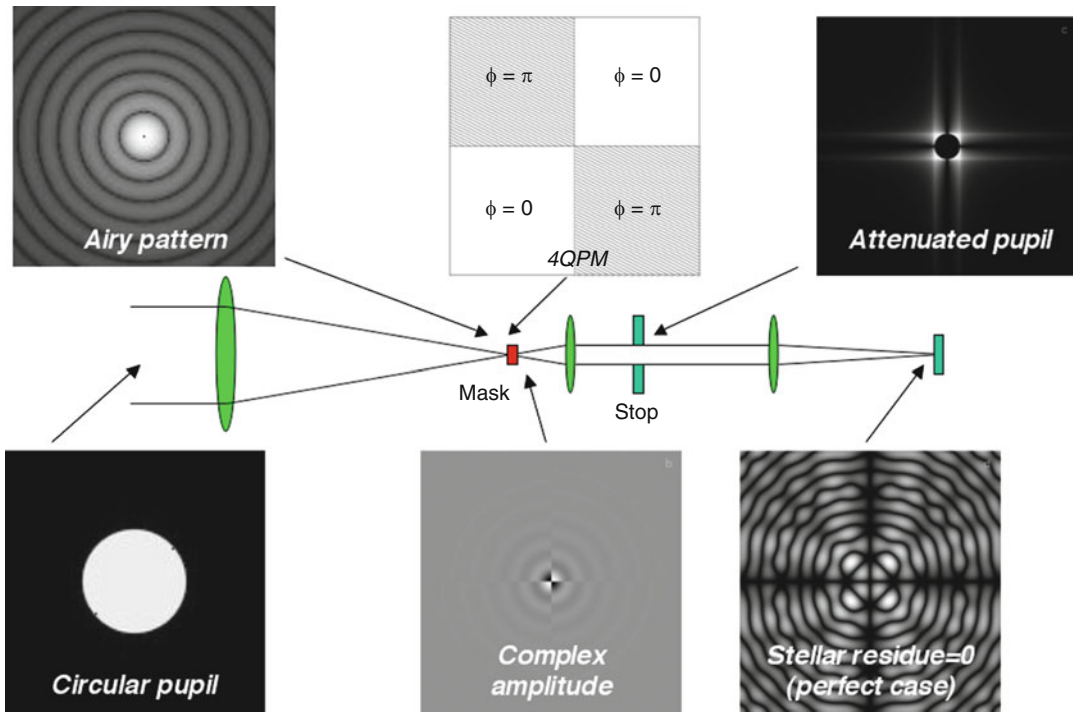
Improvement on the Lyot Concept with Amplitude Masks

Those concepts evolved from Lyot's original solar coronagraph, using a mask at an image of the star, and another mask at a later image of the entrance aperture. It can be shown that, in this basic form, Lyot's concept cannot reach the rejection required for planet detection by several orders of magnitude. An important variant of this concept is the band-limited coronagraph (Kuchner and Traub 2002), where the focal plane mask features a carefully tailored transmission profile confining the residual diffracted light to a well-defined region of the pupil plane. This type of coronagraph has produced excellent laboratory results with a measured contrast of 6×10^{-10} , albeit only in monochromatic light.

Another Lyot variant is the Apodized-Pupil Lyot Coronagraph (APLC), which modifies the entrance pupil with a dedicated transmission mask (Soummer 2004). Laboratory demonstrations to date have achieved contrast levels in the 10^{-6} range. One advantage is that it may be easily adapted to conventional telescopes with central obstruction, such as those used in the next generation of ground-based coronagraph projects.

Phase-Based Lyot Coronagraphs

A similar approach to the Lyot concept is to induce a phase shift rather than an amplitude variation in the focal plane; destructive interference is then produced for on-axis starlight at the pupil level. In the first proposed idea (Roddier and Roddier 1997), the opaque spot of Lyot was simply replaced by a transparent spot of a proper size. The best-known example of this concept remains the four-quadrant phase-mask (4QPM) coronagraph (Rouan et al. 2000), which focuses the starlight onto a mask that shifts light passing through half the focal plane by half a wavelength (see Fig. 4). Such coronagraphs have near-ideal theoretical performance with high throughput and an IWA of $1 \lambda/D$. However, they are also sensitive to star position in the focal plane with respect to the center (angle θ), with performance degrading rapidly with tip/tilt errors. One variant (Rouan et al. 2007) that allows improving on this sensitivity is the 8-quadrant phase mask, where the



Coronagraphy, Fig. 4 Schematics describing the principle of the four-quadrant phase-mask coronagraph and the distribution of the amplitude of the light at the various planes of the optical system

canceling function is proportional to θ^4 rather than θ^2 . There exist several solutions to manufacture them for broadband light: one uses polarization properties of uniaxial crystals, and another is based on the stacking of several 4QPM with rejection performance increasing exponentially with the number of devices. A recently proposed variant of the 4QPM is the optical vortex coronagraph (Foo et al. 2005), which uses a spiral-staircase phase mask. They are more robust against degradation due to the star's position.

Pupil Apodization

Using the Fresnel principle, it can be shown that the diffraction pattern at the focus of a telescope – that is, the actual distribution of intensity in the image of a point source at infinity, such as a star – is directly related to the shape of the entrance aperture. More precisely, this intensity is given by a mathematical transformation of the aperture, called the Fourier transform. The sharp edges of a conventional telescope result in the Fourier ringing that produces the well-known Airy pattern.

Conceptually, the simplest coronagraph would entail a modification of the telescope aperture so it lacks these sharp edges. Called apodization, this modification can be achieved by tapering the telescope transmission through a semitransparent mask that falls gradually to zero transmission at the edges. These masks trade throughput for inner working angle, with a typical mask designed for an IWA of $4 \lambda/D$ having a transmission of 8%. However, manufacturing such a mask with graded attenuation is extremely difficult. Significant effort has been invested in binary approximations to these apodization functions, using sharp-edged metal masks that suppress diffraction over only part of the field of view (Kasdin et al. 2003). Referred to as “shaped pupils,” these masks, which can include micron-sized features, must be carefully fabricated but are feasibly produced with current manufacturing techniques. These designs are inherently achromatic and may be attractive for characterization of planets with known positions, where they can be optimized over a narrow region of the focal

plane. Shaped-pupil masks have been demonstrated in the laboratory at the 2×10^{-9} contrast level, even in broadband light.

An alternative approach to performing apodization is to modify the phase of the light to modulate the intensity in the pupil plane. The phase-induced-amplitude-apodization coronagraph (Guyon 2003) of O. Guyon is based on this approach, using highly aspheric mirrors to redistribute the uniform beam of light into a tapered profile (see Fig. 5). The off-axis planet image is highly distorted, but this effect can be compensated. Contrary to classical apodization, no light collected by the entrance pupil is lost, and the inner working angle can be as small as $2\text{--}3 \lambda/D$ for a throughput of 80% or more. However, this requires optical surfaces very difficult to manufacture, located in various conjugate planes.

Interferometric Coronagraph

The nulling coronagraph is a coronagraph based on a nulling interferometer, as opposed to more familiar designs of an apodized aperture telescope and Lyot coronagraph. This family uses concepts of ► [interferometry](#) and aims at producing destructive interference between two beams. The achromatic interferometric coronagraph (AIC)

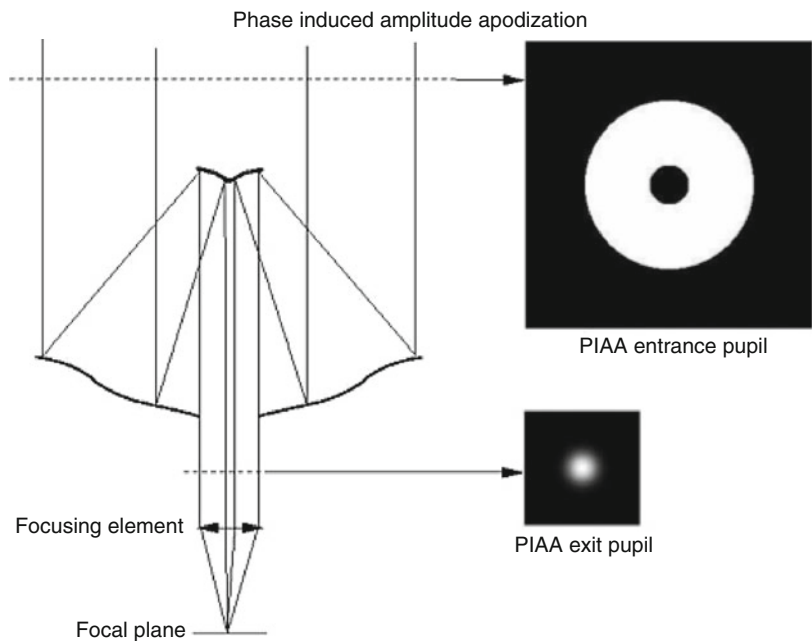
was the first of this type to be proposed, by Gay and Rabbia as early as 1997, and has been refined since then (Rabbia et al. 2007). It is basically a Michelson-Fourier interferometer modified by inserting on one arm an achromatic π phase shift and a pupil rotation by 180° (see Fig. 6). The smart idea is to produce the π phase shift by crossing of a focus, thus making it perfectly achromatic. The collimated beam from the telescope is split into two sub-beams forming the two interferometric arms, one where the focus-crossing occurs. The beams are recombined afterward. Other designs have been proposed, such as the nulling coronagraph of M. Shao (2007).

External Occulter Coronagraphs

This type of coronagraph belongs to a peculiar family, since it relies on optical systems separated by several 10, 000 km! In 1960, Lyman Spitzer proposed the combination of a telescope and a starshade in space for discovery of planets. The concept implied enormous distances and starshade dimensions. With recent studies (Cash 2006), the inter-spacecraft separation has been reduced and the level of suppression improved by using petal shapes that would permit operation using a shade with a nominal diameter of 40 m at a

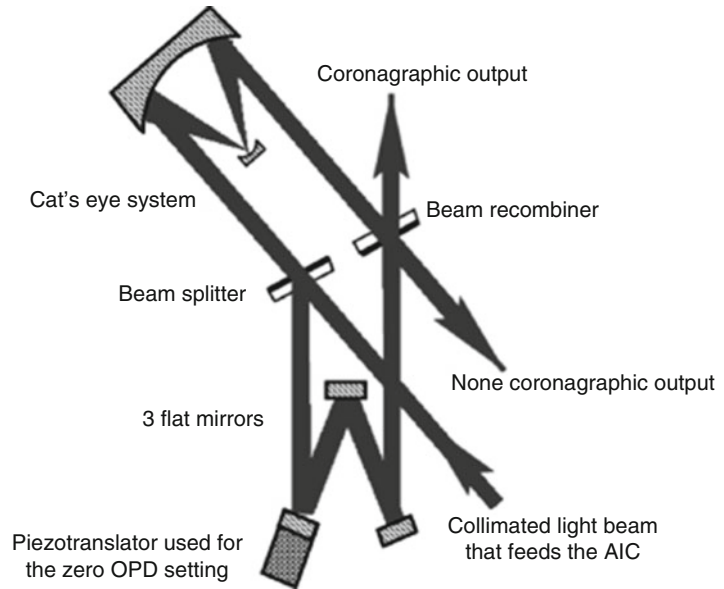
Coronagraphy,

Fig. 5 The principle of the phase-induced-amplitude-apodization coronagraph that produces apodization by modifying the light intensity within the beam



Coronagraphy,

Fig. 6 The principle of the achromatic interferometric coronagraph (AIC) based on destructive interference between two beams, one having suffered the crossing of a focus



telescope-starshade separation of 40,000 km (see Fig. 7). The telescope can be an ordinary space telescope, and its diameter is determined mainly by the requirement to detect faint planets. It has inherently achromatic properties, a strong advantage. However, operation remains the main drawback, since pointing from one star to another requires that the starshade travel several thousand kilometers. To accomplish this within a few weeks demands large starshade velocities and accelerations and thus a substantial power. However, the engineering effort recently done led to some mission scenarios that yield satisfactory efficiency with one occulter and much better with two occulters. The deployment of the large starshade and the propulsion required for many stellar observations remain major technology issues to be addressed.

Future Directions

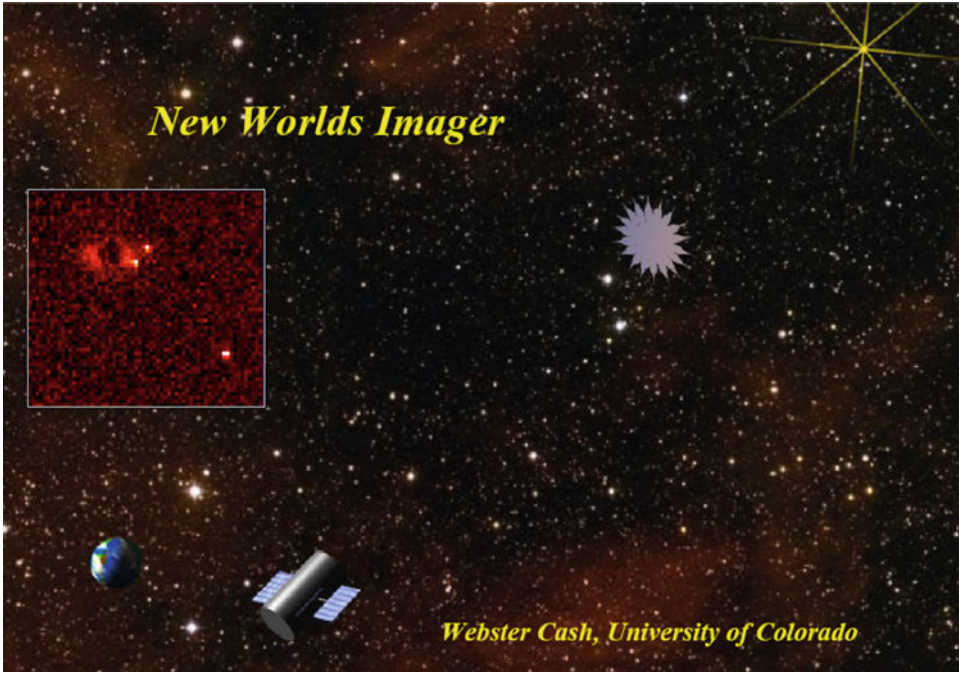
Wavefront Control

A problem common to all internal coronagraphs is wavefront accuracy and stability. Wavefront errors produced by imperfections in the telescope mirrors and coatings cause speckles in the image after the coronagraph masks have suppressed most of the starlight. The intensity and variability

of these speckles can easily make the faint exoplanet image indiscernible. Achieving Airy ring suppression sufficiently to allow detection of Earth-sized planets would require wavefront phase errors of less than an angstrom (10^{-10} m) – well beyond current polishing capabilities for telescope-sized mirrors. However, the use of a smaller deformable mirror in the optical train allows irregularities in the wavefront to be corrected by feedback, up to a spatial frequency set by the deformable mirror's actuator spacing (Bordé and Traub 2007). With state-of-the-art deformable mirrors, this allows a large fraction of low- and mid-spatial-frequency errors to be removed from the wavefront, producing an image with a characteristic “dark hole” central region (see Fig. 8). It can be shown that with two deformable mirrors, both phase and amplitude defects can be corrected, for an even better improvement.

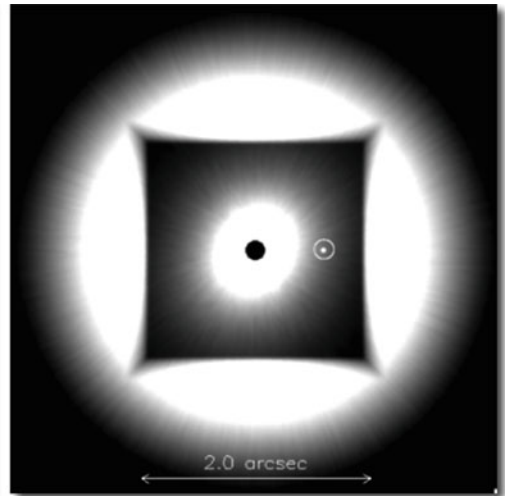
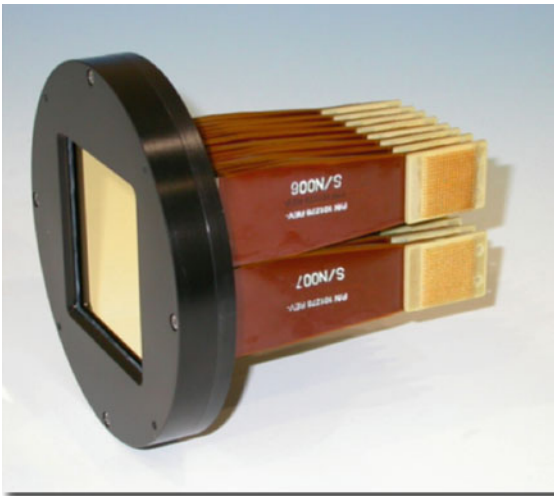
Calibration of Residual Speckles

The field image is small, a few arcsec in diameter, but an average flux of 10^{-10} times the star flux implies that there could be several hundred speckles as bright as an Earth-like planet. Only one of those speckles is a planet. One technique to identify it makes use of the coherence of starlight, that is, light from the star is coherent (i.e., will interfere coherently) with speckles whose origin is



Coronagraphy, Fig. 7 An artist view of the “New Worlds Imager” project based on a large deployable external occulter at a distance of 40,000 km from a conventional

space telescope. The insert shows a simulated image of the solar system as it would be detected



Coronagraphy, Fig. 8 A deformable mirror with many actuators (*left*) can provide a fair correction of the residual defects in the wavefront, producing an image with a characteristic “dark hole” central region (*right*)

scattered starlight, but will not interfere with light in the focal plane that comes from the planet (or dust) orbiting the star. Because of the interferences, the intensity distribution of the stellar flux features fringes that striate the speckles. The

fringes can be detected by a proper processing, such as a Fourier transform of the image. This is, for instance, the principle of the self-coherent camera proposed by Baudoz et al. (Galicher and Baudoz 2007).

Differential Coronagraphy

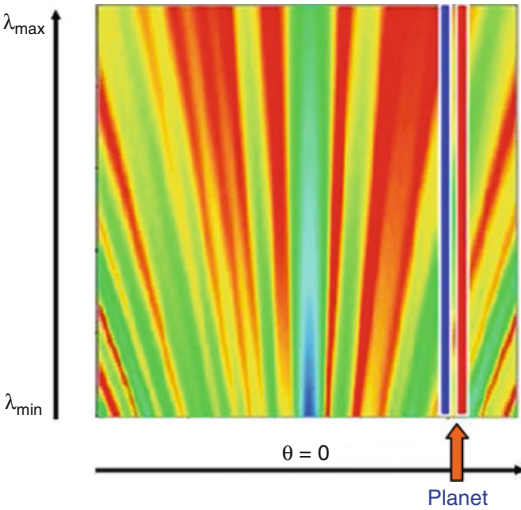
Even with the best correction of the wavefront, there will still remain some defects, and it becomes clear that a good way of correcting them is to subtract a similar image that presents the same defects, for instance, of another star or the same star, but where presumably no planet would be present. Several concepts have been proposed in that spirit and several of them have been tested on the sky: spectral differential

imaging, rotational differential imaging, and polarization differential imaging.

In spectral differential imaging (Racine et al. 1999), two images of the star are taken at two close wavelengths, carefully chosen so that the planet would have a different contrast, for instance, within and outside a spectral feature characteristic of some expected compound in its atmosphere (e.g., methane). In another version (Sparks and Ford 2002), one produces the spectra of all the pixels in the image, with a so-called integral field spectrograph, and looks for differences in behavior between speckles, whose size changes with wavelength, and a planetary image whose size is constant, as illustrated in Fig. 9.

Rotational differential imaging (Marois et al. 2006) requires that the telescope be rotated a few degrees around its axis several times, an image being taken at each position: the optical defects will rotate as well, in sky coordinates, while the planet image would remain stable. Figure 10 illustrates this technique.

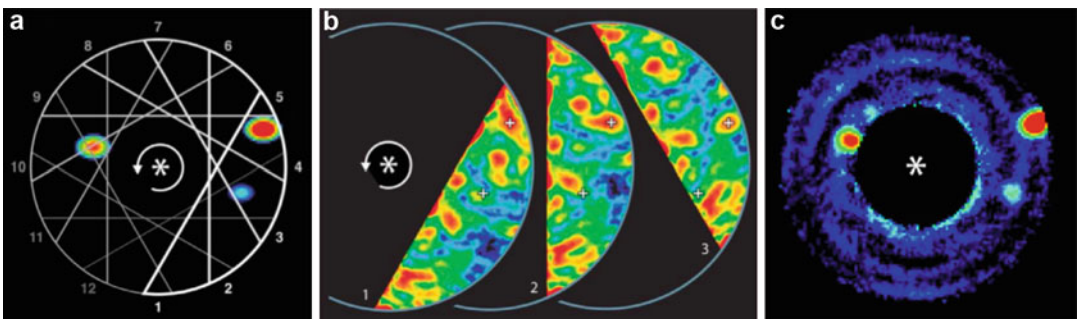
Finally, in polarization differential imaging, one makes the reasonable guess that the light from the planet is significantly polarized, while the starlight is not: images taken in different polarization states could reveal the planet after subtraction.



Coronagraphy, Fig. 9 Integral field spectroscopy produces spectra of all points in an image: most of the light that remains after coronagraphy is due to speckles whose size changes with wavelength (λ is along the vertical axis), while a planet would be of about a constant size with wavelength

Combining All Techniques

The challenge to beat a contrast of 10^{10} is so difficult that it becomes more and more evident that the good strategy cannot be to rely on one technique alone, but to combine many of them.



Coronagraphy, Fig. 10 Rotational differential imaging. The telescope is rotated around the line of sight and images are taken at each angle. The optical defects that rotate with the telescope can be subtracted

The coming years, or decades, will probably show that the winning instrument, the one that will pick up the first image of a cousin of our Earth, will have included together an efficient coronagraph combining pupil and image plane masks, a super-polished telescope with no central obstruction, one or two deformable mirrors, several differential imaging techniques, and most probably will have been operated in space.

Cross-References

- [Adaptive Optics](#)
- [Diffraction](#)
- [Direct-Imaging, Planets](#)
- [Exoplanets, Discovery](#)
- [Imaging](#)

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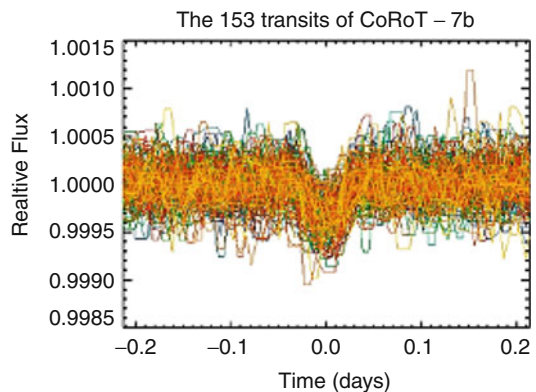
CoRoT 7b

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

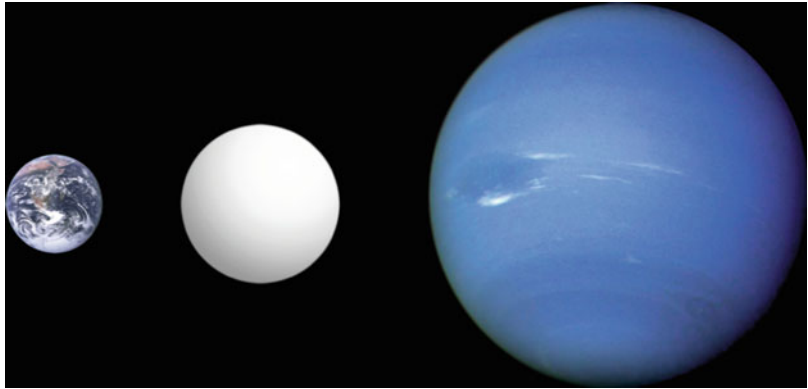
Definition

The exoplanet CoRoT-7b is the seventh planet detected via transit photometry (Fig. 1) by the European space telescope, CoRoT (Léger et al. 2009). With a radius of ~ 1.6 Earth radii (Fig. 2), this planet is the first terrestrial-like planet found outside our solar system. CoRoT-7b revolves around its central star in a very short-period orbit



CoRoT 7b, Fig. 1 Light curve of CoRoT-7 showing 153 transits of CoRoT-7b

CoRoT 7b, Fig. 2 CoRoT-7b in comparison to the solar system planets



of 20 h making this planet one of the few with extremely small orbital periods. The close proximity of this planet to its Sun-like host star (which is about 500 light-years away) implies that it must experience extreme conditions. For instance, its surface may be covered by lava or boiling oceans (Fig. 3). A total of two planets were detected in the system, and the companion CoRoT-7c has a period of 3.7 days (Queloz et al. 2009).

Since the discovery of CoRoT-7b, many attempts have been made to determine the mass of this planet using radial velocity data (Léger et al. 2009; Queloz et al. 2009; Hatzes et al. 2010, 2011; Boisse et al. 2011; Ferraz-Mello et al. 2011). However, due to stellar activities, the value of the mass of this planet is uncertain. The current estimates, using a model for stellar activity, put the mass of this planet around 4.7 Earth masses (See Haywood et al. 2014; Dai et al. 2019).

Discovery of CoRoT-7b opened a new field in the studies of extrasolar planets. The mass of this planet puts this object in the category of rocky super-Earths (e.g., Haywood et al. 2014). The latter motivated many researchers to develop models for the interior and composition of super-Earth planets.

Being so close to its host star, CoRoT-7b may not have significant atmosphere. Because this planet is in a tidally locked position with its parent star, which causes one side of it to face the star at all time. It is believed that the surface of its bright side must have been depleted of volatiles, suggesting that the atmosphere of the planet may be rich with rocky vapors.



CoRoT 7b, Fig. 3 Artist's rendering of CoRoT-7b covered with lava

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CoRoT Satellite

Olivier La Marle
Centre National d'Etudes Spatiales DSP/EU,
Paris, Cedex 01, France

Keywords

Asteroseismology · CoRoT · Exoplanet · Transit

Definition

The CoRoT mission is a satellite for the study of the stellar structure through asteroseismology and for the detection of transiting exoplanets.

Overview

CoRoT (for Convection, Rotation, and Planetary Transits) is the first space mission designed for the study of the stellar physics through ► [asteroseismology](#) and for the search for exoplanets with the method of transits. It was launched on December 27, 2006, from Baïkonour, and sent scientific data up to November 2012. CoRoT was developed and operated by the French space agency ► [CNES](#) and French CNRS laboratories LESIA, LAM, IAS, and IRAP, with significant contributions from Austria, Belgium, Brazil, ESA, Germany, and Spain.

Basic Methodology

Stars, acted on by gravity, pressure, and Coriolis forces, behave as oscillators with many specific

modes. These oscillations are detectable through tiny variations in the stellar luminosity, and their analysis provides important parameters on the stars' internal structure.

When an exoplanet travels between its host star and us, it induces a weak drop of the star's luminosity (a mini-eclipse). The detection of this periodic ► [transit](#) in the star's light curve, together with its careful analysis, reveals the existence of the exoplanet and provides important characteristics such as its radius, its orbit parameters, and the rotation period of the star.

CoRoT's wide field of view enables it to monitor the flux from thousands of stars for uninterrupted period of several months, in order to detect and measure the tiny variations in this flux, either for stellar activity measurements or for exoplanets' transit detection. The satellite carries a 27 cm, two mirrors off-axis visible telescope focusing the stars' light on a focal unit hosting the four (1) frame transfer CCD matrices of $2,048 \times 4,096$ pixels (Baglin et al. [2007](#); Auvergne et al. [2009](#)). The detectors, whose temperature is regulated at -40°C , have a high quantum efficiency in the visible wavelengths. On top of this instrument, a baffle reduces the parasitic stray light down to a few photons/s/per pixel (Fig. 1).

1. From March 2009, only two CCD matrices were left operating.

Key Research Findings

Asteroseismology

One hundred fifty-six various bright stars and 35,000 red giants were observed for uninterrupted durations of about 80–150 days in most cases. A few highlights of the results already achieved by CoRoT are presented here.

Solar-Like Pulsation, Granulation, and Convective Core

CoRoT measured solar-like oscillations and granulation in stars hotter than the Sun (Michel et al. [2008](#)). The modes' widths (inversely proportional to the lifetime of the modes) have been found to be noticeably larger than those in the Sun and larger

than expected. In terms of stellar structure, the first seismic interpretations of the measured eigenfrequencies address the crucial question of the extension of the mixing beyond the stellar convective core. This key process is responsible for

the present large uncertainty on stellar age determinations.

Red Giants and the Future of Our Sun

Toward the end of their lives, stars like the Sun expand and become ► [red giant](#) stars. Because of the turbulent convection in their outer layers, red giant stars are expected to exhibit solar-like oscillations, but in a much lower range of frequencies (10–100 μHz). CoRoT data allowed to measure clearly for the first time such oscillations in a large sample of red giants (Fig. 2).

In addition, unambiguous evidence of the excitation of both radial and nonradial modes was provided, previously an open question. CoRoT data also confirmed the existence of modes with lifetimes of the order of one month (De Ridder et al. 2009; Carrier et al. 2010).

The first theoretical modeling of this stellar evolution stage suggests that it would be possible to explain the observed oscillation spectra and their variety for different stages of the structure of stars along their expansion in the red giant phase. Indeed these red giants of different masses and ages are representative of all the successive generations of stars in the Galaxy. Through the asteroseismology of red giants, CoRoT therefore opened the door for a new method for galactic archeology.

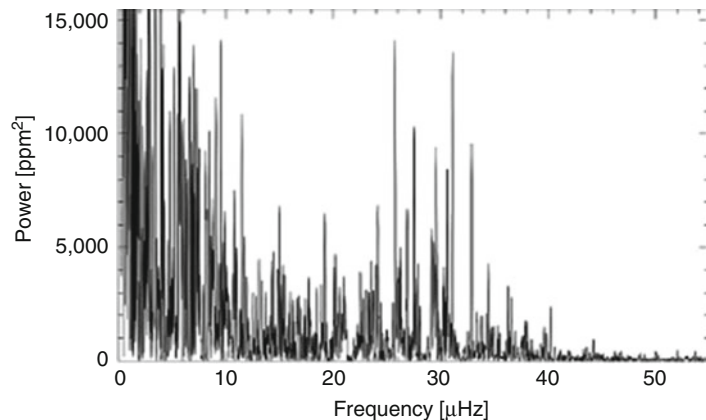
New Type of Pulsators

CoRoT data led to the discovery of new types of pulsating stars. HD180872 is one of them. This



CoRoT Satellite, Fig. 1 The CoRoT satellite during its integration onto the Soyuz launcher

CoRoT Satellite, Fig. 2 Power spectrum of the CoRoT observations of the red giant HR 7349 (Carrier et al. (2010). Reproduced with permission © ESO)



star was known to belong to the Beta Cephei class of pulsators, young massive stars which are progenitors of SN-II type supernovae and thus mainly responsible for the enrichment of the universe in carbon and oxygen. These stars classically show oscillation periods of the order of a few hours. In the lightcurve of HD180872, CoRoT data revealed, at very low amplitude, the existence of higher-frequency modes, due to stochastic oscillation, very comparable to the ones observed in the Sun (Belkacem et al. 2009). This confirms the existence of a powerful convective zone and will allow the scaling of its energy. This discovery opens new perspectives in the study of these objects where low-frequency oscillations and high-frequency ones could be used in a complementary way to probe the center and the outer layers of the star.

Search for Exoplanets

One hundred sixty three thousand six hundred eighty two stars were monitored by CoRoT for duration up to 6 months. Thirty-five companions (mainly exoplanets and a few brown dwarves) have been confirmed so far, and 130 candidates identified (Fig. 3).

These discoveries widen the variety of the known exoplanets family (Table 1). CoRoT-3b, the heaviest and the densest one, lies at the frontier with ► [brown dwarfs](#) (Deleuil et al. 2008). On the opposite side, CoRoT-7b is the first telluric exoplanet which mass and radius are known (Léger et al. 2009; Queloz et al. 2009). It provides

evidence for the existence of Earth cousins in orbit around Sun-like stars. Several planets such as CoRoT-1b, CoRoT-2b, CoRoT-11b, and CoRoT-20b challenge the current theory for planet formation and/or migration in a disk.

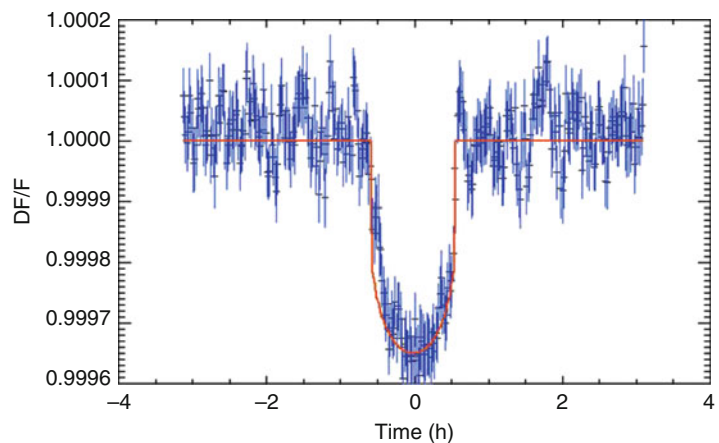
CoRoT-7b is phase-locked, that is to say that its orbital and rotational periods are equal (0.85 day). Therefore, it shows always the same face to its star (as the Moon does relatively to the Earth). This induces a very hot temperature (up to 2,600 K) on the dayside and a very cold one (down to 50 K) on the nightside.

CoRoT-9b is the first transiting temperate exoplanet. Indeed, the medium surface temperature of this Jupiter-like gaseous planet stands between -20°C and 150°C , depending on the models, and the temperature excursion between daytime and nighttime is probably low (Deeg et al. 2010). Its low eccentricity ensures a relatively low seasonal temperature variation. Further spectroscopic observations of its transits should open a new era in the study of exoplanets, allowing planetologists and biochemists to enter the game.

CoRoT also detected the secondary transit of exoplanets at the visible wavelength for the first time (Alonso et al. 2009a, b). This phenomenon occurs when the planet disappears behind its star, inducing a slight dip in the total flux received from the two of them. In the case of CoRoT-1b, for instance, this dip was only of 2/10,000. This allowed to measure the planet albedo (reflectivity), which turns to be of about 10% (compared to about 40% for the Earth).

CoRoT Satellite,

Fig. 3 CoRoT-7b light curve. The 0.03% dip in the star's flux during the planet's transit is clearly visible (© CoRoT)



CoRoT Satellite, Table 1 Characteristics of a sample of CoRoT planets

Name	Period (day)	Mass (M_{Jupiter})	Radius (R_{Jupiter})	Mean density (g/cm^3)	Star type	Main features
CoRoT-1b	1.51	1.03	1.49	0.38	G0V	Metal poor host star – secondary transit detected
CoRoT-2b	1.74	3.31	1.46	1.31	G7V	Very young star (~0.5 billion years), challenges planet formation theory – secondary transit detected
CoRoT-3b	4.26	21.6	1.0	26.4	F3V	Brown dwarf or super planet
CoRoT-5b	4.03	0.46	1.39	0.217	F9V	Very low density
CoRoT-7						
b	0.85	0.025	0.157	7.50	G9V	CoRoT-7b first telluric exoplanet ($M = 5.4 M_{\text{Earth}}$, $R = 1.6 R_{\text{Earth}}$)
c	3.7	0.043	NA	NA		
d	9	NA	NA	NA		
CoRoT-9b	95.27	0.84	1.05	0.90	G3V	First moderate temperature transiting exoplanet
CoRoT-10b	13.24	2.75	0.97	3.7	K1V	High eccentricity (0.53)
CoRoT-11b	2.99	2.33	1.43	0.99	F6V	Fast-rotating star (period < 2 days)
CoRoT-14b	1.51	7.6	1.09	7.3	F9V	Very dense hot giant
CoRoT-15b	3.06	63.3	1.12	96	F7V	Very dense brown dwarf
CoRoT-20b	9.24	4.24	0.84	8.9	G2V	Very young system (100 million years). A very dense planet challenging planet formation theories. High eccentricity (0.56)

In addition to transits, CoRoT detected a number of other effects and demonstrated how they could be used to better characterize the star-planet systems, such as the Rossiter-McLaughlin effect and the ellipsoidal and beaming effects (detected for the first time for a substellar companion with CoRoT-3b).

Applications

CoRoT will let us make a giant step forward in our knowledge of stars' and the planets' birth, life, and death and therefore bring a major contribution of our knowledge of the Universe we live in. It also paves the way for the search for life in the universe: on one hand, it identifies planets for which detailed analysis with other techniques will be of particularly high interest. On the other hand, it eased the work of its successors, the US mission ► [Kepler](#) (Basri et al. 2005) and the future European mission ► [Plato](#) (Catala et al. 2010), by providing a great know-how on the transit

method, in particular on the optimal strategy for targets selection, for data processing, and on-the-ground follow-up. It also helps the delicate thinking of the astronomical community in the definition of the best strategy for the search for extraterrestrial life.

Future Directions

In stellar physics, CoRoT was a pioneer in establishing the richness of asteroseismology. The future will probably be devoted to the increase of the sample and of the variety of stars observed. CoRoT, Kepler, and later on Plato will be major contributors; ground surveys might also contribute, especially for low-frequency oscillations.

Several international scientific bodies were set up to propose a roadmap for the exoplanets and extraterrestrial life detection, in Europe (EP-RAT, Blue Dots initiative) or in the USA (Decadal Survey). The Pathways Conference in

Barcelona in September 2009 proposed a three-step strategy:

1. Statistical study of planetary objects
2. Designate sources suitable for spectroscopic follow-up
3. Carry out spectroscopic characterization

The first and second steps would involve several methods such as transits, radial velocities, astrometry, and microlensing. The Kepler mission and, on a larger scale, the Plato mission intend to make a wide census and characterization of transiting planetary systems. TESS, CHEOPS, GAIA, Euclid, and ground surveys will also contribute. The spectroscopic characterization will require large ground telescopes, such as the ESO VLT and the future large telescopes (E-ELT, TMT), and space-based facilities such as the James Webb Space Telescope.

Cross-References

- [Asteroseismology](#)
- [Atmosphere, Temperature Inversion](#)
- [Brown Dwarf](#)
- [Exoplanets, Discovery](#)
- [Habitability, Effect of Eccentricity](#)
- [Habitable Zone, Effect of Tidal Locking](#)
- [Hot Jupiters](#)
- [Hot Neptunes](#)
- [James Webb Space Telescope](#)
- [Kepler](#)
- [Planetary Migration](#)
- [PLATO 2.0 Satellite](#)
- [Radial Velocity](#)
- [Red Giant](#)
- [Secondary Eclipse](#)
- [Spectroscopy](#)
- [Stellar Pulsation](#)
- [Stellar Rotation](#)
- [Super-Earths](#)
- [Transit](#)
- [Transiting Planets](#)
- [VLT](#)

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Corotation Torque

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

The corotation torque is that exerted on a planet's orbit by material (usually gas) co-orbiting with the planet. This has a very important effect on the orbital migration of planets of less than roughly 50 Earth masses that form in gaseous ► [protoplanetary disks](#). Recent analysis suggests that very rapid, inward “type 1” migration – caused by tidal interaction between the disk and a planet – may in fact be slowed or even reversed in certain situations due to the corotation torque.

Cross-References

- [Lindblad Resonance](#)
- [Planetary Migration](#)
- [Protoplanetary Disk](#)

Corrosion

- [Oxidation](#)

Cosmic Background Radiation

Stéphane Le Gars
Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Arno Penzias · Astronomy · Big Bang ·
Cosmic background radiation · Cosmology ·
George Gamow · Georges Lemaître · History ·
Nucleosynthesis · Physics · Robert Wilson

Synonyms

[CMB](#); [Cosmic microwave background](#)

History

In 1965, two American physicists, Arno Penzias and Robert Wilson, accidentally discovered electromagnetic background noise at 7.35 cm wavelength in the millimeter radio wave region. Penzias and Wilson were working for the Bell Telephone Laboratories on satellite communication improvement when they brought to light this homogeneous and isotropic radiation resulting from the universe as its whole; it was quickly read as fossil radiation from a universe that was originally dense and hot and had cooled off because of its expansion to a 3.5 K temperature today. In 1978, Penzias and Wilson got the Nobel Prize for this discovery.

However, there had been some previous investigations in this general area. The French physicist Charles-Edouard Guillaume had calculated in 1896, by Abney's works and according to the black body's law that Stefan granted in 1879, that an isolated body in the space, only subdued to stars' radiation, would see its temperature increasing of nearly 5 K. In 1926, Sir Arthur Eddington shows that the real temperature of the space, due to star's radiance, is 3.18 K. But there was a lack of theoretical framework to give sense to theoretical calculations assuming some model of the universe. Indeed, Edwin Hubble proved in 1924, with detailed observations, that the universe is formed of myriads of galaxies. In 1929, he also discovered empirically that these galaxies all move away from one another. At the same time, the works of the Belgian physicist Georges Lemaître interpreted the observational data in terms of relativity theory to show that the universe is expanding.

In the 1940s, the American astrophysicist George Gamow laid down the basis of nucleosynthesis, the formation of the chemical elements. According to Gamow, the chemical

elements could have been made at a hot and dense period of the universe, in the bosom of an “original soup” that he named “ylem” and that represented an early stage of the Big Bang. In 1948, two Gamow’s collaborators, Alpher and Herman, developed Gamow’s ideas and predicted the existence of a diffuse radiation background with a 5 K temperature. Within this theoretical framework, this cosmic background radiation has become the experimental mainstay of the Big Bang theory, which includes the universal expansion and the nucleosynthesis of the lightest elements. The background radiation has recently been measured very accurately in 2001 and 2006, respectively, with satellites COBE and WMAP.

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Cosmic Dust

- [Interstellar Dust](#)

Cosmic Microwave Background

- [Cosmic Background Radiation](#)

Cosmic Ray, Ionization Rate

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

The cosmic ray ionization rate in the ► [interstellar medium](#) is the rate at which H₂ molecules as well as atomic H and He are ionized by the flux of galactic cosmic rays. This process is fundamental to driving the chemistry in dense interstellar clouds. Current estimates place the value in the range $1\text{--}40 \times 10^{-17} \text{ s}^{-1}$ with the higher values being more appropriate for lower-density diffuse interstellar clouds.

Cross-References

- [Cosmic Rays in the Heliosphere](#)
- [Diffuse Cloud](#)
- [Interstellar Chemical Processes](#)
- [Molecular Cloud](#)

Cosmic Rays

Nikos Prantzos¹ and Jun-Ichi Takahashi²

¹Institut d’Astrophysique de Paris, Paris, France

²Yokohama National University, Faculty of Engineering, Yokohama, Japan

Keywords

Cosmic rays · Electrons · Energetic particles · Nuclei

Definition

Galactic cosmic rays are high-energy (relativistic) electrons and nuclei, accelerated by supernova explosions and massive stellar winds and

traveling through the Galaxy by scattering on fluctuations of interstellar magnetic fields, which render their flux isotropic.

Overview

The energy spectrum of galactic cosmic rays (CR) covers the energy range from a few MeV/nucleon up to 10^{15} MeV/nucleon and is well approximated by a power-law $N(E) \propto E^{-\alpha}$ of slope $\alpha = -2.7$ below 10^6 GeV/nucleon and $\alpha = -3$ above that. Below a few GeV/nucleon, the CR spectrum progressively flattens (with α even becoming positive) and its intensity varies, in a way that anticorrelates with solar activity ("solar modulation"); the solar wind prevents the lowest energy CR from entering the heliosphere. The total galactic power of CR is estimated to be 10^{41} erg/s, that is, about 10 % of the total kinetic power of [supernovae](#) and stellar winds, which are thought to be the main CR accelerators. However, no galactic accelerator can account for the highest energy CR (up to $\sim 10^{12}$ GeV), the origin of which remains unknown. The residence time of CR in the galactic disk is $\sim 10^7$ years. The composition of CR nuclei is overall similar to the solar one: it consists of ~ 87 % protons, 12 % alpha nuclei (helium atoms), and 1 % heavier nuclei (in addition to the nucleonic component ~ 3 % of the CR flux are high-energy electrons). The major uncertainties are at extremely high energies and for elements heavier than iron. There are several important differences: the metallicity (see [► Metallicity](#)) of CR is ~ 10 times solar, with refractory elements (Fe-peak nuclei) relatively more enhanced than the volatiles; and the fragile Li, Be, and B nuclei are 10^6 times more abundant in CR than in the Sun. These features suggest that CR are accelerated from a mixture of interstellar gas and dust grains (where refractory elements are overabundant), and during their propagation in the Galaxy, they spallate abundant CNO nuclei to produce Li, Be, and B.

From the standpoint of astrobiology, CR may play a crucial role, either as effective energy sources for synthesizing the precursors of

terrestrial bioorganic compounds in interstellar media or as agents inducing mutations in living organisms and thereby promoting biological evolution. They may even be lethal in case of a nearby supernova.

Cross References

- [Biostack](#)
- [Cosmic Rays in the Heliosphere](#)
- [Evolution, Biological](#)
- [HZE Particle](#)
- [Ionizing Radiation, Biological Effects](#)
- [Mutation](#)
- [Nucleon](#)
- [Proton Irradiation](#)
- [Radiation Biology](#)
- [Radiochemistry](#)
- [Spallation Reaction](#)
- [Supernova](#)

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Cosmic Rays in the Heliosphere

Don F. Smart
Air Force Research Laboratory (Emeritus),
Bedford, MA, USA

Keywords

Cosmic radiation · Solar modulation

Definition

Cosmic rays are very energetic particles thought to pervade space. Within the solar system, the cosmic ray flux is modulated by the solar activity cycle.

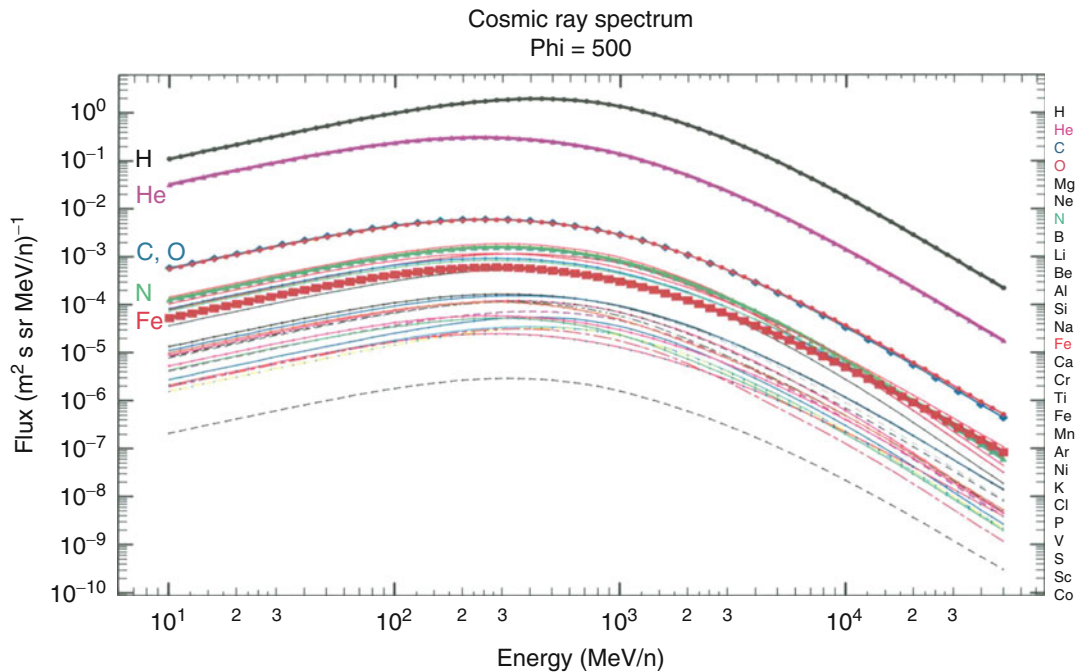
Overview

Cosmic radiation observed at the Earth consists of ~83% protons, 12% alpha particles, 1% heavy nuclei with atomic number >2, and ~3% electrons. The cosmic ray composition of the most common elements has been measured to a reasonable precision (see Fig. 1). The major uncertainties are at extremely high energies and for elements heavier than iron. The local interstellar spectrum (outside the heliosphere) is constant, but inside the heliosphere, the spectrum and fluence of particles below ~10 GeV/nucleon are modified by solar activity with a phase that is the inverse of the solar sunspot cycle. The cosmic ray flux decreases with increasing energy and the proton flux is reduced by 50% at 1.5 GeV. The cosmic ray flux of the heavier nuclei is reduced by 50% at 0.9 GeV/nucleon. The maximum total isotropic flux in free space at 1 AU is ~3 particles cm⁻² s⁻¹ during solar minimum conditions; during solar maximum conditions, the total cosmic ray flux is

reduced by ~40%. The diffusion of the cosmic ray flux inwards through the turbulent interplanetary medium results in an average radial cosmic ray gradient of a few percent per AU. The cosmic radiation flux at Mars (1.5 AU) is only a few percent larger than at Earth.

The major factors modulating the cosmic radiation intensity include the solar wind speed, turbulence in the solar wind, and solar magnetic polarity. Cosmic ray modulation theory adequately models the flux at the Earth and at our most distant space probes. The modulation parameter, designated by the symbol ϕ , is normally expressed in units called MV. The modulation parameter at 1 AU during solar minimum typically ranges between 400 and 500 MV; however, extreme solar activity can generate transient modulation levels in excess of 1,600 MV (see Fig. 2).

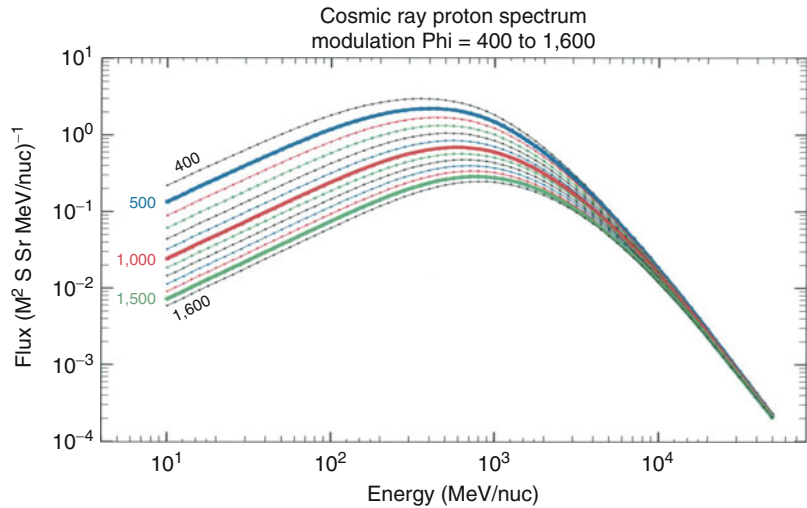
The particle flux below ~2 GeV/nucleon makes the most important contribution to radiation dose. Since the energy deposition in matter is proportional to the square of the atomic charge,



Cosmic Rays in the Heliosphere, Fig. 1 A model of the modulated differential cosmic ray spectrum at 1 AU for the most abundant elements in the cosmic ray flux during

average low solar activity conditions. The elements listed on the right side of the figure are in the order of their observed abundance. Original figure created by the author

Cosmic Rays in the Heliosphere, Fig. 2 A model of the modulated differential cosmic ray proton spectrum at 1 AU for modulation conditions, ranging from near solar minimum to solar maximum. Original figure created by the author



the heavy elements are important for computing radiation dose.

Cross-References

► [Cosmic Ray, Ionization Rate](#)

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their extraterrestrial origin. Cosmic spherules are predominantly found in ocean floor deposits on Earth and are mainly produced by frictional heating, melting, and ► [ablation](#) of ► [meteoroids](#) upon atmospheric entry. Solidified impact-induced molten droplets of meteoroid and target materials are less abundant on Earth but would predominate on the exposed surfaces of atmosphere-less bodies like the Moon that were strongly gardened by impacting meteoroids in their early history.

Cross-References

► [Ablation](#)
 ► [Meteoroid](#)
 ► [Moon, The](#)

Cosmic Spherules

Frank Sohl
 Deutsches Zentrum für Luft- und Raumfahrt
 (DLR), Institut für Planetenforschung, Berlin,
 Germany

Definition

Spherule comes from the Greek word “sphaira” for sphere. Cosmic spherules are solid, rounded particles ranging from micrometer to millimeter in size with distinct chemical compositions indicating

Cosmic-Ray-Induced Desorption

Eric Herbst
 University of Virginia, Charlottesville, VA, USA

Definition

Cosmic rays, high-energy nuclei, travel throughout the universe at nearly the speed of light and bombard both gas-phase molecules and dust particles in interstellar space. The bombardment of dust

particles leads both to sputtering of material and to the heating up of the particles. The heating in turn allows molecules to “evaporate” into the gas, a term more accurately known as “desorption.”

Overview

Cosmic rays are high-energy (MeV–GeV) particles, mainly protons but including a range of heavier atomic ions such as metals, likely formed in supernova explosions. When these particles enter an interstellar cloud, they interact with both the gas, producing gaseous ions, excited neutrals, and photons, and dust particles, with and without ice mantles. The interactions between cosmic rays and atoms and molecules in and on the grain can be divided into elastic collisions (with nuclei) and inelastic collisions (with electrons). Cosmic rays of heavy elements can play an important role in these collisions. The elastic collisions can be regarded as ballistic events, which can blow material off of the grains via a process known as “sputtering,” in which backward scattering of the target material occurs. The inelastic collisions with electrons can be partially converted into heat, which raises the temperature of a whole grain to a maximum temperature, depending upon the size and heat capacity of the grain, before cooling ensues. At the standard initial grain temperature of 10–20 K, only very weakly bound species can desorb within a physically reasonable lifetime, but higher temperatures lead to a dramatic enhancement in thermal desorption, especially from outer layers of ice mantles found in cold clouds (Hasegawa and Herbst 1993). The enhancement of the rate coefficient for thermal desorption is clearly shown by the equation

$$k_d = \nu \exp(-E_d/kT),$$

where ν is the so-called trial frequency for physisorbed adsorbates ($\approx 10^{11} - 10^{12} \text{ s}^{-1}$) and E_d is the energy needed for thermal desorption. With a desorption energy for physisorbed species of 1000 K ($\approx 0.1 \text{ eV}$), the rate coefficient for desorption increases from 10^{-31} s^{-1} at 10 K to 10^6 s^{-1} at 70 K, a maximum temperature estimated for grains of size 0.1μ with the low cosmic-ray flux

present inside dense interstellar clouds. Recent observations indicate that the cosmic-ray flux can be up to two orders of magnitude greater in lower-density clouds or on the edges of dense clouds, with special enhancement in lower-energy cosmic rays, which possess high cross sections for inelastic collisions. The net result in such sources is an increase in the rate of cosmic ray induced heating events by up to two orders of magnitude. A new estimate for the size of the enhancement in dense clouds is at least one order of magnitude (Kalvans 2016). In addition, it should be noted that much of the surface area for grain populations occurs at smaller sizes than 0.1μ , and these smaller grains will rise to still higher temperatures. Other desorption mechanisms caused by cosmic rays include spot heating, and ejection of ice fragments, although there is still little evidence for grain explosions, which would require large populations of radicals.

Cross-References

► [Interstellar Dust](#)

References and Further Reading

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Cosmochemistry

Matthieu Gounelle

Laboratoire de Minéralogie et Cosmochimie du Muséum (LMCM) MNHN USM 0205 – CNRS UMR 7202, Muséum National d'Histoire Naturelle, Paris, France

Keywords

Accretion disk · CAIs · Chondrites · Chondrules · Protoplanetary disk

Synonyms

Meteoritics

Definition

Cosmochemistry is the study of the formation and evolution of the Solar System and its individual components through the analysis of extraterrestrial samples in the laboratory.

History

The first mention of a meteorite in western literature concerns the prediction of the fall of a meteorite by Anaxagoras of Clazomenae in the year 467 BC. During Antiquity, ► [meteorites](#) were revered as gods in many places of the Mediterranean basin. During the Middle Ages, they were still considered with superstition and fear. Though more rational interest was paid to meteorites in the Renaissance, they still belonged to the reign of natural wonders. Interestingly, the Enlightenment era failed to identify the true provenance of meteorites, probably because analytical chemistry was yet to be developed.

Ernst Florens Chladni (1756–1827) can be seen as the founder of cosmochemistry. At a time when most scientists believed meteorites were mere stones from volcanoes or atmospheric condensations, he proposed in a provocative pamphlet published in 1794 that meteorites were extraterrestrial objects. This bold proposition was harshly discussed for the next 10 years among the European scientific community. It was finally accepted in 1803 after the fall of a meteorite at L'Aigle in France and the publication of a detailed report by Jean-Baptiste Biot (1774–1862, Fig. 1). Being the first scientist to travel to the place of a meteorite fall and helped by a beautiful literary style, Biot was able to convince his peers that stones fell from the sky.

At that time, many of the early cosmochemists such as Chladni, Laplace (1749–1827), or Biot thought meteorites came from the Moon. It is not until the mid-nineteenth century that scientists



Cosmochemistry, Fig. 1 Jean-Baptiste Biot (1774–1862). After the fall of the L'Aigle meteorite in 1803 in France, he wrote a report which definitely established the extraterrestrial origin of meteorites

realized that most meteorites come from ► [asteroids](#), the first of which, Ceres, was discovered in 1801. After the recognition of the extraterrestrial nature of meteorites, the field of cosmochemistry blossomed. It started with the development of elaborate classification schemes (strikingly similar to the one used now) and chemical analyses, which expanded on the pioneering studies of Lavoisier (1743–1794) and Howard (1774–1816). The identification of new minerals and of chondrules, a major component of the primitive meteorites unknown in terrestrial rocks, clearly set meteorites apart from terrestrial rocks.

Basic Methodology

Meteorites are studied using the same techniques as terrestrial rocks. The petrography (relative

abundance and textural relationships between the different components and individual minerals) and mineralogy (structure and chemical composition of minerals) are made on rock sections (i.e., cut and polished) with a diversity of optical and electronic microscopes. Isotopic analyses are performed with a diversity of mass spectrometers. Secondary ion mass spectrometers and thermo ionization and inductively coupled plasma mass spectrometers are used for a wide range of rock-forming elements. While the former provide a very good spatial resolution (micron scale), the latter have reached precisions of the order of tens of ppm. Organic matter within meteorites is now studied in detail with techniques imported from the oil industry (► [Meteorite, Murchison](#)).

Key Research Findings

Today, extraterrestrial samples can be collected directly from space thanks to sophisticated and expensive space missions, such as Stardust, which brought back cometary dust from the Wild 2 comet in January 2006. But these missions are still rare. Most cosmochemists focus their work on meteorites and micrometeorites that fall on Earth, a cheaper way to sample celestial bodies millions of kilometers away. Roughly 50 t of meteorites (size range 1 g–100 kg) and 7000 t of micrometeorites (<mg) fall on the Earth's surface every year. In April 2010, the number of meteorites registered by the Meteoritical Society was 38,800.

Nowadays, cosmochemistry is a very active scientific discipline, which greatly benefits from its proximity with other fields, especially astrophysics, but also geology and material sciences. Thanks to the diversity of extraterrestrial samples (meteorites as well as lunar rocks and cometary dust brought back by space missions) and to the wealth of techniques used and its fecund interaction with a large number of neighboring fields, it can address a diversity of fundamental scientific questions. The following point of view on cosmochemistry is complementary to that presented in the entry ► [meteorites](#); special emphasis will be given to important discoveries and open questions.

What Do Meteorites Look Like?

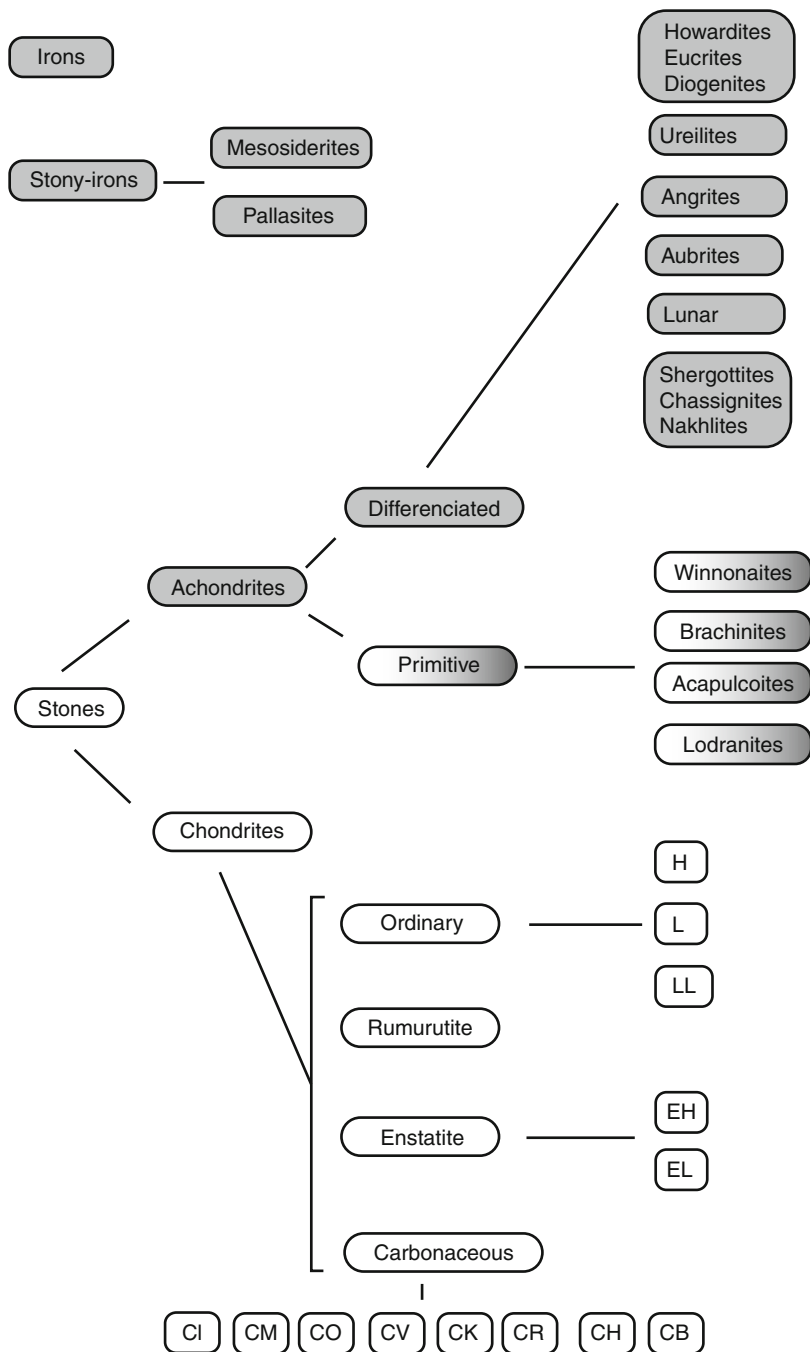
Meteorites are rocks made of minerals (and occasionally glasses). They can be distinguished from terrestrial rocks mainly by their fusion crust (► [Meteorite, Allende](#)), i.e., a mm-thick veneer of glass produced during their entry at cosmic velocity (~10–20 km/s) into the Earth's atmosphere.

Though meteorites can be divided into 135 different classes, mineralogically there exist three main groups of meteorites (Fig. 2): stones (94% of the observed falls), stony irons (1%), and irons (5%). Though some of them might have an impact origin, irons are believed to represent the cores of large, differentiated asteroids or planetesimals; and stony-iron meteorites are thought to be mixtures of core and mantle or core and crust material. Stony meteorites can be divided into chondrites and achondrites. The former are characterized by a large abundance of small mm-sized blobs known as chondrules (see below) that have a chemical composition similar to that of the Sun. Achondrites are magmatic rocks. They lack chondrules and have a strongly fractionated chemical composition relative to that of the Sun; they are believed to originate from the crust of planets and other smaller differentiated bodies.

Chondrites are made of calcium-aluminum-rich inclusions (CAIs), chondrules, and matrix (Fig. 3). The relative abundance of these three components varies between chondrite groups. In most chondrites (except CIs), chondrules represent the dominant component. CAIs are an assemblage of calcium and aluminum oxides and silicates (► [CAIs](#)). Some of them show evidence of melting. Chondrules are an assemblage of iron-magnesium silicates plus metal and sulfides. Chondrules usually show an igneous texture indicating they were at some point extensively melted in the solar protoplanetary disk. Matrix is made of fine-grained (<1 μm) iron-magnesium silicates, metal, and sulfides. In the case of carbonaceous chondrites, the matrix is rich in organic matter. For most chondrite groups, the matrix has been modified on the parent asteroid due to secondary geological processes such as thermal metamorphism or hydrothermal alteration.

Cosmochemistry,

Fig. 2 Simplified classification of meteorites. *Gray boxes* indicate differentiated meteorites, while *white boxes* indicate primitive meteorites. Primitive achondrites (shaded gray) are objects having the composition of chondrites and the texture of differentiated rocks

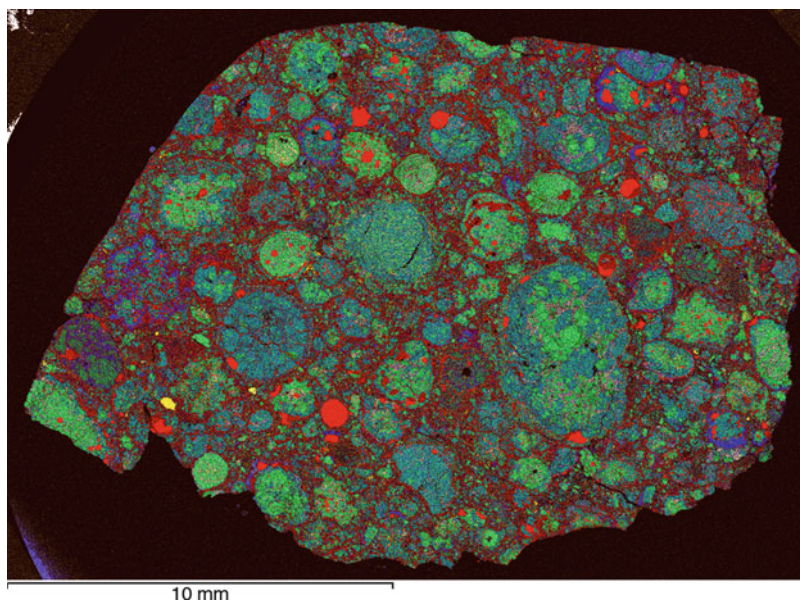


Achondrites, at first sight, look like terrestrial igneous rocks. They are made of mafic minerals such as olivine and pyroxene and an aluminum-rich silicate, plagioclase. If it were not for the

fusion crust, they would be difficult to distinguish from terrestrial basalts, though detailed studies show they come from evolved bodies, which had a different geologic history than the Earth.

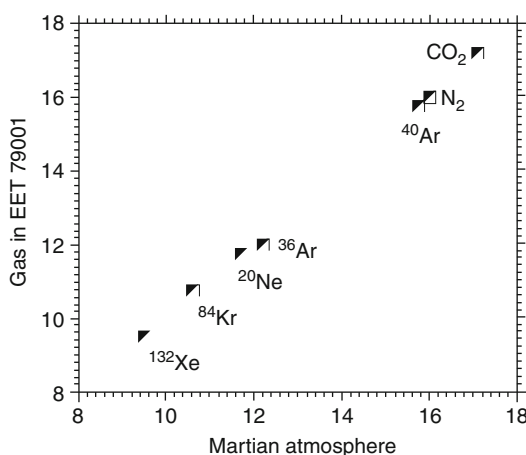
Cosmochemistry,

Fig. 3 Chemical composition of the chondrite GRO 03116. Red, green, blue, yellow, and white code, respectively, for iron, magnesium, silicon, calcium, and aluminum. One can appreciate the richness in reduced iron (red), the high abundance of chondrules (green-blue iron-magnesium silicate spheres), and the rarity of CAIs (in yellow white). (Picture courtesy of Anton Kearsley (NHM))

**Where Do Meteorites Come From?**

Most meteorites are chondrites. They are cosmic sediments whose components were made in the protoplanetary disk and cemented together via poorly characterized processes. Chondrites were not differentiated, i.e., metal and silicates were not segregated after melting. The larger a body is, the easier it is to melt; therefore, the undifferentiated nature of chondrites indicates they originate from small celestial bodies, ► [asteroids](#) or ► [comets](#). The determination of the orbits of a few meteorites has confirmed that most chondrites come from asteroids, though some, such as CI chondrites, could come from comets (► [Meteorite, Orgueil](#)). It is however not possible to pinpoint from which specific asteroid meteorites come from, except for one noticeable exception. The good match between the infrared spectrum of HED meteorites and the asteroid (4) Vesta suggests these meteorites come from that asteroid.

On the other hand, the compositional and mineralogical similarities of roughly 100 meteorites to lunar samples collected by the space missions Apollo and Luna establish that they come from the Moon. The same number of meteorites – forming the SNC (Shergottite-Nakhilite-Chassignite) group – come most likely from the planet Mars. This was demonstrated by the excellent match in



Cosmochemistry, Fig. 4 Chemical composition of the gas trapped in the SNC (Martian) meteorite EET 79001 compared to that of the Martian atmosphere determined by the Viking spacecraft in the 1970s. (From Bogard et al. (1984))

composition between gas bubbles trapped within meteorites from the SNC group and the Martian atmosphere composition measured by the Viking landers in 1976 (Fig. 4).

The origin of micrometeorites is still debated. Recent work suggests they come mostly from comets rather than from primitive asteroids. It is worth noticing that the precise origin of

micrometeorites does not matter much, as the analysis of cometary samples returned by the Stardust mission has demonstrated that comets and primitive carbonaceous asteroids are similar in nature.

Dating Meteorites and Other Bodies: A Rough Sequence of Events

One of the major achievements of cosmochemistry has been to date extraterrestrial samples. In 1956, Claire Patterson proposed an age of 4.55 Ga for the Solar System and the Earth (see ► [Earth, Age of](#)). To accomplish this fundamental task, he used two long-lived radionuclides ^{235}U and ^{238}U which decay into ^{207}Pb and ^{206}Pb , with respective half-lives of 0.7 and 4.5 Ga. The long-lived radioisotope ^{87}Sr ($T_{1/2} = 48$ Ga) was also extensively used to date early Solar System processes during the 1960s and 1970s, but is today too imprecise for the task (compared to other systems). Iodine-129 with half-life of 15.7 Ma was the first short-lived radionuclide whose past presence in a meteorite was unambiguously demonstrated. Many more were to follow (see below).

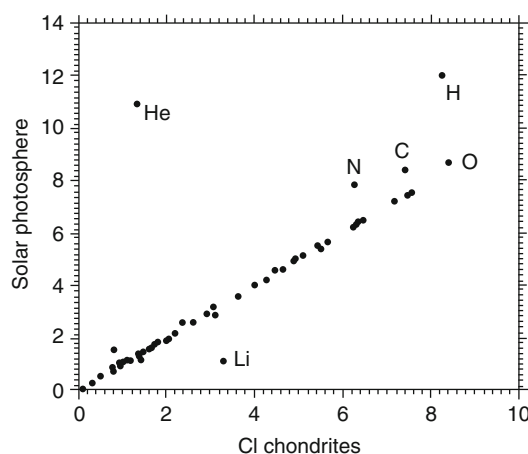
The use of chronometers, combined with astronomical observations, made it possible to date the sequence of events from the collapse of the portion of a molecular cloud to the Solar System in its present configuration. The lifetime of the molecular cloud precursor of our Solar System is not known, but molecular clouds usually live for a few million years before they get disrupted by the harsh effects (photoionization, powerful winds) of the stars to which they gave birth. The following stage, i.e., the gravitational collapse of a portion of the molecular cloud, takes some 100,000 years and can be seen as a transition phase during which, however, important gas-grain chemistry occurs. In the next stage, the protosun is surrounded by an accretion disk through which it is fed with matter. Because it is within the same disk that the components of chondrites, chondrites themselves, planetesimals (from 1 km up to 1000 km), and large planetary embryos (1000 km-sized bodies) are formed, the accretion disk or solar nebula is also called a protoplanetary disk.

CAIs most likely formed first in the protoplanetary disk 4568 Ga ago, followed by chondrules which formed 1.5 Ma later. The accretion of chondrites from their components and of planetesimals from chondrites occurred as soon as chondrules were formed. The disk was dissipated after a few million years, according to astronomical observations of other stellar systems. Embryos probably grew on that same million-year timescale.

Chemical and Isotopic Composition

CI chondrites have the same chemical composition as the Sun for all elements except for the most volatile ones, such as H, He, C, and N (Fig. 5). This discovery suggests that chondrites are extremely primitive rocks that sample the earliest phases of the protoplanetary disk. The relatively small chemical fractionation of other chondrites relative to CI chondrites is attributed to physical processing in the protoplanetary disk, either before or during chondrule formation.

The bulk isotopic and chemical composition of chondrites is the result of the chemical evolution of the Galaxy over the last 10 billion years. Interestingly enough, the isotopic composition of all but a few elements in Solar System bodies (chondrites, achondrites, Earth, Mars, etc.) is remarkably identical in meteoritic, lunar, and terrestrial samples. This indicates that Solar System matter was well homogenized by high-



Cosmochemistry, Fig. 5 Chemical composition of the Sun's photosphere compared to that of the CI chondrites (shown on a logarithmic scale, normalized to silicon)

temperature processes in the protoplanetary disk, possibly linked to chondrule formation.

A few solids escaped this processing and preserved their chemical and isotopic properties. These are called presolar grains. They were discovered in the matrix of chondrites in the late 1980s at the University of Chicago. They were isolated thanks to severe chemical treatments and recognized because of their isotopic composition, radically different from that of Solar System matter. Presolar grains were made in the atmospheres of stars formed hundreds of millions before our Solar System. Thanks to their study, stellar nucleosynthesis has become an experimental field.

The oxygen isotopic composition of meteoritic components, e.g., CAIs and chondrules, is an exception to the similarity discussed above, in that it varies a great deal. While chondrules have a composition roughly similar to that of the Earth, CAIs are enriched in ^{16}O by at least 4% relative to chondrules. The origin of that enrichment – known since 1973 – is not well understood. The most popular model – the self-shielding model – invokes photochemical processes either in the parent molecular cloud or in the protoplanetary disk (► [Oxygen Isotopes](#)).

Short-Lived Radionuclides

Short-lived radioisotopes (SRs) are radioactive elements with half-lives ranging from a few weeks to 100 Ma. Their presence in the nascent Solar System is inferred from excesses of their daughter isotopes in meteoritic components, mostly in primitive components such as the CAIs. Some SRs were present in the protoplanetary disk at abundances significantly higher than the expected average contribution of the interstellar medium. These SRs therefore require a last-minute origin. They were either made within a star such as a supernova and injected into the nascent protoplanetary disk or produced within the disk itself via nuclear reactions between solar cosmic rays and ambient dust. The origin of SRs is a hotly debated topic of cosmochemistry, as it has important consequences for our understanding of: (1) the early Solar System chronology, (2) planetesimal heating, and (3) the astrophysical context of our Solar System birth.

If SRs were homogeneously distributed in the Solar System, they can be used to define a chronology of Solar System events. Aluminum-26 ($T_{1/2} = 0.74$ Ma), ^{53}Mn ($T_{1/2} = 3.7$ Ma), and ^{182}Hf ($T_{1/2} = 9.0$ Ma) are especially useful as chronometers because their initial content is known in a diversity of objects. Ages based on SRs confirm the early formation of CAIs relative to chondrules and the rapid evolution of Solar System bodies. Dating of some iron meteorites indicate indeed that differentiation of large planetesimals or asteroids occurred contemporaneously with CAI formation.

Aluminum-26 and ^{60}Fe ($T_{1/2} = 2.6$ Ma) emit gamma rays when they decay. They have been proposed as heat sources for planetesimals. The extent of heating and therefore the subsequent geological evolution depends on the initial content of these two SRs in the parent-body considered – and therefore on their initial content in the Solar System – as well as on the timing of formation of the bodies considered. Current models indicate that ^{26}Al is a more efficient heat source than ^{60}Fe .

The presence of ^{60}Fe in the Solar System seems to indicate that the Sun was born in a second-generation molecular cloud enriched in radioactive elements by massive stars. At present, there is no satisfactory model accounting for the presence of ^{26}Al in our Solar System. It might result from an improbable sequence of events, in which case the Solar System would be special in having hosted ^{26}Al while it formed. In such a case, our Solar System might be unlike others in having evolved (differentiated) parent bodies. Given that life, as we know it, is intimately linked to the geological history of our planet, it means that its development might result from a rare astrophysical event.

High-Temperature Processes in the Protoplanetary Disk

CAIs are very abundant in carbon-rich carbonaceous chondrites, while they are virtually absent from other chondrites. They are especially large and abundant in CV chondrites (► [Meteorite, Allende](#)). They therefore represent on the whole a tiny fraction of chondritic matter. Understanding

their formation is, however, important because they are the first solids to have formed in the protoplanetary disk. Their mineralogy is compatible with that of condensation from a gas of chondritic composition. Some of them show evidence of remelting and evaporation. It is widely believed that CAIs were formed close to the Sun (~ 0.1 AU), where temperatures in the disk were higher than 1600 K. They were subsequently transported to asteroidal distances, where chondrites formed, either by turbulent diffusion or via magneto-hydrodynamic winds rooted at the disk inner boundary.

Chondrules are far more abundant than CAIs. They make up to 80% of ordinary chondrites in volume. As ordinary chondrites represent more than 80% of the meteorites, chondrules were probably the most abundant solids in the disk. Some authors estimate that there might have been between 10^{24} and 10^{25} g of chondrules produced in the asteroid belt. Understanding how they were made from precursor solids and disk gas is therefore a key task of cosmochemistry.

It is widely believed that chondrules were heated up to ~ 2000 K on timescales of a few minutes and cooled relatively slowly (10–1000 K/h) compared to a cooling controlled by free radiation into space. Because of these short timescales, one speaks of flash heating. Most chondrules have been flash-heated several times, suggesting that a repetitive process was responsible for high-temperature processing. At present, the most popular mechanism for chondrules formation is the shockwave model, whereby a shockwave of speed ~ 10 km/s impacts dusty aggregates and heats them. The source of these shockwaves in the protoplanetary disk is not well identified. Gravitational instabilities, X-ray flares, and planetesimals supersonic motions have been proposed. All three models seem to face important difficulties.

Formation and Early Evolution of Telluric Planets

When the protoplanetary disk gas dissipated, we were left (in the inner Solar System) with a swarm of planetesimals and planetary embryos. It took

roughly 100 Ma to collect these bodies into the terrestrial planets we know, such as the Earth. Growth occurred through random encounters of embryos. Though many embryos contributing to a given planet came from its neighborhood (the feeding zone), a significant number of embryos came from more distant regions.

Though accretion was mostly constructive, some impacts were also partly destructive. It is widely believed that the Moon was made when a planetary embryo, roughly the size of Mars, hit the proto-Earth. The Moon was built from that embryo, sometimes called Theia, and the Earth's mantle. Thanks to the Hf-W isotopic system, it is possible to constrain that catastrophic event which gave birth to our satellite. Latest measurements suggest it occurred 62^{+90}_{-10} Ma after Solar System formation, taken as the CAI formation.

It is worth noting that dynamical studies demonstrated that the presence of the Moon stabilized the Earth's obliquity. Were the Moon absent, the Earth's obliquity would vary chaotically and Earth's climate would have been far less stable than it has been. This singular, hazardous, event might therefore have played an important role in the development of life as we know it.

While planets were forming, they developed a magma ocean and iron cores appeared. Measurements based on the Hf-W isotopic system demonstrated that the Martian core formation was completed 10 Ma after the start of the Solar System. At present there is no undisputed estimate for the age of the Earth's core.

The origin of the terrestrial atmosphere is an unsolved problem. It is a combination of delivery of volatile compounds from extraterrestrial matter and of a primordial, solar-type atmosphere trapped in the Earth's mantle and subsequently degassed. The excess of ^{129}Xe (daughter isotope of ^{129}I) in the Earth's mantle compared to the Earth's atmosphere indicates that the degassing occurred early, possibly during the first 150 Ma.

The origin of terrestrial oceans has long been debated. Because they have a hydrogen isotopic composition different from that of Earth water, long-period comets such as comet Halley probably did not contribute significantly to the water

budget. Jupiter-family comets and dark, water-rich asteroids are the best candidates. Their D/H ratio – measured in carbonaceous chondrites – is compatible with that of the terrestrial oceans. These celestial bodies might also have delivered organic matter which might have provided precursors to life chemistry. The timing of Earth's water delivery relative to the formation of the Moon is debated, though it seems pretty secure to state that water was delivered during the first 150 Ma.

At that point, all bodies were formed, and the architecture of the Solar System was only to be significantly changed once, during the Late Heavy Bombardment (LHB) 3.8 Ga ago. At that epoch, after 0.8 Ga of slow migration, the giant planets Jupiter and Saturn crossed a resonance and destabilized a disk of planetesimals, which were sent to the inner Solar System. Many of the large craters seen today on the Moon date from that time. It is actually thanks to the return of the Moon rocks and their detailed study that the LHB was identified. If there was any life present on Earth at that time, it may have been severely affected. Some other authors proposed that these impacts could have, on the other hand, stimulated life.

Future Directions

It is a challenging task to foresee the development of a scientific discipline whose future depends on the advancement of techniques, on the emergence of individuals, and on the general policy adopted by a few prosperous countries which might not remain so indefinitely. Some progress will be made on the – already populous – data collection front. That should serve to solve pending key questions such as the homogeneity of short-lived radionuclides or the locus and timing of organosynthesis. Instrumental developments should also help to revisit dogma that is rarely disputed, such as the flash-heating model of chondrule formation for which evidence is thin.

Laboratory experiments trying to reproduce key processes of the early Solar System should

also be developed. Condensation and evaporation experiments will illuminate the complex relationships between gas and solids within the protoplanetary disk and establish chemical as well as isotopic modifications induced by these fundamental processes.

An almost virgin direction of research is the study of the mechanical property of meteorites. Very little is known, for example, on their tensile strength which is key to our understanding of planetary accretion and evolution. Such measurements are desperately needed in the light of several space missions.

It is striking that, while a great deal is made of deuterium (^2H) and ^{15}N excesses in organic matter, the processes that gave rise to them are still debated. Developments on the modeling front are highly needed.

Cosmochemistry will certainly benefit from increased interaction with astrophysics. Observations of star-forming regions can be seen as a proxy of the environment of our Solar System formation. Thanks to space telescopes, such as *Herschel*, or ground-based interferometers, such as [ALMA](#), our understanding of accretion disks will be bettered, enabling us to “see” closer to the central star, in regions where precursors of planets similar to the Earth might form. Theoretical astrophysics should be a daily companion of cosmochemists, and one could dream of a world in which most, if not all, data collected are interpreted within a theoretical framework.

One exigency could represent a horizon for cosmochemistry: that of holding things together. Too many disparate interpretations coexist without being really coherent one with the other. Though some patches of the jigsaw puzzle have been thoroughly assembled and though the global vision is probably correct, many of the data collected find no explanation within our current knowledge. In that respect, astrophysics will, as always, teach us humility. Though there is no reason for our Solar System to be special, there are many possible outcomes of star and planetary formation. Ours is one among billions in the Galaxy.

Cross-References

- Asteroid
- CAIs
- Comet
- Geochronology
- Meteorite, Allende
- Meteorite, Murchison
- Meteorite, Orgueil
- Oxygen Isotopes

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Cosmogony

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A cosmogony is any theory about the origin of the universe and/or the objects it contains. Most cultures developed their own cosmogony. In astronomy, the term usually refers to theories of formation of the solar system.

Cosmogony: Greece

Delphine Acolat
Centre François Viète, Université de Bretagne
Occidentale, Brest, France

Keywords

Universe · Greece · Myths · Origins · Earth · Cosmos

Definition

Cosmogony is a theory about the origin and development of the cosmos or universe. The word comes from the Greek κοσμογονία (from κόσμος “cosmos,” “the world”) and the root of γί(γ)νομαι/γέγονα (“to be born, come about”). It is different from cosmology, which is the study of the universe structure as a whole. Cosmos is not only a word for matter but for order, for process.

History

There are two types of Greek cosmogonies. One, mythical, is very similar to the Mesopotamian myths, based on a divine couple who give birth to all beings. The second, introduced by the Greek philosophical tradition, is the first intellectual approach based on evidence, reason, and debate.

But the earliest speculations were still consistent with the mythical world structure.

Overview

First Mythical Cosmogonies

Hesiod's *Theogony* (Θεογονία), written in the sixth century BC, is the first Greek mythical cosmogony: it is a large-scale synthesis of Greek traditions concerning the gods. In the language of the Archaic period (eighth to sixth century BC), *arche* (ἀρχή) designates the source, origin, or root of things that exist. If a thing is to be well established or founded, its *arche* or static point must be secure, and the most secure foundations are those provided by the gods: the indestructible, immutable, and eternal ordering of things. The initial state of the universe or the origin (*arche*) is Chaos (χάος): a gaping and indefinite void considered as a divine primordial condition from which everything else appeared. Hesiod gives no idea about what preceded the appearance of Chaos.

Chaos was the first of the primordial deities, followed by Gaia (Mother Earth), Tartaros (the underworld), the later-born Erebus (the darkness between the earth and underworld), and Nyx (Night). Eros is sexual desire – the urge to reproduce, not the emotion of love, as is the common misconception. Erebus and Nyx reproduced to make Aether (the outer atmosphere where the gods breathed) and Hemera (Day).

Gaia was the Protogenos (primeval divinity) of earth, one of the primal elements who first emerged at the dawn of creation, along with air, sea, and sky. She was the great mother of all palpable beings: the heavenly gods were descended from her union with Ouranos (the Sky), the sea gods from her union with Pontos (the Sea), the Gigantes from her mating with Tartaros (the hell pit), and mortal creatures were sprung or born from her earthly flesh. With a cosmic order under the presence of Zeus, cosmogony is complete.

But we also know the existence of variant cosmogonies. In Homer's *Iliad* (XIV, 210–246)

and later authors, Hera qualifies Oceanus and Tethys as the “father and mother of gods,” the primordial couple. This can establish an allusion to a different cosmogony where primordial chaos is watery.

The Orphism (known by orphic fragments, Greek hymns C3rd–C2nd BC), the religious trend which took place away from the traditional practices of the cult, developed several cosmogonies. It is placed at the origin of the universe the Night or the Time, which engenders a world egg, primordial mixture of elements, which gives birth to Gaia, Chaos, and Phanes, the primeval god of procreation, the driving force behind reproduction in the early cosmos. Phanes was the first king of the universe, who passed the royal scepter on to his daughter Nyx (Night), who in turn handed it down to her son Ouranos (Heaven). From him, it was first seized by Khronos (Time) and then by Zeus, the ultimate ruler of the cosmos. Phanes also incorporated the aspects of other primordial beings described by various ancient writers, including Thesis, Phusis, Ophion, Khronos, and Ananke. All these gods are concepts rather than real characters.

Representations of Mother Earth and Phanes

In Greek cosmology, Earth was conceived as a flat disk encircled by the river Okeanos and topped above by the solid dome of heaven and below by the great pit of Tartaros. She herself supported the sea and mountains upon her breast.

Mother Earth's personification of the soil-ground whose products support human existence, a cosmogonical symbol of the material aspect of the universe, was depicted as a buxom, matronly woman, half risen from the earth in Greek vase painting and Roman mosaics (see ► [“Cosmogony: Rome”](#)). She was portrayed as inseparable from her native element.

Phanes was portrayed as a beautiful, golden-winged hermaphroditic deity wrapped in a serpent's coils. The poets describe him as an incorporeal being invisible even through the eyes of the gods. His name means “bring to light” or “make appear” from the Greek verbs, *phanaō* and *phainō*.

Birth of Philosophical Cosmology

There were many pre-philosophical cosmogonies among the ancient Greeks, but the pre-Socratics and the Atomists differed fundamentally from all of them by seeking the origin of the world on a rational basis rather than by appealing to a supernatural force.

Their understanding of the world applies the idea of order and harmony of a cosmos in all the elements that have to obey physical and mathematical laws. The Greek science tries to report most rationally the possibility of appearances observed in the sky, by elaborating explanatory models which allow to foresee the return.

All of the pre-Socratics, only known by fragments, held that the cosmos has a beginning. *Arche* is basic stuff of the universe, the element and the first principle of existing things. This is considered as a permanent substance or nature (*physis*), either one or more which is conserved in the generation of the rest of it. From this, all things first come to be and into this they are resolved in a final state. This source of entity is always preserved (Aristotle, *Metaph.A*, 983, b6ff).

For Thales of Miletus (c. 624–547 BC), the *arche* is water. His theory was supported by the observation of moisture throughout the world and coincided with his theory that the earth floated on water. His ideas were influenced by the Near-Eastern mythological cosmogony and probably by the Homeric statement that the surrounding Oceanus (ocean) is the source of all springs and rivers.

Anaximander of Miletus (610–545 BC) believed the beginning or ultimate reality is eternal and infinite, or boundless (*apeiron*), subject to neither old age nor decay, which perpetually yields fresh materials from which everything we can perceive is derived.

Apeiron generated the opposites, hot-cold, wet-dry, etc., which acted on the creation of the world. Everything is generated from *apeiron* and then it is destroyed there according to necessity. It acts as the substratum supporting opposites, such as hot and cold and wet and dry, and directs the

movement of things, by which there grew up all of the hosts of shapes and differences which are found in the world. Out of the vague and limitless body, there sprang a central mass – this earth of ours – cylindrical in shape. A sphere of fire surrounded the air around the earth and had originally clung to it like the bark round a tree. When it broke, it created the sun, the moon, and the stars.

Anaximenes of Miletus (588–524 B.C.) posits air as the *arche* and ascribes to it divine attributes; he provides a theory of change and supported it with observation. Using two contrary processes of rarefaction and condensation (thinning or thickening), he explains how air is part of a series of changes. Thinned air becomes fire and when condensed becomes first wind, then cloud, water, earth, and stone in order.

For Heraclitus of Ephesus (540–480 BC), *arche* is fire. For Empedocles, it is composed of some combination of four elements: earth, water, fire, and air. He is claiming that the primary opposites, hot and cold and wet and dry, evolved from these principles and that the other parts of the cosmos evolved from these opposites. For the Atomists (Leucippus (fl. 430 BC) and Democritus (460–370 BC), the universe contains an infinite number of such indestructible beings, “atoms”; space (as void) is not continuous, since where atoms are, void is not.

The generation of the gods is described by Plato (427–346 BC); but the origin of the cosmos is philosophically explained by him, in the same work, as the result of the planned actions of a constructor or demiurge. He conceived the earth as a sphere at the center of the world. Aristotle taught that matter had natural motions depending on its composition. The questions about the earth were summarized by Aristotle (*On the Heaven* 1956, II 293a) with the question of the place of the earth in the universe, of its shape, and of its size.

Cross-References

► [Cosmogony: Rome](#)

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Cosmogony: Mesopotamia

Gregory Chambon

Faculty of Arts and Humanities, Ecole des Hautes Etudes en Sciences Sociales, Paris, France

Definition

Cosmogony is a narration about the origin and development of the cosmos or universe. It is different from cosmology, which is the study of the structure of the universe as a whole.

History

In Mesopotamia, the interest was more about the origins and functions of gods than about the origins of universe and life.

“Water” was the prime element in all the traditions of Mesopotamia (Sumerians, Akkadians,

Hittites, Assyrians, etc.), and the roles of Tigris and Euphrates were particularly central in mythological texts.

Overview

In Mesopotamia, it seems at first glance that a much greater interest was taken in the origins and functions of the gods than in the processes whereby the universe originated. The Mesopotamian myths and rituals do not actually deal with *how* and *why* the world was formed but rather *how* and *why* gods created specific things like human beings and living nature. In order to approach this ancient thought concerning the origin of the cosmos, we have first to understand the different cosmogonic associations between a deity and prime elements of the universe. These associations may vary by regions and traditions over a period of more than 2500 years of Mesopotamian history, within different cultures (Sumerians, Akkadians, Hittites, Assyrians, etc.).

One of the main prime elements in these traditions is “water.” The terms used in mythological text are often Sea and River, which refer directly to the geographical description of Mesopotamia with the main rivers, Euphrates and Tigris, and the Arabic and Mediterranean seas. The Babylonian creation epic *Enuma Elish*, so-called from the first two words of the poem “When on High” and probably composed in the early part of the second millennium BC, describes how, during the very first separation of order out of watery chaos, the primeval parents of the gods, Apsû (sweet waters underground) and Tiâmat (the sea), mingle their waters together and create the second generation in the theogony. This second generation kills Apsû, who planned to destroy his descendants, and asks Marduk, god of Babylon, for help and sent him against Tiâmat. Armed with his winds and storms, he slices Tiâmat’s body in half, forming Heaven with the upper part and Earth with the lower. Her members were used to supply its physical features: the Tigris and Euphrates flow from her two eyes, the bases of the Mountains

were formed from her breasts, and her tail becomes the Milky Way. The remainder of the story in the creation epic deals with Marduk's organization of the cosmos with the offices that he assigns to the other gods and his creation of man. The contrast between the old chaos and the present order of the cosmos is underlined by the difference of "dynamic" by the gods: the second generation of the theogony is considered as a generation of dynamic and moving gods, whereas the chaos creatures Apsû and Tiāmat stand for inertia and rest.

Others poems and epics show that Mesopotamian tradition considered the physical universes as a superimposition of levels. Above an underworld at the bottom, Apsû could be found as the dead body of the chaos monster of that name and ruled by Ea, the god of wisdom, crafts, and creation. The second level consisted of the Earth, where men were living and which was controlled by Enlil, the god of breath and wind. The stars moved in an orbit above space, separating the lower parts from their upper counterparts. Two heavens were situated at the top of these levels: the upper one was ruled by An, god of Heaven.

Cross-References

- [Cosmogony: Greece](#)
- [Cosmogony: Rome](#)

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Cosmogony: Rome

Delphine Acolat

Centre François Viète, Université de Bretagne Occidentale, Brest, France

Keywords

Universe · Rome · Myths · Origins · Earth · Cosmos

Definition

Cosmogony is a theory about the origin and development of the cosmos or universe. It is different from cosmology, which is the study of the structure of universe as a whole.

History

Roman cosmogony is founded on those of earlier classic age. The Romans took over Greek myths and philosophic science (see Cosmogony: Greece) but added nothing to Greek cosmogony. The Hellenistic view was relatively unchallenged until the time of Nicolaus Copernicus (1473–1543) and Galileo Galilei (1564–1642).

Overview

Roman cosmogony is depicted by Ovid (43 BC–AD 17) in the *Metamorphoses* 1.1. He described Chaos as “a rude and undeveloped mass, that nothing made except a ponderous weight; and all discordant elements confused, were there congested in a shapeless heap” (see Cosmogony: Greece). Like ancient Greeks, Romans begin the genesis of gods and nature with a feminine entity, Gaia, which appears after Chaos and before Eros. Chaos contains primitive elements (earth, water, air, and fire). Gaia is a natural element which produces and supports the world. In Ovid, an unknown god organizes all these elements, and



Cosmogony: Rome, Fig. 1 Roman mosaic from a Roman villa in Sentinum (now known as Sassoferrato, in Marche, Italy), (ca. 200–250 A.D., Glyptotek Munich, Inv. W504). The Mother Earth goddess, Tellus, is sitting with four children, who represent the four seasons. Aion, the god of eternity, is standing inside a celestial sphere decorated with zodiac signs, in between a green tree and a bare tree (summer and winter)

living beings occupy ether and stars (gods), air (birds), water (fishes), and earth (animals and men).

In the first century AD, Roman people pictured the Mother Earth, supreme goddess of the earth (Roman counterpart of Gaia) (Terra Mater/Tellus), as a sweet mother: her role is reduced to the dream giving and to the feeding of plants and children. *Tellus* thus refers to the guardian deity of Earth and by extension, the globe itself. The attributes of Tellus were the cornucopia or bunches of flowers or fruit. She was typically depicted reclining. In mosaic art, Gaia appears as a full-figured, reclining woman, often clothed in green, and sometimes accompanied by grain spirits – the Karpoi (e.g., in Antakya Museum, inv. 847, the fourth century) (Fig. 1).

Cross-References

► [Cosmogony: Greece](#)

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Cosmological Principle

► [Copernican Principle](#)

Cosmology: Native American

E. C. Krupp
Griffith Observatory,
Los Angeles, CA, USA

Keywords

Cosmology · Americas

Definition

Indigenous American cosmologies are archaic, integrated worldviews conceived by the ancient and protohistoric peoples of the Americas prior to substantive contact with European peoples in the sixteenth century. The cosmos in these worldviews usually comprises several layered and axially organized realms. Rooted in observation and interaction with nature, these cosmologies portray the primary components of the environment, including the sky, the ground, the subterranean realm, the waters, atmospheric processes, plants, animals, and more, as an integrated system energized and managed by the power of spirits and gods. The structure and order attributed to the cosmos underpins a system of thought that

orders the social structure, political mechanisms, the economy, and religious expressions of the community.

Overview

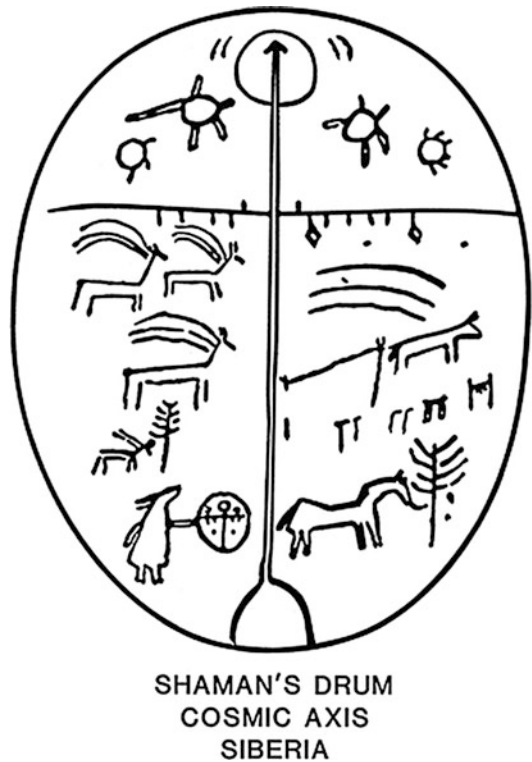
There is no room in the indigenous cosmologies of the Americas for the plurality of worlds and extraterrestrial life. These traditional cosmologies are delineated in mythic narrative that does not engage physical law, the geography of outer space, and modern astronomical knowledge.

The most fundamental character of these traditional cosmologies is the same throughout the Americas and, in fact, beyond. Although the exact architecture may differ from culture to culture, and even within a culture over time and distance, each of these conceptual structures acknowledges three primary realms – the surface of the earth, the upper world of the sky, and the lower zone of the underworld (Fig. 1).

Rooted in an animist sensibility, the indigenous Americans north of Mexico, in Mesoamerica, and throughout South America understood the world to be fortified with power controlled by spirits that attend singular places as well as defined territories and natural environments. In this traditional cosmovision, celestial objects are not places but animate beings, and often personified powers – spirits and gods – require attention and warrant caution.

Some of the indigenous peoples of the Americas linked the creation and the peopling of the world to “sky people” and celestial gods, while others did not. Celestial divinities in the Americas are neither a necessary nor sufficient condition for the creation of life in these mythic tales.

In detail, the ancient perspective on the sky was modulated by many factors, including geographic latitude, climate, subsistence pattern, social complexity, and historic circumstance. The sky was not extraterrestrial real estate but rather an essential domain of a bounded and finite cosmos centered on the world inhabited by people, animals, and plants. Through celestial events, the sky helped disclose nature’s cyclical patterns, define



Cosmology: Native American, Fig. 1 The sky, the ground, and the underworld are fundamental elements of traditional cosmologies worldwide. The drawing on this Siberian shaman’s drum depicts the structure of the cosmos in Siberian belief. The sky is the realm above the horizontal line, and it is populated with rayed celestial objects and a circle that represents the “hole” in the sky, the north celestial pole, which is at the summit of the vertical axis that extends down to the terrestrial world, inhabited by animals, plants, and a drum-carrying shaman, and terminates at the bottom in an aperture to the underworld (Griffith Observatory illustration)

the frame of the cosmos, sustain the social fabric, and put a lid on personal experience of the universe. It helped demonstrate the connection between the cosmic and the divine. It integrated society and individual destiny. It revealed the world’s center and edge.

Lifestyles and topography prompt anthropologists to divide indigenous North America north of Mexico into 11 cultural regions: Arctic, Subarctic, Northwest Coast, California, Southwest, Plateau, Plains, Southeast, and Northeast. Each of these, in turn, is subdivided into tribal territories. Great differences in ways of life are evident among all

of these Indian peoples, but they share the fundamental concept of a more or less flat earth – often imagined to be a disk – sandwiched between the subterranean world and the sky. It is a static cosmos that changes cyclically but remains fundamentally the same, although sometimes long-term cataclysmic transformations are projected onto the mythic past and anticipated in visions of the future.

In the Arctic, the Inuit saw the world operating according to the principles of a traditional cosmos. They recognized multiple layers in the sky – as many as five. Each is a tenanted realm that superficially resembles the earth, and each has another sky above it. Some Inuit say the stars are actually holes in the canopy. Light from the higher realm pours through the celestial colander. Shamans who visit those supernal precincts pass through the holes, especially the aperture closest to the pole of the sky, and gain access to the spirits of the next heaven. Alternatively, other Inuit believe the stars are people and creatures luminously transformed. Personifying the sun and the moon as sister and brother, the Inuit regard them as glowing disks who circle through the upper sky (Fig. 2).

The Seneca, an Iroquoian people in Western New York, attribute the world's creation to a woman in the sky world. This Northeast tribe identifies her as the wife of the Great Chief of the Sky. Angered by the accidental uprooting of the sky world's Tree of Life, the Great Chief pushed his young spouse through the hole left in the sky by the tree's removal. The tree was the source of everything that grows, and as the woman slipped over the edge, she grabbed a fistful of seeds and then fell toward the primordial waters below. She was caught in midair, however, by ducks that had been swimming on the face of the deep, and they set her down upon the back of a vast turtle that emerged from below. A muskrat dredged mud from the bottom, covered the turtle's shell with it, and created an island, which was seeded by the fallen woman and transformed into the world we know (Fig. 3).

The Wyandot, or Huron, also spoke an Iroquoian language and resided in the Great Lakes area. According to Wyandot myth, the



Cosmology: Native American, Fig. 2 Multiple levels of the Inuit cosmos are references in this moon face mask from Alaska. The ring around the face symbolizes one of those realms, and the feathers stand for stars. The four holes are passages through which animal spirits descend to earth from the sky. (Photograph E.C. Krupp, University of Pennsylvania Museum of Archeology and Anthropology)

world was originally almost nothing but water, and the Wyandot lived in the sky. There were no sun, moon, or stars, and the cosmos was lighted instead by a tree near the lodge of the Sky Chief. In a narrative that parallels and amplifies Seneca myth, an ordered cosmos is eventually constructed, and it is driven by complementary oppositions: light and dark and summer and winter. It has a sky world with two levels, a solid earth, a subterranean land for the dead, deified forces of nature, and personified celestial objects.

In the Pacific Northwest, the Kwakiutl of British Columbia constructed their cosmos with the usual three levels. The sun, the dawn, the thunderbirds, and other celestial beings resided above the clouds in an axial universe that skewered the three layers on a copper pole that supports each one in place.

On the Great Plains, the Sioux imagined a layered universe with four levels above the ground and four below.



The Woman who fell down from Heaven

Cosmology: Native American, Fig. 3 In Iroquoian myth, the tale of the woman who fell from the sky accounts for the Creation of the world below. The Wyandot (Huron) version of the story is illustrated by William Wallace Clark in *Indian Myths*, published in 1928. The woman is suspended here between the sky and the lower waters, over which the thunder god is rolling and throwing lightning, and land has begun to form (Collection E.C. Krupp)

The Creek Indians, a Southeast tribe originally settled in Georgia and Alabama, judged the world to be flat and square. The sky was roofed with a solid vault, and the celestial domain belonged to meteors, the Milky Way, the moon, and the sun. The god of the sky and some of the spirits of the dead lived on the dome. An underworld, or perhaps a series of them, lay beneath the earth.

According to María Solares, an Ineseño Chumash, who lived in southern California until her death in 1922, “There is this world in which we live, but there is also one above us and one below us.” Two giant snakes support the flat earth in the underworld, and when they move, they cause earthquakes. The Sky People include Sun, Morning Star, Sky Coyote, Evening Star, and Moon, and they live in houses in the upper



Cosmology: Native American, Fig. 4 The Chumash of southern California imagined the earth as island surrounded by oceanic waters. Celestial objects, including the Sun, the Moon, the Morning Star, and the North Star, reside in the upper world. Two great snakes support the underground world below the earth (Collection E.C. Krupp)

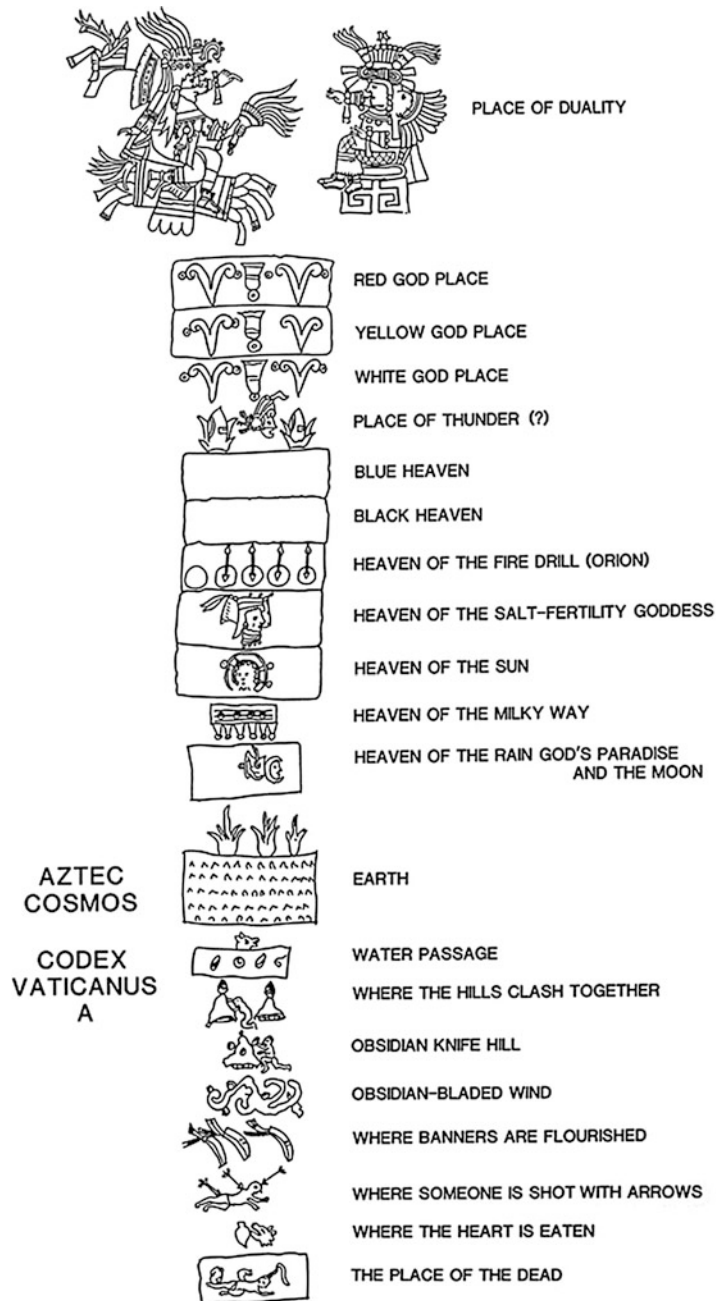
world. All of the worlds of the universe are flat and circular, with one positioned directly above another. Sun is an old man who daily carries a torch across the sky. Moon is a woman and the independent scorekeeper of the annual gambling game that determines what our world can expect from the Sky People each year (Fig. 4).

In Mesoamerica, cosmological traditions of the Aztecs, the Maya, and others survived the Spanish Conquest and confirmed the prevailing notion of a multilevel, axial stack of worlds with the inhabited earth in the middle of the universe with one foot at the bottom of the heavens and the other at the top of the underworlds. The earth, in this scheme, is the upper surface of a solid disk ringed by waters that pool outward as far as the horizon, where they blend with the sky. The Aztecs divided the disk into quarters, each of which was associated with a cardinal direction – north, south, east, and west.

The *Codex Vaticanus A*, a post-Conquest illustrated manuscript from sixteenth-century central Mexico, depicts the Aztecs’ layered universe. There are 13 “heavens” and 9 underworlds, and the earth is counted as both. The second layer of the sky is the Paradise of the Rain God and the track through which the moon moves. The stars and Milky Way are in the third level, and the sun travels through the heaven above that. The next

Cosmology: Native American, Fig. 5

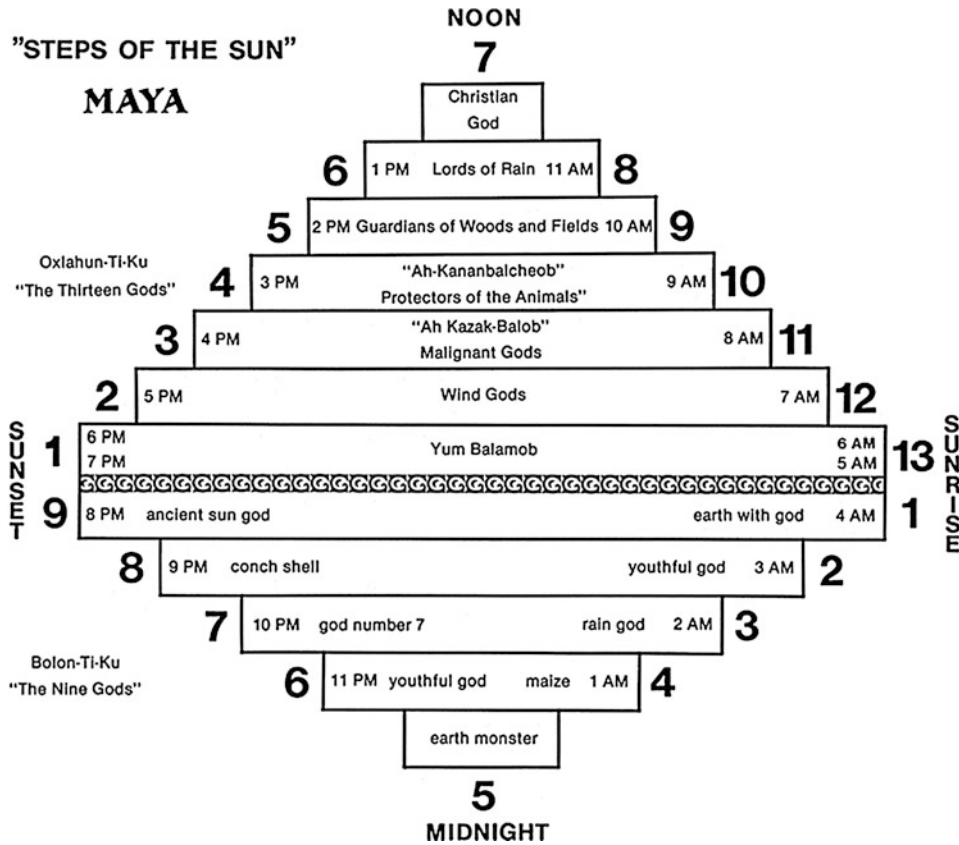
The layered cosmos of ancient Aztecs of central Mexico is a skyscraper with 13 upper stories that share the floor at ground level with the nine basements. The levels of this universe are identified and illustrated in *Codex Vaticanus A*, or *Codex Rios*, a sixteenth-century manuscript written in Italian and thought to be a copy of a lost indigenous original. The treatise deals with Aztec religion, history, customs, and calendar (Illustration Griffith Observatory, Joseph Bieniasz, after *Codex Vaticanus A*)



floor accommodates the salt-fertility goddess and probably Venus, and the story over that is dedicated to the fire drill constellation (Orion's belt and sword) and comets. Beyond Orion are the Black Heaven of winds (#7), the Blue Heaven of dust (#8), the Place of Thunder (#9), the White

God Place (#10), the Yellow God Place (#11), the Red God Place (#12), and the Place of Duality (#13), where the remote divine couple who parents gods and people presides.

The second underworld layer of the stratified Aztec cosmos, just beneath the earth disk, is the



Cosmology: Native American, Fig. 6 The Maya and other peoples of Mesoamerica incorporated a solar metaphor into the architecture of their traditional universe and likened the levels of the sky and the underworld to the sun's daytime ascent and descent and to an imagined

descent into and emergence from the underworld at night. Late indigenous sources assign 13 steps to the day and 9 steps to the night. The concept parallels the layered architecture of the pyramids built in ceremonial centers (Illustration Griffith Observatory)

Water Passage, and the Place Where Hills Clash Together (#3) is below that. In descending order, the rest of the underworlds include Obsidian Knife Hill (#4), Place of the Obsidian-Bladed Wind (#5), Where Banners Are Flourished (#6), Where Someone Is Shot with Arrows (#7), Where Someone's Heart Is Eaten (#8), and the Place of the Dead Where the Streets Are on the Left (#9). All of the underworlds are dangerous, and most involve sacrifice or death (Fig. 5).

No comprehensive, detailed, and explicit accounts of traditional central Mexican cosmology exist, and other fragmentary sources suggest at least one other, and likely older, version of the layered universe was embraced. More like a multileveled pyramid, this alternate universe

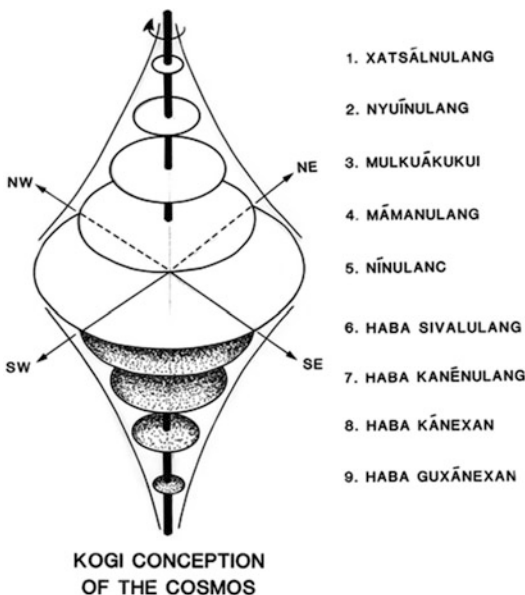
ascended in nine platforms that were associated with the daily ascent of the sun. An inverted, nine-level pyramid extended in the opposite direction, directly below the earth. In a similar way, it echoed the sun's nightly passage into and out of the underworld. The watery stream that encircles the earth disk and belts this pair of opposed pyramids around the middle was called "Nine Stream" in deference to the nine levels of day and the nine levels of night (Fig. 6).

The Castillo, or Temple of Kukulcán, the primary pyramid at Chichén Itzá, in northern Yucatán, is in Maya territory, but it belongs to the Post-Classic era, which was strongly modulated by central Mexican iconography and architectural conventions. Built in the eleventh century



Cosmology: Native American, Fig. 7 Mesoamerican pyramids appear to miniaturize the cosmos through symbolic architecture. Some Maya are believed to have assigned nine levels to heaven and nine levels to the underworld. The nine levels of the Castillo, or Pyramid of Kukulcán, of Post-Classic Chichén Itza, in northern Yucatan, transform the design of the site's primary

ceremonial building into the structure of the cosmos. The display of luminous triangles on the balustrade of the north stairway also mimics the diamondback appearance of the Feathered Serpent, Kukulcán, close to sunset at the equinoxes, after the sun has ascended from the eastern horizon and as it approaches the western horizon. (Photograph E.C. Krupp, 20 March 1982)



Cosmology: Native American, Fig. 8 The Kogi assign four levels to the upper or “day” world that is affiliated with the sun and four levels to the subterranean “night” world. Our world is in the middle of this spindle of worlds (Illustration Griffith Observatory, after Gerardo Reichel-Dolmatoff)

A.D., it is a stack of nine levels of symbolic monumental architecture that miniaturizes the Maya cosmos and puts the sun’s daily endeavor on public display in a ritual environment (Fig. 7).

Elsewhere in southern Mexico and western Central America, some Maya peoples also portrayed the universe as a kind of stepped pyramid, and different communities adopted differing tallies of the layers. The heavens vary from 3 to 15. The Lacandón, in Chiapas, appear to have inherited some of the archaic traditions of the southern Maya, and they picture a seven-tier cosmos with five heavens, the earth, and one underworld, all piled up like a stack of floating plates. The upper heavens are negotiated by the sun, moon, and stars.

The indigenous cultures of South America, like those of North America and Mesoamerica, are numerous and disparate, but just a sample of traditional South American cosmologies demonstrates they conform to the basic principles of indigenous cosmologies elsewhere in the Americas and, for that matter, in most of the rest of the world. The Kogi, in northern Colombia’s

mountains, see the cosmos as a spindle and relate the sky's motions to weaving. There are nine levels in this axial, layered universe: four heavens, the flat central disk of the earth, and four underworlds (Fig. 8).

The Inca, who established an empire centered in Andean Peru, are the best known pre-Columbian people of South America. They and their current Quechua descendants divide the cosmos into the earth, a subterranean world beneath the earth, and a celestial realm above it. Today's Quechua in Andean farming villages say the sun moves through the world below at night and the waters of the Milky Way circulate between the sky and the cosmic ocean that surrounds the world and flows beneath it.

Key Research Findings

While “extraterrestrial” realms are fundamental components of the indigenous cosmologies in the Americas and the rest of the world, these places are not other worlds where conditions on earth are imagined to be duplicated in a way that would sustain biological life. They are instead transcendent territories that are traveled by gods, ruled by spirits, visited by shamans, and occupied by the dead, and the celestial lights modern astronomy identifies as physical components of the solar system are powerful gods who make the world the way it is.

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COSPAR

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

After the USSR launched its first Earth satellite in 1957 and thereby opened the space age, the International Council of Scientific Unions (ICSU), now the International Council for Science, established its Committee on Space Research (COSPAR) during an international meeting in London in 1958.

COSPAR's objectives are to promote on an international-level scientific research in space, with emphasis on the exchange of results, information, and opinions, and to provide a forum open to all scientists. These objectives are achieved through the organization of Scientific Assemblies, publications, and other means. COSPAR's first Space Science Symposium was organized in Nice in January 1960. Now general assemblies are organized every other year.

In its first years of existence, COSPAR played an important role as an open bridge between East and West for cooperation in space. When this role became less prominent with the decline in rivalry between the two blocs, COSPAR, as an interdisciplinary scientific organization, focused its objectives on the progress of all kinds of research carried out with the use of space means (including balloons).

These activities are divided in “commissions,” and inside the commission F is dedicated to life sciences and subcommission F3 is devoted to astrobiology.

COSPAR has also concerned itself with questions of biological contamination and spaceflight while exploring the solar system. This proceeds from Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (also known as the UN Space Treaty of 1967). COSPAR, based on the work of a dedicated planetary protection panel, proposes and maintains a planetary protection policy for the reference of spacefaring nations.

Cross-References

- ▶ [Cosmogony: Greece](#)
- ▶ [Outer Space Treaty](#)
- ▶ [Planetary Protection](#)

COST

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[European Cooperation in Science and Technology](#)

Definition

COST is a program of the European Union (EU) designed to support transnational cooperation

in science and technology. It was established in 1971 to foster scientific excellence and increase the mobility of researchers across Europe. COST features three main elements: geographical spread, involving member states that are currently less research-intensive; involving early career investigators; and promoting gender balance. To reach its goals, COST funds COST Actions, which seek to allow European researchers to network and develop ideas in any field of science and technology.

History

In 2013, the COST Action “Life Origins” was approved for the period 2014–2018, with the objective of addressing fundamental questions about the origin, evolution, and distribution of life in the Universe.

Cross-References

- ▶ [Astrobiology](#)

Counter glow

- ▶ [Gegenschein](#)

Covalent Bonds

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Covalent bonds are molecular bonds formed via the sharing of electrons, according to Lewis rules,

to form closed electron shells of two, four, or six electrons (for single, double, or triple bonds, respectively). They are differentiated from ionic and ► [weak bonds](#) by the amount of energy required to break them, typically on the order of 150–1000 kJ/mole ($\sim 1.5\text{--}10$ eV/mole), depending on the species. Covalent bonds tend to form between atoms of similar electronegativity. Covalent bonds formed between atoms of dissimilar electronegativity (i.e., C–Cl) will be polar, with a greater amount of the electron density centered around the more electronegative nucleus.

Cross-References

- [Hydrogen Bond](#)
- [Weak Bonds](#)

Crater Chain

- [Catena, Catenae](#)

Crater Lakes (Mars)

Alessandro Airo

Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Berlin, Germany

Definition

It is widely accepted that liquid water was present on the surface of ► [Mars](#) during its early history. Consequently, this surface water must have migrated downhill, accumulating in topographic depressions. Besides the ocean-size northern lowlands, the most prominent basins on Mars are the numerous impact craters. There is much evidence for prolonged water ponding within individual or interconnected impact craters, such as (1) channels leading into the craters and having deposited delta

fans, (2) the presence of paleoshorelines along the crater walls, or (3) the occurrence of horizontally layered deposits composed of phyllosilicates or sulfates interpreted to represent lacustrine sediments and evaporites (e.g., Michalski et al. 2013; Pondrelli et al. 2005).

Although there are no substantial amounts of liquid water on Mars' surface today, a sufficiently large impact into ground-ice baring terrain could potentially create a transitional crater lake. Impact-induced ground-ice melting is supported by the presence of fluidized ejecta around rampart craters, which are thought to require liquid water for their formation (Mouginis-Mark and Boyce 2012). Under current Mars conditions, a lake would quickly freeze at the surface, but modeling studies predict that such an ice layer would protect the underlying water from rapid evaporation and therefore preserve the lake for up to a few hundreds of thousands of years (McKay and Davis 1991). Furthermore, it can be assumed that the impact-related heating of the crater floor would delay the freezing of the entire lake water and potentially drive long-term hydrothermal circulation.

Cross-References

- [Crater, Impact](#)
- [Habitability on Mars](#)

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Crater, Impact

Roland J. Wagner

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Keywords

Asteroid · Collision · Comet · Impact · Micrometeorite · Surface

Definition

An impact crater is a mostly circular or elliptical elongate depression, generally with a raised rim, which is created by the impact of a minor body on the solid surface of a ► [planet](#) or satellite. Impact craters range in size from microcraters seen only microscopically on surfaces of ► [rock](#) samples (e.g., rocks from the lunar surface) to large craters and ► [impact basins](#) several hundreds or thousands of kilometers across. Impacts into the atmospheres of the large gaseous planets in the outer ► [Solar System](#) can produce transitory circular or semicircular features resembling craters, as has been observed on ► [Jupiter](#) after the impact of ► [Comet Shoemaker/Levy-9](#).

Overview

Impact craters on solid surfaces of planets and satellites are created by hypervelocity collisions with smaller bodies. These bodies, termed *impactors* or *projectiles*, range in size from ► [micrometeorites](#) to large bolides up to tens or hundreds of kilometers in diameter, which form impact basins several hundreds or thousands of kilometers across (Pike 1980; Melosh 1989). Candidate impactors are (1) ► [asteroids](#) from the main belt (MBA) or from other asteroid families, for example, Near-Earth asteroids (NEA) (Neukum et al. 2001; Strom et al. 2005; Bottke et al. 2012), (2) ► [comets](#) including ► [ecliptic](#) or short-period comets (EC, orbital period <200 years) derived from the ► [Kuiper belt](#) and

nearly isotropic or long-period comets (NIC, orbital period >200 years) from the ► [Oort cloud](#) (Zahnle et al. 2003), (3) bodies or debris in planetocentric orbits (Neukum 1985; Chapman and McKinnon 1986), and (4) remnants of planetary accretion (planetesimals) (Wetherill 1975).

The number or frequency of craters on a surface per unit area records its age: the higher the crater frequency, the older the age of the surface due to the longer exposure time to the incoming impactor flux. This relationship can be used as an important tool in planetary chronology.

Morphology and sizes of impact craters reflect impact conditions, projectile properties, target properties, and changes of target properties with time (Schenk et al. 2004). The smallest craters identified in camera images are simple craters, characterized by a bowl-shaped, parabolic crater morphology (e.g., Melosh 1989). With increasing diameter, crater forms become more complex. The simple-to-complex transition diameter approximately scales with the inverse of the gravity acceleration, except for icy surfaces as on ► [Mars](#) (ice in the regolith) and the icy satellites in the Outer Solar System (Chapman and McKinnon 1986; Melosh 1989; Schenk et al. 2004). Features observed in complex craters include (Pike 1980; Chapman and McKinnon 1986; Melosh 1989; Schenk et al. 2004) (a) flat crater floors, (b) terraces at crater wall interiors, (c) central peaks, or (d) peak rings. On icy satellites, complex crater forms include (e) central pits (also observed on Mars [e.g., Barlow 2009]), (f) central domes, or (g) bright, almost flat circular areas termed *palimpsests* (Faculae) devoid of prominent topographic features such as crater rims.

The largest impact structures are ► [impact basins](#), which exhibit two or even more rings (ridges or graben) and are termed multi-ring basins (e.g., Spudis 1993).

Cross-References

- [Asteroid](#)
- [Asteroid Belt, Main](#)

- Catena, Catenae
- Chronostratigraphy
- Comet
- Comet Shoemaker-Levy 9
- Ecliptic
- Facula, Faculae
- Impact Basin
- Jupiter
- Kuiper Belt
- Mars
- Micrometeorites
- Oort Cloud
- Planet
- Planet Formation
- Planetesimals
- Rock
- Satellite or Moon
- System Solar Formation, Chronology of

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Cratering Chronology

- Chronostratigraphy

Craton

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

A craton (from the Greek *kratos* – force) is an old, thick, cool, and rigid part of the continental lithosphere. Its crustal part is typically composed of granitoids, and high-grade, strongly deformed, metamorphic rocks and less metamorphosed meta-volcanic and metasedimentary rocks (greenstone belts). The crustal section of a craton is thicker than that of normal continental crust (which is ~30–40 km) and is underlain by a thick (up to several hundred km) root of low-density, depleted lithospheric mantle. Cratons formed through orogenies (mountain-building processes) and accretion of crustal fragments during the Archean eon when mantle and crustal temperatures were higher than those of today. When covered by younger sedimentary basins, they are referred to as platforms. Examples of well-known Archean cratons are the Slave Craton of Northwest Canada, the Pilbara Craton of Northwest Australia, and the Kaapvaal Craton of Southern Africa.

Cross-References

- [Archean Eon](#)
- [Continental Crust](#)
- [Greenstone Belt](#)
- [Kaapvaal Craton, South Africa](#)
- [Lithosphere, Planetary](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Metasediment](#)
- [Pilbara Craton](#)

Crenarchaeota

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid,
Spain

Definition

Crenarchaeota is one of the first phyla described for ► [Archaea](#). Crenarchaeota comprises both hyperthermophilic and cold-dwelling prokaryotes. The hyperthermophilic species of Crenarchaeota tend to cluster closely together and occupy short branches on the 16S rRNA gene phylogenetic tree. These organisms are considered good models for early Archaea. Phylogenetically, these are a more rapidly evolving species. Most hyperthermophilic Crenarchaeota have been isolated from geothermal heated soils, waters containing elemental sulfur and sulfides, or hydrothermal vents. Among the hyperthermophilic Crenarchaeota, we can find members of the Sulfolobales, Thermoproteales, and Desulfurococcales orders. One species of *Sulfolobus*, *S. acidocaldarius*, was the first hyperthermophilic Archaea discovered. It was isolated by Thomas Brock and colleagues in Yellowstone National Park, USA, in 1970. Special mention should be given to *Pyrodictum fumarii*, which can grow at 113 °C.

Cross-References

- [Acidophile](#)
- [Archaea](#)
- [Deep-Sea Microbiology](#)
- [Hyperthermophile](#)
- [Phylogeny](#)
- [Sulfur Cycle](#)
- [Yellowstone National Park, Natural Analogue Site](#)

Cretaceous/Paleogene (KPg)

- [KT Boundary](#)

Cretaceous/Tertiary Boundary (KT)

- [KT Boundary](#)

CRISPR

Lluís Montoliu
National Centre for Biotechnology (CNB-CSIC),
Madrid, Spain

Keywords

Genome · Repeated DNA · Nuclease ·
Antiviral · Bacteriophage · Virus · RNA

Synonyms

[CRISPR/Cas](#); [CRISPR/Cas9](#)

Definition

CRISPR is an acronym standing for Clustered Regularly Interspaced Short Palindromic Repeats, and refers to a genomic pattern found in bacteria and archaea of adjacent unique and repetitive

alternating DNA fragments, constituting the genetic compound of an ancestral adaptive immune system used by prokaryotes to fight against bacteriophages and plasmids. A set of CRISPR-associated (Cas) proteins, most with nuclease-type activities, represent the effector compound of this system. Currently, there are at least two classes, six types and 33 subtypes of CRISPR-Cas systems. About half of the bacteria and more than 80% of archaea carry at least one CRISPR-Cas system.

History

The acronym CRISPR was invented by Francis J.M. Mojica, a microbiologist from the University of Alicante (Spain) and was first used in a scientific publication in 2002 by Ruud Jansen and collaborators in *Molecular Microbiology*. Mojica was also the first to foresee the function of these curious genomic arrangements in 2005. He realized that the unique DNA sequences in between repetitive fragments found in the CRISPR arrays were, actually, fragments of bacteriophage genomes. He also observed that bacteria and archaea carrying genomic pieces of some viruses were resistant to infection by the same viruses. These observations led him to propose that CRISPR arrays would be part of an ancestral adaptive immune defense system.

Overview

The first reports about CRISPR repeats in prokaryote genomes came from Japan (Ishino et al. 1987) and the Netherlands (Hermans et al. 1991). This was extended to archaea by Mojica (1993). Subsequently, numerous reports have confirmed the presence of CRISPR arrays in most archaeal and about half of the bacterial genomes. The first clues about the putative function of these singular genome arrangements were published by Mojica (2005) who deciphered that some of the unique spacer sequences matched with bacteriophage genomes. And the presence of a piece of a viral genome

rendered the prokaryotes resistant to the same virus, hence proposing that CRISPR arrays would be part of an adaptive immune defense system. This proposal was confirmed experimentally by Barrangou (2007) where they engineered the CRISPR arrays by adding and removing spacer DNA with fragments of viral genomes, thereby transforming the bacteria into resistant or susceptible to the infection by the same virus, respectively. Soon thereafter, it was discovered that the CRISPR system would also work to fight intruding plasmids. Van der Oost found in 2008 that some small RNA molecules (crRNA, for CRISPR RNA) were guiding the antiviral response. Mojica and other found in 2009 the existence of conserved short DNA sequences next to the target site and named them as PAM (Protospacer Adjacent Motif). In 2010, Moineau integrated the evidences available and demonstrated that antiviral or antiplasmid activities were associated with target DNA cleavage. In 2011, Charpentier identified additional small RNA molecules in CRISPR-Cas systems (tracrRNA, for trans-activating crRNA). Also in 2011, Siksnys reported the first successful transfer of a CRISPR-Cas system between two evolutionary distant organisms: from *Streptococcus thermophilus* to *Escherichia coli*. Finally, in 2012, Charpentier and Doudna described the compounds of the CRISPR-Cas9 system of *Streptococcus pyogenes* and suggested its potential use for editing any genome, a proposal for which they were awarded the Nobel Prize in Chemistry in 2020.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [DNA](#)
- [Genome](#)
- [Genome Editing](#)
- [Nucleic Acids](#)
- [Recombination](#)
- [Replication \(Genetics\)](#)
- [RNA](#)
- [Virus](#)

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CRISPR/Cas

► [CRISPR](#)

CRISPR/Cas9

► [CRISPR](#)

Critical Core Mass (Giant Planet Formation)

Yann Alibert¹ and Ravit Helled²

¹Space Research and Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland

²Geophysical, Atmospheric and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

Keywords

Planet formation · Core accretion (Model for Giant Planet Formation)

Definition

In the core accretion model for giant planet formation, the critical core mass is the minimum core mass that is required to initiate rapid gas accretion, which leads to the formation of a gaseous planet.

Gas accretion begins after the protoplanet has reached (planetesimal/pebble) isolation mass.

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Planet Formation](#)

Crossing Over

► [Recombination](#)

Crust

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

The crust is the outer rocky layer of the Earth or any other telluric or “rocky” planet or moon. The Earth’s crust has a relatively low density and floats on the underlying mantle. Oceanic crust, which covers about two thirds of the Earth’s surface, is 6–9-km thick and composed mainly of basalt, thus its older acronym identifying the main chemical composition, SIMA for silicate magnesium. Continental crust is thicker (about 10 km thick in rifted portions and >80 km thick beneath active mountain belts), averaging about 30 km. Continental crust is composed mainly of granitic-andesitic and metamorphic rocks, thus the older acronym SIAL for silicate aluminum. Oceanic crust forms at the mid-ocean ridges and is never older than 200 Ma. Continental crust has formed continuously throughout the Earth’s history, from 3.8 or even 4.3 Ga. Mars and probably Venus have basaltic crusts. The lunar crust is basaltic in maria and composed of anorthositic breccia in lunar highlands.

Cross-References

- ▶ [Basalt](#)
- ▶ [Breccia](#)
- ▶ [Continental Crust](#)
- ▶ [Mantle](#)
- ▶ [Mid-Ocean Ridge](#)
- ▶ [Oceanic Crust](#)
- ▶ [Venus](#)

Crustal Deformation

- ▶ [Archean Tectonics](#)

Cryocooler

- ▶ [Cryostat](#)

Cryophile

- ▶ [Psychrophile](#)

Cryosphere

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

The cryosphere is that part of the Earth and of other planets or moons in which temperatures are low and water is solid (ice). On Earth, it constitutes the polar ice caps and pack ice, mountain glaciers, cold deserts, and regions of permafrost which make from 7–17% of the surface of our planet. During the time of near-global glaciations in the Neoproterozoic – the so-called Snowball Earth – the cryosphere encompassed almost all the planet, as is the case at present time for icy moons such as Europa, Callisto, or Ganymede.

Cross-References

- ▶ [Callisto](#)
- ▶ [Europa](#)
- ▶ [Ganymede](#)
- ▶ [Glaciation](#)
- ▶ [Snowball Earth](#)

Cryostat

Inge Loes ten Kate
Department of Earth Sciences, Utrecht University,
Utrecht, Netherlands

Synonyms

[Cryocooler](#); [Dewar flask](#)

Definition

A cryostat is an apparatus used to maintain very low (“cryogenic” $< \sim 100$ K) temperatures. It typically consists of two vessels, one mounted inside of the other. The inner vessel contains the cold sample (cryogen) mounted inside an evacuated outer vessel. The vessels are held together by a material with low thermal conductivity. The vacuum in the outer vessel serves as a thermal insulator. The two vessels are separated by a radiation shield to prevent heat transfer. The radiation shield is cooled by a cryocooler.

In medicine, a cryostat is a device to cut histological slides, consisting of a microtome (ultrathin slicer) in a freezer. In astrobiology, cryostats are used to generate low temperature conditions, for example, for simulating surfaces of icy moons or Titan or even the surface of Mars. Furthermore, studies of ices and chemistry taking place in ices require the use of a cryostat; examples of these are interstellar and cometary ices.

Cross-References

- [Comet](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Ices](#)

Cryovolcanism

Therese Encrenaz
LESIA, Observatoire de Paris, PSL, CNRS,
Sorbonne University, University Paris-Diderot,
Meudon, France

Definition

Cryovolcanism is a volcanic phenomenon that occurs in environments with extremely low temperatures. There, instead of molten silicates, cryovolcanoes erupt liquid water, methane, ammonia, or sulfur dioxide onto the icy surface of a planet or satellite. It has been observed on several satellites of the outer solar system. In

particular, active cryovolcanism has been discovered at the surface of Jupiter’s Galilean satellite Europa and on Saturn’s satellites Enceladus and possibly Titan. Traces of cryovolcanism are also found on Triton and possibly Pluto. The ejection products of cryovolcanism include water (H_2O), methane (CH_4), ammonia (NH_3), and dinitrogen (N_2). Cryovolcanism could also be present on other outer satellites and trans-Neptunian objects.

Cross-References

- [Enceladus](#)
- [Titan](#)
- [Trans-Neptunian Object](#)
- [Triton](#)
- [Pluto](#)

Cryptoendolithic

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto
Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Cryptoendolithic refers to one of the three subclasses in which ► [endolithic](#) microorganisms are classified. Cryptoendolithic microorganisms are those able to colonize the empty spaces or pores inside a rock with the connotation of being hidden. This connotation is important to astrobiology as these protected environments inside rocks are putative habitable niches where life could be sustained in very adverse conditions or space environments. Cryptoendolithic microorganisms can survive on inorganic metabolites from the surroundings; thus, these microbes are mainly lithotrophs. Depending on the physicochemical properties of the mineral structure of the rock, it can provide protection against damaging radiation. Some reported examples have been described in basaltic rocks from Antarctica where low temperatures are very restrictive for life or from high-altitude environments with high radiation doses.

Cross-References

- [Chemolithotroph](#)
- [Endolithic](#)

CS

- [Carbon Monosulfide \(CS\)](#)

CSA

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The Canadian Space Agency was established in 1989 and is committed to lead the development and application of space knowledge for the benefit of Canadians and humanity. Canada began space activities at the early stage of the space era, through an agreement with the US National Aeronautic and Space Administration (► [NASA](#)) to build and launch satellites to study the upper atmosphere. For several years from 1958, Canada operated jointly with the USA, the Fort Churchill base in Manitoba, to launch sounding rockets. In 1969, the federal government created Telesat Canada to build and exploit Canadian communication satellites. The government also set up a Department of Communications that immediately took over from the Communications Research Centre and the Interdepartmental Committee on Space. In 1974, NASA awarded Canada the responsibility of designing, developing, and building the Shuttle Remote Manipulator System (SRMS) for the Space Shuttle. This agreement resulted in Canadarm, the shuttle's 15-m robotic arm, and led to the flight, in 1984, of the first Canadian astronaut (Marc Garneau). In 1979, Canada became an associate member of the European Space Agency (ESA), and in 1985, Canada accepted to participate in the ► [International](#)

[Space Station](#) program. Canadian scientists are cooperating worldwide in manned space flight, space sciences, and exploration of the solar system. For astrobiology, Canada offers also several sites that could be studied or used as Martian analogues.

Canada is pursuing a strategy to develop its expertise in remote sensing, space robotics, and space telecommunication.

In 2010, the CSA employed around 700 full-time equivalents.

1934 CT

- [Toutatis](#)

Culture Media

- [Macronutrient](#)

Curation Facilities and Sample Receiving Facilities

Sara Russell
Natural History Museum, London, UK

Keywords

Curation · Planetary protection · Contamination · Sample science · Sample return missions

Acronyms

SRF Sample Receiving Facility

Definition

Sample Return Curation is the characterization, digitization, cataloguing, distribution, and especially long-term secure care of samples returned from space.

A Sample Receiving Facility is used to receive samples that require biocontainment

due to the potential presence of extant extraterrestrial organisms.

History

Extraterrestrial sample curation began with the curation of meteorites at museums, first in Vienna and London in the 1700s, and then at other museums and universities in Europe and across the world. The first curation facilities for samples returned from space missions were developed in the USA and Russia in the late 1960s and 1970s to curate rocks and regolith returned from the Moon during the Apollo and Luna missions. Lessons learned at these facilities have been used to inform curation at facilities that have subsequently been established, or are planned, in Japan, China, and Europe.

Overview

Sample return missions are essential to answer many important questions in space sciences. High-precision geochemical measurements, for example, high-precision isotope measurements required for radiogenic age determinations, and the analysis and identification of complex organic molecules and some potential biomarkers, require the presence of a sample in a laboratory on Earth. The two overriding requirements for curation are that the sample is contained in a way that does not expose the Earth to any risk, and that the samples are kept in pristine form, with minimal chemical or biological contamination or reaction with the atmosphere or the terrestrial environment.

Curation of returned samples begins at the moment the return capsule touches down on the terrestrial ground, which may be at a large distance from the planned primary curation facility. A temporary and portable receiving facility may be established in proximity to the return site for use as a base for the sample recovery, for inspection and packaging, and for salvage operations if the return is non-nominal.

“Restricted” space missions, for which the returned samples have not been proved to be

nonhazardous (for example, returned from the surface of Mars), will require transportation to a Sample Receiving Facility (SRF) for preliminary assessment and characterization. Samples will be held in biocontainment until they have been determined not to contain biohazards or until they are made safe by sterilization. Therefore, measurements that are sensitive to sterilization or which are particularly time sensitive must be performed prior to removal from biocontainment. Crewed missions returning from visits to planets considered as potential hosts to pathogens will additionally involve quarantine of astronauts at a suitable facility.

The preliminary examination phase provides a first look at the sample, and initial characterization that will enable subsequent measurements to be made. First, prebasic characterization is undertaken on the unopened sample capsules. This may involve analysis of dust adhering to the capsule and potentially any nondestructive measurements that can be undertaken through the sealed capsule. Next, the sample will be opened and basic characterization takes place including analysis of gas trapped in the dead spaces, weighing, and imaging. Preliminary analysis may then be undertaken on a subsample of the complete returned material. This will include basic chemical, mineralogical, and petrological tests and the databasing of information on individual grains. This cataloguing is essential for future decisions about further analysis both within the facility and externally. After preliminary characterization and biohazard assessment and resolution, the samples can be moved (if required) to their more permanent curation facility/facilities for further work and long-term storage in a physically secure environment.

Sample curation facilities require stringent contamination control to minimize the effect on the returned samples of the conditions on Earth. This will necessitate a strictly controlled temperature and atmosphere, clean (dust-free) conditions, and carefully selected composition of containers and manipulation tools. Robotic manipulation may become increasingly important to minimize contamination by human handling. The exact conditions of the curatorial storage will

depend on the scientific requirements and objectives. The appropriate curation of samples will also depend on the specific nature and condition of the material on the celestial body of origin. For example, future facilities may be required to store samples cryogenically and also provide storage for returned fluids. As well as contamination control, an important aspect of the function of the curation facility is contamination knowledge. Quantifying the degree of inevitable interaction of the specimens with their surroundings is essential. This can be evaluated by the use of witness plates (an object used to monitor the environmental effects experienced by a sample by exposure to the same conditions) and routine analysis of stored samples.

Any curation facility will require a suite of analytical instruments in order to record and characterize the samples and for contamination knowledge. Among typical instruments will be those for making non- or minimally destructive analyses, such as optical and electron microscopes, spectral instruments, and X-ray instruments such as X-Ray Diffraction (XRD) and Computed Tomography (CT).

A fundamental role of the curation facility is to provide effective and stable long-term storage and preservation for research by future generations and as a resource for public engagement. It is imperative that a proportion of any samples returned is kept pristine for decades or centuries to come. This requires curation facilities to have a long-term (decades +) plan for its continued operation and upkeep to a suitable standard to protect the samples. This will enable the returned samples to become a lasting legacy of human exploration of the worlds beyond Earth.

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Curiosity

- [Mars Science Laboratory](#)

Curiosity Rover

- [Mars Science Laboratory](#)

Cuvier's Conception of Origins of Life

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes,
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Nantes, France

History

The French naturalist Georges Cuvier (1769–1832) was one of the most important comparative anatomists and paleontologists of the beginning of the nineteenth century. Concerning history of life, Cuvier claimed a form of fixism explaining

changes of species during geological time. He imagined several disasters during which certain species would disappear and after which new species would come from other places. During the first part of the nineteenth century, his proposal had a very significant place in biology and paleontology.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [Lamarck's Conception of Origins of Life](#)

Cyanamide

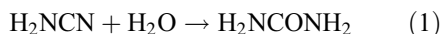
Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

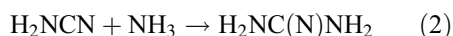
[Amidocyanogen](#); [Carbamonitrile](#); [Carbimide](#);
[Carbodiimide](#); [Cyanoamine](#); [Cyanogenamide](#);
[Cyanogen nitride](#); H_2NCN ; [Hydrogen cyanamide](#); [N-Cyanoamine](#)

Definition

Cyanamide is a simple compound (H_2NCN) formed by the irradiation of cyanide. Cyanamide has been detected in the ► [interstellar medium](#) (see ► [Molecules in Space](#)) and has been shown to be an effective condensation agent for both peptides and nucleotides. Reaction of cyanamide with water yields urea:



Reaction with ammonia gives guanidine:



Reaction with amines, such as amino acids, gives *N*-carbamoylamino acids and hydantoins.

Cross-References

- [Hydantoin](#)

Cyanic Acid

- [HCNO Isomers](#)

Cyanide Anion

- [Cyanide Anion \(\$\text{CN}^-\$ \)](#)

Cyanide anion (CN^-)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Cyanide anion](#); [Cyanide ion](#)

Definition

Radio astronomers have detected the cyanide ► [anion](#), CN^- , in the circumstellar envelope of the evolved carbon-rich star CW Leo (also called IRC+10216). It is the smallest molecular anion (2 atoms) thus far identified in such regions (the anions C_3N^- and C_5N^- , for example, had previously been observed). For references, see ► [Molecules in Space](#).

Cross-References

- [Circumstellar Chemistry](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)

Cyanide Ion

- [Cyanide Anion \(\$\text{CN}^-\$ \)](#)

Cyano Radical

► Cyanogen Radical (CN)

Cyanoacetylene

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Synonyms

CA

Definition

Cyanoacetylene, HC_3N ($\text{H}-\text{C}\equiv\text{C}-\text{C}\equiv\text{N}$), is an organic molecule that is the simplest cyanopolyne ($\text{H}(-\text{C}\equiv\text{C})_n-\text{C}\equiv\text{N}$). It was one of the first molecules detected in space using radio astronomical techniques (Turner 1971). The observation of its rotational lines is used in radio astronomy to derive the physical conditions of interstellar and circumstellar clouds. It is also an important component of Titan's atmosphere (Kunde et al. 1981), where it is found in the gas phase in the upper atmosphere and in ice form in the lower stratosphere (see, e.g., Anderson et al. 2010). It is a trace constituent in cometary atmospheres (comae). Cyanoacetylene has been proposed as a prebiotic reagent for the formation of pyrimidine bases, nucleosides, and nucleotides (Sanchez and Orgel 1970; Powner et al. 2009).

Cross-References

► Titan

References

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Cyanoacetylde Anion

► C_3N^- Anion

Cyanoamine

► Cyanamide

Cyanobacteria

Josef Elster^{1,2} and Jana Kvidrová²

¹Faculty of Science, Centre for Polar Ecology,
University of South Bohemia, Ceske Budejovice,
Czech Republic

²Institute of Botany, Academy of Sciences of the
Czech Republic, Trebon, Czech Republic

Keywords

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Desiccation · Endosymbiosis · Extremophiles ·
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Psychrophily · Thermophily · Ultraviolet
radiation

Synonyms

Blue-green bacteria; Cyanophyceae

Definition

Cyanobacteria are photosynthetic ► **bacteria** that use ► **water** as reducing power to release

O₂. They evolved early in Earth's history. As bacterial primary producers, cyanobacteria occupy a privileged position among organisms due to their role in the carbon and nitrogen cycles. They are widely adapted to different extreme environments and play an important role, especially in cold polar and alpine environments, because of their tolerance of a wide temperature range, ► [desiccation](#), freeze-melt, and salinity stress.

Overview

Cyanobacteria are oxygenic photosynthetic prokaryotes responsible for the transformation of a reduced atmosphere to an oxidized one. The oxygen produced by this photosynthetic group of bacteria drove life to adapt to the newly formed aerobic environments, resulting in the evolution of novel physiologies, biochemistries, and morphologies. In addition, cyanobacteria, as the photosynthetic partner in the primary endosymbiotic event, introduced photoautotrophy to eukaryotes. The geopaleological record indicates that cyanobacterial ► [photosynthesis](#) took place early in our planet's history. As primary producers, cyanobacteria occupy a privileged position among organisms because of their role in carbon and nitrogen (N-fixers) biological cycles (Whitton and Potts 2000; Knoll 2008; Swingley et al. 2008).

In comparison with other groups of bacteria, cyanobacteria exhibit an unusually wide range of morphologies. Traditional taxonomic cyanobacterial classification is based on morphology and development, recognizing five principal groups: Group I, *Chroococcales*, solitary and colonial unicellular forms; Group II, *Pleurocapsales*, unicellular to pseudo-filamentous, with cells capable of multiple and binary fission; Group III, *Oscillatoriales*, filamentous forms with ► [cell](#) differentiation; Group IV, *Nostocales*, filamentous with cell differentiation to produce akinetes and heterocysts; and finally Group V, *Stigonematales*, with cell differentiation and complex multicellular organization (Komárek and Anagnostidis 1998, 2005). Results of the

application of recent molecular techniques (e.g., sequence of the 16 S rRNA gene) support some but not all these groups. Features like cell differentiation or multiple fissions are supported by molecular analyses, whereas unicellular forms and simple filaments do not generate monophyletic groups. It has been possible to reconstruct an evolutionary history of the cyanobacterial groups, establishing a framework for resolving how their metabolic and phenotypic diversity came about (Six et al. 2007).

Probably due to their evolutionary antiquity, cyanobacteria are widely adapted to all extremes related to changes in geological time (Elster et al. 2001). Tolerance of low-oxygen conditions is still widespread among cyanobacteria and free sulfide is tolerated by some strains. In addition, some cyanobacterial strains can use H₂S as a hydrogen donor. They also tolerate high doses of ultraviolet B and C radiation. All these features have been especially important in the early evolution of cyanobacteria.

Many cyanobacteria can develop in extreme environments, at extremely high (geothermal springs) and low (Antarctic, Arctic, alpine areas, permafrost) temperatures, in hypersaline (halophiles) and alkaline (alkaliphiles) habitats, under high radiation conditions, desiccation, and toxicity stress, etc. A brief survey follows the occurrence of cyanobacteria in different extreme environments.

Thermophilic Cyanobacteria

Results of recent molecular biological studies provide new information about cyanobacteria that inhabit high-temperature habitats. A number of earlier reports proposed that thermophilic cyanobacteria had branched out at the beginning of their evolution. However, recent studies have brought arguments for a later emergence of thermophilic cyanobacteria. The present analyses (Ward and Castenholz 2000) strongly confirm two distinct thermophilic lineages. Geothermal springs can be considered as isolated islands and therefore an ideal site for the origin and evolution of endemic species. Some species of *Thermosynechococcus* spp. are clearly restricted in geographical distribution, although other

thermophilic cyanobacteria, such as *Mastigocladus laminosus* and *Cyanothece minervae*, appear to be cosmopolitan.

Cyanobacteria occupying geothermal springs are not observed below ►pH 4, and their diversity is quite restricted at pH below 6. Temperature, in combination with availability of nitrogen and the presence of free sulfide, determines the cyanobacterial species composition, because sulfide is an efficient inhibitor of oxygenic photosynthesis. The detected upper-temperature limit for cyanobacteria (*Synechococcus lividus*) and for global photosynthesis is presently 73–74 °C.

Cyanobacteria Under Low Temperature, Desiccation, and Salinity Stress

Cyanobacteria, frequently considered warm-water organisms, play an important role in the carbon and nitrogen cycles in cold polar and alpine environments. The ecophysiological features that predetermine their dominance in these environments include: slow growth rate over a wide temperature range, tolerance to desiccation, freeze-melt and salinity stress, and a variety of photoacclimation strategies to both high and low solar irradiance. In cold environments, where invertebrate grazing pressure is limited, the large standing stocks of cyanobacterial biomass are the result of its gradual accumulation over many seasons (Vincent 2000).

At present, endemism of polar and alpine cyanobacteria is under discussion. Castenholz (1992) noted that due to the slow rates of speciation and high dispersal abilities together with the relatively young age of most polar ice-free areas, cyanobacterial endemism in extremely cold environment is improbable. However, recent studies based on 16S rDNA and 16S–23S rDNA intergenic spacer sequences from the Antarctic and Arctic (Taton et al. 2006; Comte et al. 2007; Komárek et al. 2008; Strunecký et al. 2010, 2012a, b) introduced that for selected cyanobacterial clusters apparently belonging to generic entities, geographical limitation plays a prominent role. The north and south polar regions are remarkably different from each other in their geological histories, biodiversity, energy balance, and transport, yet they share the common

challenges for the life that exists there, the fluctuating extremes of cold, and desiccation stress. The Arctic is a geologically young and open area in which rapid glacial and periglacial processes occur. There is a relatively (to Antarctica) higher level of biodiversity and a greater capacity for geographical genome transfers to take place, aided by biological vectors, land mass continuity, and air and oceanic currents. In contrast, a thick ice sheet covers most of the Antarctic continent, which has been geographically isolated for a very long period of time. As a consequence, glacial and periglacial processes are much slower, and genome exchange and movement, and consequently biodiversity, are more limited in the south polar region of Antarctica (Elster and Benson 2004). It has been tested that cyanobacteria survived Antarctic glaciations directly on site after the Gondwana breakup by using the relaxed and strict molecular clock in the analysis of the 16S rRNA gene (Strunecký et al. 2012a). In the contrary, in the Arctic, molecular studies revealed the similarity of strains from Ellesmere Island, the Canadian Arctic, and Abisko, Sweden, with strains from Svalbard. The rate of biological colonization of the Arctic from southern latitudes is relatively high (Strunecký et al. 2012b).

Most polar and alpine cyanobacterial species tested up to now are rather more psychrotolerant than psychrophilic. Polar cyanobacteria have long doubling times in comparison with psychrophilic eukaryotic ►algae and heterotrophic bacteria.

Diverse evidence indicates that the unsaturation of ►membrane lipids correlates with low-temperature sensitivity, although this is not the only factor that regulates low-temperature resistance in cyanobacteria. The unsaturation apparently protects the photosystem II complex from low-temperature photoinhibition.

Cyanobacteria have several strategies to minimize osmotic and mechanical stresses. They are able to produce mucopolysaccharides (exopolymeric substances), which slow down the flow of liquid water during freeze up and thaw (Vincent 2000). Cyanobacteria also respond to these stresses by producing compatible solutes. Large disaccharide sugars, such as trehalose,

sucrose, and glucosylglycerol, are typical compatible solutes in water-stressed cyanobacteria (Reed et al. 1984). The extreme tolerance of cyanobacteria to desiccation is exemplified by their ability to tolerate very low water potential. *Chroococcus* and *Chroococcidiopsis* can both fix CO₂ at remarkably low water potentials.

Cyanobacteria are an important component of hypersaline ecosystems. Compatible solutes are especially vital for cyanobacterial survival in saline desert evaporate soils when they are under the combined stress of desiccation and hypersaline conditions (Oren 2000). In these habitats, glycine betaine is the most common compatible solute. A wide range of species belonging to different taxonomical groups has been reported to thrive at high salt concentrations (e.g., *Microcoleus chthonoplastes*, *Oscillatoria limnetica*, *Synechocystis* spp.).

Light and UV Radiation

Under natural conditions, cyanobacteria experience light conditions that fluctuate rapidly, frequently reaching suboptimal levels for photosynthesis. Both the intensity and quality of the irradiance can vary dramatically during the day and among habitats. In desert terrestrial environments, irradiance may be very bright and cause photoinhibition or damage to the reaction centers of PSII (photooxidative bleaching). Cyanobacteria can modify the protein composition of PSII at high irradiance, making the PSII reaction centers less susceptible to photoinhibition. Rapid light intensity or quality fluctuations result in rapid photoacclimation processes, such as state transition that can modify the photosynthetic apparatus within minutes. These short-term modifications usually do not need protein synthesis. For example, during the state transitions, the phycobilin antennae migrate between the photosystems to optimize the distribution of incoming radiant ► [energy](#) (Bhaya et al. 2000).

In addition, many cyanobacteria are exposed to environmental conditions where continuous ultraviolet radiation (UVR) plays an important role. UVR can lead to direct photochemical damage and degradation of cellular components or to indirect effects produced by reactive oxygen species.

Cyanobacteria possess four lines of defense against UVR (Vincent 2000): they can avoid UVR injuries by (1) selection of ► [habitat](#) (move to deeper water, live beneath rock surface, or live deep within microbial mats); (2) production of umbrella compounds that filter UVR, such as the black or dark pigment Scytonemin (absorbance at ca. 390 nm) and mycosporine-like amino acids (absorbance at 310–360 nm); (3) production of carotenoids (canthaxanthin, myxoxanthophyll, and related compounds), which protect the cells from the oxidative stress caused by the UVR; and (4) further protection against long-term effects of UVR exposure due to the ability to identify and repair the photochemical damage to DNA or the photosynthetic apparatus (Vincent 2000).

Key Research Findings

Some extreme environments on Earth are used as field analogues of extraterrestrial conditions, allowing the limits of survival of various ► [microorganisms](#) including photosynthetic cyanobacteria to be determined. Since cyanobacteria dominate in the polar regions, they can serve as model organisms for evaluation of survival at low temperatures and other stress factors common to the polar ► [environment](#). In the most extreme Antarctic conditions, cyanobacteria play a determining role in (1) desert communities, including soil crust and ► [epilithic](#) and ► [endolithic](#) species of cold polar deserts, e.g., in Dry Valleys in the Antarctic, where the conditions resemble those of the ► [Mars](#) surface (Friedmann 1982), and (2) benthos of permanently frozen lakes, e.g., Lakes Hoare and Fryxell in the Antarctic, which represent another environment that could occur on Mars (de Pablo et al. 2008). The conditions of permanently ice-covered lakes and seas could also be relevant for ► [Europa](#); however, cyanobacteria are not common components of polar seas.

Simulation of conditions on other planets or during interplanetary transport is another approach to the estimation of limits of survival. *Chroococcidiopsis* sp. is able to survive in Mars-like conditions when it is covered by at least 1 mm

of Mars soil analogue that reduces the incoming ► [UV radiation](#). Due to its resistance, this cyanobacterium was proposed as a pioneer microorganism for Mars terraforming (Friedmann and Ocampo-Friedmann 1995). The resistance of the halotolerant *Synechococcus* to space conditions was evaluated during the BIOPAN-3 mission and the effect of space radiation on primary producers, including cyanobacteria, as part of the EXPOSE-R mission launched on 2008 (Rabbow et al. 2009).

Future Directions

As mentioned, cyanobacteria represent the earliest organisms capable of oxygenic photosynthesis. Together with other non-oxygenic photoautotrophs, such as sulfur bacteria, they provide insight into the origin and evolution of photosynthetic processes and data for the estimation of their possible modifications on planets orbiting stars of different spectral classes (Xiong and Bauer 2002).

Cross-References

- [Adaptation](#)
- [Bacteria](#)
- [Biofilm](#)
- [Carbon Cycle, Biological](#)
- [Chlorophylls](#)
- [Chloroplast](#)
- [Colonization, Biological](#)
- [Cryosphere](#)
- [Cryptoendolithic](#)
- [Desiccation](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Endolithic](#)
- [Endosymbiosis](#)
- [Epilithic](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [Fossil](#)
- [Halophile](#)
- [Halotolerance](#)

- [Mars Analogues](#)
- [Membrane](#)
- [Mesophile](#)
- [Microbial Mats](#)
- [Microfossils](#)
- [Nitrogen Cycle, Biological](#)
- [Nitrogen Fixation](#)
- [Osmolite](#)
- [pH](#)
- [Photosynthesis](#)
- [Phototroph](#)
- [Phylogeny](#)
- [Psychrophile](#)
- [Stromatolites](#)
- [Thermophile](#)
- [UV Radiation](#)
- [Water](#)

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Cyanobacteria, Diversity and Evolution of

Lucas J. Stal
Department of Marine Microbiology, Royal Netherlands Institute of Sea Research (NIOZ), Yerseke, The Netherlands

Keywords

Carbon dioxide fixation · Chloroplast · Cyanobacteria · Diversity · Evolution · Heterocysts · Nitrogen fixation · Oxygenic photosynthesis · Photosynthesis

Synonyms

Blue-green algae; Oxygenic phototrophic bacteria; Oxyphotobacteria

Definition

Cyanobacteria are oxygenic phototrophic microorganisms. They belong to the ► [Bacteria](#) domain of life and have a plant-type photosynthetic apparatus. They possess two photosystems, PS-I and PS-II, which are connected in series, and their reaction centers usually contain chlorophyll *a*. Water is used as the electron donor and is split into electrons and oxygen by PS-II. The electrons are transported through an electron transport chain through PS-I and eventually reduce electron carriers. These are mainly used for the fixation of carbon dioxide through the reductive pentose phosphate pathway. Their main light-harvesting pigments are the blue- and red-colored phycobiliproteins.

Overview

Cyanobacteria are a monophyletic but highly diverse group of microorganisms (Rippka et al. 1979). Although they are often called “blue-green algae,” they belong to the domain Bacteria and they lack a nucleus or other cell organelles (Stanier and Cohen-Bazire 1977). The confusion with algae, which belong to the domain Eukarya, is understandable since cyanobacteria possess a plant-type photosynthetic system, with two photosystems, PS-I and PS-II, connected in series. Cyanobacteria use water as the electron donor, which by its splitting results in the evolution of oxygen, and their reaction centers normally contain the plant pigment chlorophyll *a*. Cyanobacteria fix CO₂ through the reductive pentose phosphate pathway (Calvin-Benson-Bassham cycle) with ribulose-1,5-bisphosphate carboxylase/oxygenase (RubisCO) as the CO₂-fixing enzyme. This pathway is also common among phototrophic Eukarya (plants and algae) and other autotrophic bacteria. Cyanobacteria occur in almost any illuminated habitat on Earth, including those characterized by extreme environmental conditions.

It is now well established that the eukaryotic plant cell evolved through an endosymbiotic event during which a cell engulfed a cyanobacterium, which subsequently evolved to become a chloroplast, the photosynthetic factory of plant cells (Raven and Allen 2003). The 16S rRNA genes of the chloroplast cluster phylogenetically with the cyanobacteria. Modern cyanobacteria enter into a large variety of symbioses with microalgae and plants, often providing their hosts with fixed nitrogen (Rai et al. 2000).

Cyanobacteria invented oxygenic photosynthesis and were therefore responsible for the oxygenation of the Earth's atmosphere (Knoll 2003). The first big oxygen event occurred 2.4 billion years ago when the oxygen concentration reached 10% of its present value (GOE: Great Oxygenation Event). Besides this rise in the oxygen level of the atmosphere, there are other geological and geochemical evidences for the presence of cyanobacteria at that time. There are microfossils that resemble modern cyanobacteria since 2.1 Ga,

and there are molecular fossils such as methylhopanoids that are considered to have originated from them since at least 1.6 Ga, perhaps 2.5 Ga. Moreover, phylogenetic evidence also points to the presence of cyanobacteria at that time (e.g., Sanchez-Baracaldo et al. 2005). Recently, several geochemical studies point to “whiffs” of oxygen before the GOE. Other studies have suggested an even earlier origin of cyanobacteria of up to almost 3.5 billion years. This goes back to the earliest evidence of life on Earth. This evidence was based on microfossils interpreted to possess similarity to modern cyanobacteria and stable isotope data suggestive of CO₂ fixation by autotrophic organisms as well as other organic signatures. Although these fossil traces could have been produced by other organisms, perhaps anoxygenic photosynthesizers, there is no doubt that cyanobacteria must have evolved long before free oxygen appeared in the atmosphere. It must have taken some time until the oxygen evolved by the first cyanobacteria had oxidized the massive reducing crust and the euphotic layer of the ocean. Thus, it is likely that the origin of cyanobacteria occurred early in the evolution of life on Earth, earlier than 2.5 Ga.

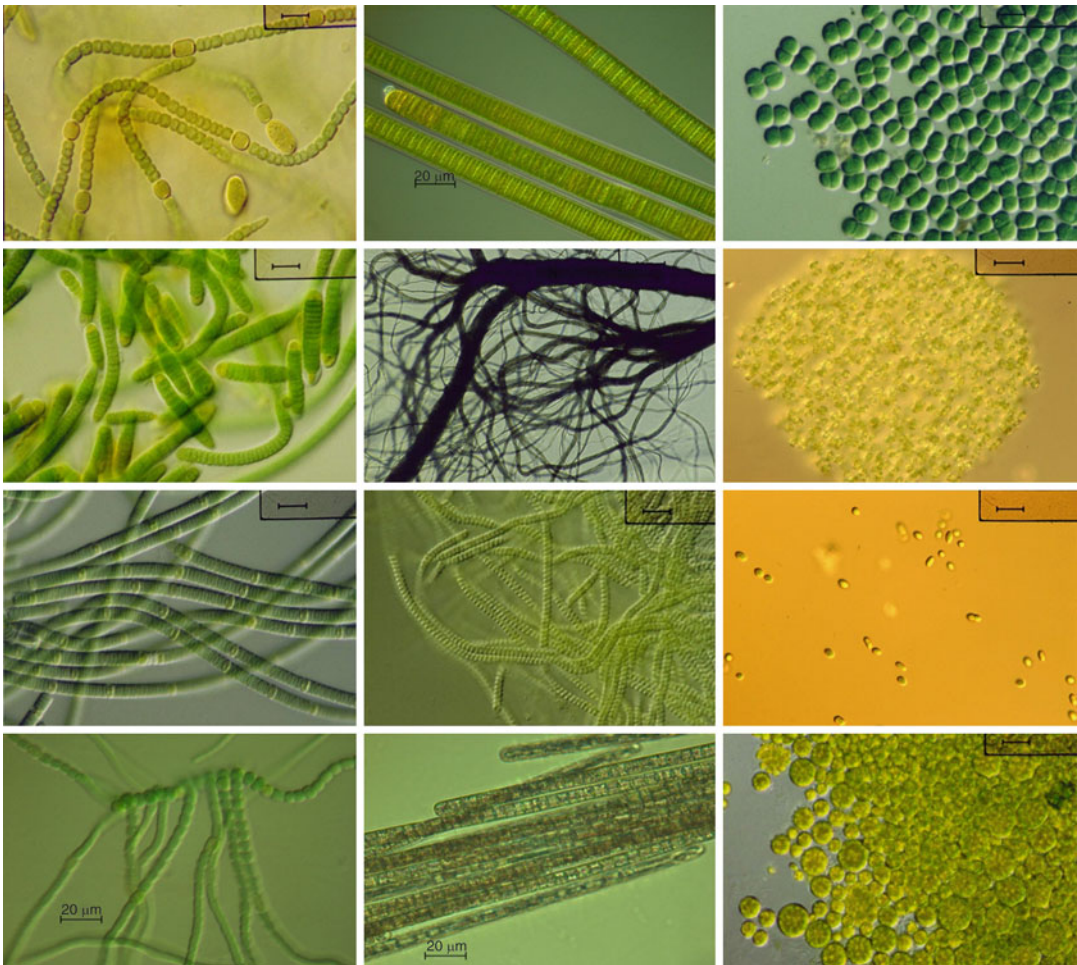
Obviously, an oxygenic phototrophic organism with two photosystems did not evolve at once (Olson and Blankenship 2004). There is no doubt that the predecessor of the cyanobacteria was an anoxygenic phototrophic organism with one photosystem. However, such organism might have been morphologically indistinguishable from modern cyanobacteria. Some modern cyanobacteria are capable of anoxygenic PS-I-dependent photosynthesis using sulfide as the electron donor.

Although monophyletic, cyanobacteria exhibit an amazing diversity. They differ two orders of magnitude in size from the smallest cyanobacteria measuring ~0.5 µm to the biggest of ~50 µm and from unicellular forms to filamentous species of which the trichomes can be as long as 10 mm. Cyanobacteria are also quite unique since they are among the very few organisms outside the Eukarya that display true cell differentiation. Moreover, the growth of populations of

cyanobacteria may be macroscopic in the form of well-defined structured aggregates.

Cyanobacteria are divided into five large divisions that are supported by the phylogeny of the 16S rRNA gene (Fig. 1). Divisions 1 and 2 are unicellular. Cyanobacteria of Division 1 may divide in one, two, or three planes, resulting in typical morphologies of the aggregates. Division 2 is composed of cyanobacteria that divide by multiple fissions and produce small daughter

cells, called baeocytes. Although considered unicellular, several representatives form more or less regular aggregates or colonies, often surrounded with a structured sheath. Division 3 comprises all filamentous cyanobacteria with solely undifferentiated cells. Also these cyanobacteria may form various forms of more or less structured sheathed colonies and bundles. Divisions 4 and 5 comprise filamentous cyanobacteria that show true cell differentiation. Under nitrogen



Cyanobacteria, Diversity and Evolution of, Fig. 1 Diversity of Cyanobacteria and examples from each of the five divisions. *Left column*: heterocystous cyanobacteria. Top three belong to Division 4: *Anabaena* sp. with heterocysts (lighter cells) and akinetes (very large cells), *Calothrix* sp. with terminal heterocysts, and *Nodularia* sp. with intercalary heterocysts. *Bottom*: *Fischerella* sp. with true branching (Division 5). *Middle*

column: non-heterocystous filamentous cyanobacteria (Division 3). *From top to bottom*: *Lyngbya* sp., *Phormidium* sp., *Spirulina* sp., and *Trichodesmium* sp. *Right column*: unicellular cyanobacteria. Top three belong to Division 1: *Gloeocapsa* sp., the colony-forming *Microcystis* sp., and the tiny *Crocosphaera* sp. *Bottom*: *Dermocarpa* sp. with baeocytes (Division 2)

starvation, some cells in the filaments differentiate into heterocysts (also called by the more appropriate but less common name heterocytes). Heterocysts have only photosystem I and therefore do not evolve oxygen and do not fix CO₂. For carbon and reducing equivalents, heterocysts depend on their neighboring vegetative cells. Heterocysts are the site of N₂ fixation. The special thick glycolipid cell envelope represents a gas diffusion barrier, limiting the flux of oxygen into the cell, thereby providing an anaerobic environment for the oxygen-sensitive nitrogenase. Many heterocystous cyanobacteria also produce akinetes (Adams and Duggan 1999). These are differentiated cells that have also been termed incorrectly “spores” and serve to enhance survival of the organism under unfavorable conditions. Akinetes are drought and radiation resistant but are not heat resistant like bacterial endospores. Akinetes contain ample amounts of storage compounds, such as glycogen (carbon and energy storage) and cyanophycin (nitrogen storage). Akinetes germinate and form hormogonia, another form of differentiation. Hormogonia may also differentiate from vegetative cells when the organism is exposed to environmental stress. Hormogonia are short, motile trichomes with cells smaller than those of the mature organism and do not possess heterocysts. They serve as a dispersion mechanism for the organism and are also important for entering into symbiotic relationships. The main difference between Divisions 4 and 5 is that the latter shows true branching. This occurs when a cell divides in more than one plane and distinguishes it from apparent branching that may occur in both divisions. Heterocystous cyanobacteria also may form colonies and aggregates.

Cyanobacteria are phototrophs and therefore possess photopigments. The great variety of photopigments of cyanobacteria gives these organisms a plethora of colors and allows them to adapt to a variety of light conditions. The main pigment in the photosynthetic reaction centers is the plant-type chlorophyll a. The main light-harvesting pigments are the phycobiliproteins. These pigments are organized in phycobilisomes that are connected to the photosynthetic thylakoid

membranes (Adir 2005). All phycobilisomes contain allophycocyanin. In addition, phycocyanin (blue) or phycoerythrin (orange to red) or both may be present, rendering the organism a blue-green, orange, red, or brown color. Phycoerythrocyanin is another phycobiliprotein with a reddish color that has a rather limited distribution and occurs only in some heterocystous cyanobacteria. Phycoerythrin comes in two forms, namely with the chromophore phycoerythrobilin (PEB) (red) and phycourobilin (PUB) (orange). Both chromophores can be bound to phycoerythrin in various ratios. Some cyanobacteria are capable of complementary chromatic adaptation (Mullineaux 2001). Depending on the wavelength of light, the amounts of phycocyanin and phycoerythrin will vary, turning cells blue green in red light and red in green light. Another form of more subtle chromatic adaptation occurs when organisms vary the ratio of PEB: PUB as a response to the prevailing underwater light conditions (Everroad et al. 2006).

Prochloron and *Prochlorothrix* are cyanobacteria that lack phycobiliproteins and contain chlorophylls a and b. The oceanic picoplanktonic cyanobacterium *Prochlorococcus* contains the divinyl derivatives of chlorophyll a and b, which are specific for this genus (Scanlan et al. 2009). Some strains contain small amounts of phycoerythrin, but phycobilisomes are lacking, and this pigment does not serve as a light-harvesting pigment in *Prochlorococcus*. Another unusual cyanobacterium is represented by the genus *Acaryochloris* which contains chlorophyll d instead of chlorophyll a and is an adaptation to the specific light conditions in its natural environment.

Cyanobacteria utilize a variety of nitrogen sources (Herrero et al. 2001). Many but not all cyanobacteria are capable of fixing atmospheric dinitrogen (N₂). Nitrogenase, the enzyme complex that reduces N₂ to NH₃, is inactivated by oxygen (Bergman et al. 1997). Therefore, the occurrence of N₂ fixation in the oxygenic cyanobacteria is paradoxical. N₂-fixing cyanobacteria have evolved mechanisms to ensure an anoxic intracellular environment for

nitrogenase. Many cyanobacteria are capable of fixing N_2 only under anaerobic and anoxygenic conditions, a strategy that can be termed avoidance (of oxygen) (Gallon 1992). The most advanced strategy is the differentiation of heterocysts (see above). These cells contain nitrogenase, and the strategy is a temporal separation of oxygenic photosynthesis (in the vegetative cells) and N_2 fixation (in the heterocysts). Many non-heterocystous N_2 -fixing cyanobacteria (filamentous as well as unicellular) exhibit a spatial separation of both incompatible processes by confining the fixation of N_2 to the night (Sherman et al. 1998). The oceanic non-heterocystous species *Trichodesmium* is an enigma as it fixes N_2 exclusively during the daytime. It is hypothesized that this organism employs a combination of spatial and temporal separation of N_2 fixation and oxygenic photosynthesis, i.e., that nitrogenase activity is confined to temporary non-oxygenic photosynthetic cells which have also been termed “diazocytes.”

Cyanobacteria possess a remarkably versatile, flexible, and reactive metabolism. In addition to the typical cyanobacterial metabolisms mentioned above, some cyanobacteria exhibit also efficient anaerobic metabolism. For instance, they can perform anoxygenic photosystem I-dependent photosynthesis during which sulfide is used as the electron donor. Some species do this in concert with oxygenic photosynthesis while others rely only on anoxygenic photosynthesis and CO_2 fixation. Cyanobacteria obviously possess dark metabolism in order to survive and cope with the natural day and night cycle. Under aerobic conditions, the glycogen reserve is respired through the oxidative pentose phosphate cycle (the reverse of the Calvin-Benson-Bassham cycle of CO_2 fixation) using oxygen as the electron acceptor. Under anaerobic conditions, some cyanobacteria are capable of fermenting glycogen via a variety of different pathways, and when available they can use elemental sulfur as electron acceptor (Stal and Moezelaar 1997). In order to tune all these processes to the natural day-night cycle, cyanobacteria are the only Bacteria with a circadian clock, which occurs otherwise only within the Eukarya (Golden 2003).

Cross-References

- [Archaeal Traces of Life](#)
- [Bacteria](#)
- [Belcher Group, Microfossils](#)
- [Great Oxidation Event](#)
- [Microfossils](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Photosynthesis](#)
- [Stromatolites](#)

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Cyanobacterial Mats

- [Microbial Mats](#)

Cyanobutadiynyl Radical

- [Cyanobutadiynyl Radical \(C₅N\)](#)

Cyanobutadiynyl Radical (C₅N)

William M. Irvine
Department of Astronomy,
University of Massachusetts,
Amherst, MA, USA

Synonyms

[Cyanobutadiynyl radical](#)

Chemical Formula

C₅N

Definition

The C₅N radical is found in both the envelopes of carbon stars (evolved stars whose atmospheres contain more carbon than oxygen, the excess carbon presumably produced by helium fusion in the latter stages of the star's life) and in cold, dark

interstellar molecular clouds (typically those that have not been heated by star formation). It is an intermediary in the chemistry of the cyanopolyynes and related molecules (Guelin et al. 1998). The rotational transitions of the cyanobutadiynyl radical are observed by radio astronomers at millimeter wavelengths. The anion of this species, C₅N[−], has also been found in space (Cernicharo et al. 2008).

Cross-References

- [Cyanopolyne](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radical](#)
- [Stellar Evolution](#)

References and Further Reading

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Cyanoethane

- [Ethyl Cyanide \(CH₃CH₂CN\)](#)
- [Vinyl Cyanide \(CH₂CHCN\)](#)

Cyanoethynyl Radical (C₃N)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[C₃N](#)

Definition

The four-atom ► [radical](#) C_3N is found in the gas phase in both interstellar ► [molecular clouds](#) and in the expanding envelopes of evolved carbon-rich stars (evolved stars are those which have completed their main hydrogen fusion stage and are thus nearing the end of their energy-producing lifetimes). C_3N is an intermediary in the chemistry of the ► [cyanopolyynes](#) and related radicals.

History

The presence of C_3N in the envelope of the carbon star IRC + 10216 was announced from the pattern of detected emission lines at millimeter wavelengths by Guelin and Thaddeus (1977), before the frequencies of these transitions had been measured in the laboratory. Friberg et al. (1980) stated that the chain of logic leading to this deduction was “worthy of Hercule Poirot (Christie 1945).” This identification is a particularly good example of the ability of heterodyne (high frequency resolution) astronomical measurements to contribute to fundamental molecular physics.

Cross-References

- [Cyanopolyyne](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radical](#)
- [Stellar Evolution](#)

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Cyanogen

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

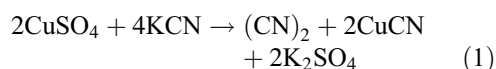
Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Synonyms

[Carbon nitride](#); [Dicyan](#); [Dicyanogen](#); [Nitriloacetonitrile](#); [Oxalic acid dinitrile](#); [Oxalonitrile](#); [Oxalyl cyanide](#)

Definition

Cyanogen is a compound of formula $(CN)_2$. It is a colorless gas at standard temperature and pressure. A cyanogen molecule consists of two CN groups bonded together at their carbon atoms ($N\equiv C-C\equiv N$). Cyanogen is the anhydride of oxamide. It can be generated from cyanide compounds and solutions of metal salts (such as copper (II) sulfate).



It is also formed when ► [nitrogen](#) and ► [acetylene](#) are acted upon by an electrical discharge.

It is implicated as a possible phosphorylating agent for nucleosides and a possible precursor to cyanates and ureas.

Cross-References

- [Electric Discharge](#)
- [Hydrogen Cyanide](#)

Cyanogen Nitride

- [Cyanamide](#)

Cyanogen Radical (CN)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

CN; Cyano radical

Definition

The diatomic radical CN, containing carbon and nitrogen, is widely observed in the ► [interstellar medium](#) of the ► [Milky Way](#) and external galaxies. It plays an important role in interstellar chemistry, being an intermediary in the production and destruction of such important species as HCN and HNC. The CN radical is also prominent in the visible wavelength spectra of cometary comae (atmospheres), where it is presumably a photodissociation product of molecules such as HCN that are sublimated from the icy nucleus. Note that the molecule C_2N_2 is also referred to as the cyanogen radical. A chemical compound that contains the CN functional group (carbon triple bonded with nitrogen) is called a cyanide, while an organic compound with this CN group is called a nitrile.

History

Unlike most interstellar molecules, which were discovered by radio astronomical observations, CN was first identified at ultraviolet wavelengths in 1940, and it was one of the first known interstellar molecular species. The fundamental rotational line was observed radio astronomically in 1970 by Jefferts et al.

Cross-References

- [Comet](#)
- [Hydrogen Cyanide](#)
- [Hydrogen Isocyanide \(HNC\)](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

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Cyanogenamide

- [Cyanamide](#)

Cyanomethane

- [Acetonitrile](#)

Cyanomethanimine

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

HCN dimer; HNCHCN

Definition

Cyanomethanimine is an organic molecule that is a less saturated relative of ► [aminoacetonitrile](#)

(glycine nitrile, $\text{NH}_2\text{CH}_2\text{CN}$). It has three ► [isomers](#), N-, E-, and Z-cyanomethanimine. Cyanomethanimine has been proposed as an intermediary in the prebiotic synthesis of the purine nucleobase adenine.

History

Both E-Cyanomethanimine and Z-Cyanomethanimine have been detected by radio astronomers in the interstellar medium (Zaleski et al. [2013](#); Rivilla [2019](#)). Cyanomethanimine has been suggested to be a possible precursor to adenine.

Cross-References

- [Adenine](#)
- [Aminoacetonitrile \(\$\text{NH}_2\text{CH}_2\text{CN}\$ \)](#)
- [Glycine](#)
- [Molecules in Space](#)

References

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Cyanomethylamine

- [Aminoacetonitrile \(\$\text{NH}_2\text{CH}_2\text{CN}\$ \)](#)

Cyanophyceae

- [Cyanobacteria](#)

Cyanopolyynes

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Cyanopolyynes are long carbon-chain molecules found in many astrochemical sources. Whereas polyynes are organic compounds with alternating single and triple bonds, the simplest being ► [diacetylene](#) ($\text{HC}\equiv\text{C}-\text{C}\equiv\text{CH}$), cyanopolyynes are end-capped by the cyano group ($-\text{CN}$). Examples are $\text{HC}\equiv\text{C}-\text{C}\equiv\text{C}-\text{CN}$ and $\text{HC}\equiv\text{C}-\text{C}\equiv\text{C}-\text{C}\equiv\text{C}-\text{CN}$.

Cross-References

- [Circumstellar Chemistry](#)
- [Diacetylene \(\$\text{C}_4\text{H}_2\$ \)](#)
- [Molecules in Space](#)

Cyclic Nucleotide

- [Cyclic Nucleotide Monophosphate](#)

Cyclic Nucleotide Monophosphate

Bruno Mattia Bizzarri
Organic, Bioorganic and Natural Substances
Chemistry, Biological and Ecological Sciences
Department (DEB), University of Tuscia, Viterbo,
Italy

Synonyms

[Cyclic nucleotide](#)

Acronyms

cNMP

Definition

A cyclic nucleotide monophosphate (cNMP) is a nucleotide containing a cyclic phosphodiester bond between the sugar and the phosphate moiety. As the noncyclic nucleotides, the cyclic form is composed of the sugar, the nucleobase, and the phosphate group. The cyclic phosphodiester bond occurs at 3'-5' (2' deoxy-ribose) or, in alternative, at 3'-5' and 2'-3' (ribose) position of the sugar. They are produced under prebiotic conditions (Schwartz 1997; Yamagata et al. 1991; Schoffstall 1976; Bizzarri et al. 2019). cNMPs are possible intermediates for the formation of RNA oligonucleotides in one-pot conditions without the presence of template (Costanzo et al. 2009; Saladino et al. 2018). The oligomerization of 3'-5' cGMP to ribo-oligomers containing up to 25 nucleotides without pre-activation is reported, both in water and formamide (Costanzo et al. 2011, 2012; Šponer et al. 2016a, b).

Cross-References

- [Nucleotide](#)
- [Origin of Life](#)
- [Phosphates](#)
- [Prebiotic Chemistry](#)

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Cyclic Replicator Equation

- [Hypercycle](#)

Cyclohexa-1,3,5-triene

- [Benzene \(C₆H₆\)](#)

Cyclopropenylidene (C₃H₂)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

C₃H₂, c-C₃H₂

Definition

The 3-carbon ring molecule C_3H_2 is classified chemically as a ► [carbene](#) and is highly reactive in the laboratory. It was the first cyclic molecular species detected in interstellar ► [molecular clouds](#). Immediately following its identification at short radio wavelengths, it was discovered to be nearly ubiquitous in the ► [interstellar medium](#) (Matthews and Irvine 1985), and it has subsequently also been found in the envelope of evolved carbon-rich stars (evolved stars are those which have completed their main hydrogen fusion stage and are thus nearing the end of their energy-producing lifetimes). The linear ► [isomer](#) of C_3H_2 is also detected in molecular clouds, but its abundance is typically an order of magnitude lower than that of the cyclic isomer (Cernicharo et al. 1991). In diffuse clouds, the abundance ratio between the linear and the cyclic isomers increases by a factor 10 with respect to that observed in dense molecular clouds (Cernicharo et al. 1999). Both 13-carbon and deuterated isotopic forms of C_3H_2 have been detected astronomically.

History

The laboratory measurement of the frequencies of several C_3H_2 rotational transitions by Thaddeus et al. (1985) proved the identification of emission lines that they had earlier observed astronomically.

Cross-References

- [Carbene](#)
- [Deuterium](#)
- [Isomer](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Stellar Evolution](#)

References and Further Reading

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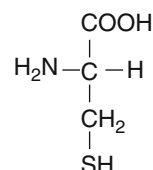
Cysteine

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Definition

Cysteine is one of the 20 protein ► [amino acids](#), whose structure is shown in Fig. 1. Its three-letter symbol and one-letter symbol are Cys and C, respectively. Among the protein amino acids, only cysteine and methionine contain a sulfur atom. The side chain of cysteine contains a thiol ($-SH$) group, which is often present in the active site of enzymes. In proteins, two cysteine residues often form a disulfide bond (► [Cystine](#)) which is essential in stabilizing the protein 3D structure. Cysteine has been produced in a variety of prebiotic experiments from reducing gas mixtures but has not been detected in carbonaceous chondrites, possibly due to its instability.

Cysteine,
Fig. 1 Chemical structure
of cysteine



Cross-References

- ▶ [Amino Acid](#)
- ▶ [Cystine](#)
- ▶ [Proteins, Primary Structure](#)

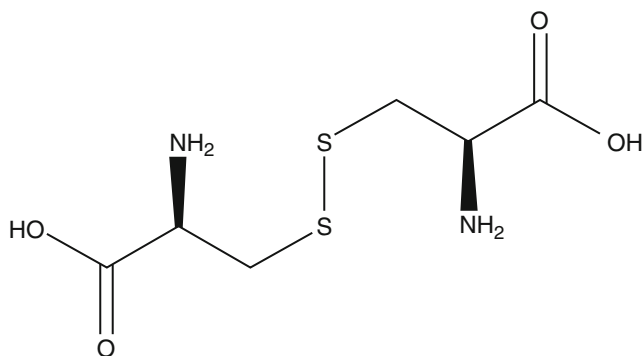
Cystine

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Definition

Cystine (Fig. 1) is formed by the oxidative condensation of two ▶ [cysteine](#) molecules. Cysteine, one of the 20 ▶ [protein](#) amino acids, has a ▶ [thiol](#) (–SH) group. In aqueous solution, two thiol groups readily oxidize to form a ▶ [disulfide bond](#) (–S–S–). Thus, cystine rather than cysteine is usually determined when the amino acid composition of protein hydrolysates is analyzed. It can be easily reduced to give two cysteine molecules. In protein molecules, cysteine residues make intramolecular disulfide bonds, which stabilize protein tertiary structure.

Cystine, Fig. 1 Chemical structure of cystine



Cross-References

- ▶ [Amino Acid](#)
- ▶ [Cysteine](#)
- ▶ [Disulfide Bond](#)
- ▶ [Protein](#)
- ▶ [Thiol](#)

Cytochromes

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Cytochromes are a class of electron-transferring metalloproteins containing a heme as prosthetic group and that participate in many different respiratory and photosynthetic ▶ [electron transport](#) chains, usually as membrane-bound electron carriers. The function of cytochromes as electron carriers involves the alternate ▶ [oxidation](#) and ▶ [reduction](#) of the iron ion present in the heme group, one electron each time (i.e., between the reduced ferrous state and the oxidized ferric state),

and with a standard ► [redox potential](#) between –100 and +500 mV. The cytochromes are classified on the basis of their characteristic, redox-sensitive, visible absorbance spectra.

Cross-References

- [Electron Carrier](#)
- [Electron Transport](#)
- [Oxidation](#)
- [Photosynthesis](#)
- [Redox Potential](#)
- [Reduction](#)
- [Respiration](#)

Cytoplasm

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Cytoplasm is the internal space of a ► [cell](#) containing all soluble chemical components and, in the case of eukaryotic cells, the organelles (► [nucleus](#), mitochondria, plastids, microbodies, etc.), the cytoskeleton, and the endomembrane system (endoplasmic reticulum, Golgi apparatus, etc.). The fluid, non-particulate fraction of the cytoplasm is known as cytosol.

Cross-References

- [Cell](#)
- [Cell Membrane](#)
- [Nucleus](#)

Cytoplasmic Membrane

- [Cell Membrane](#)
- [Membrane](#)

Cytosine

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

Cytosine (C) is one of the four heterocyclic nitrogenous bases found in DNA (A, T, C, and G) and RNA (A, U, C, and G). It is a pyrimidine with two functional group substituents: an amine at the C⁴ position and a keto group at the C² position. When cytosine is combined with ribose via a glycosidic linkage between its N¹ nitrogen and the C¹ position of the sugar, it forms a nucleoside called cytidine; removal of the 2'OH group of this molecule results in the formation of 2'-deoxycytidine also known as deoxycytidine. In Watson-Crick base pairing in nucleic acids, these derivatives form three hydrogen bonds with guanine.

Cytosine and its derivatives hydrolyze fairly rapidly under physiological conditions to give uracil via deamination, with a half-life of approximately 73 years at 37 °C at pH 7. In biological systems, this relatively rapid loss of structural genetic information is corrected by DNA repair enzymes.

Cytosine has been synthesized under simulated prebiotic conditions from cyanoacetaldehyde

and urea as well as from ► [cyanoacetylene](#) and cyanate. It can also be derived from the deamination of 2,4-diaminopyrimidine, itself derived from the condensation of guanidine with cyanoacetaldehyde.

Cross-References

- [Cyanoacetylene](#)
- [Pyrimidine Base](#)
- [Uracil \(Ura\)](#)

D

D-Amino Acids

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

D-amino acids are α -amino acids that have the *R* configuration at their α -carbon atom (see ► “[Cahn Ingold Prelog Rules](#)”), with the exception of cysteine, which is of the *L* configuration. D-amino acids are produced by enzymatic post-translational modification of the isomeric L-amino acids, which are ribosomally encoded. D-amino acids are found in some bacterial cell walls as well as in some fungal antibiotic peptides.

Cross-References

- [Amino Acid](#)
- [Cahn Ingold Prelog Rules](#)

D-Value

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

The D-value (or decimal reduction value) is the amount of a bioburden reduction process needed to achieve inactivation of 90% of a population of the test microorganism population under stated conditions (temperature, pressure, etc.). This value could be a dose or a concentration for an antibiotic, a time (in minutes, hours, or days) for DHMR or pasteurization, or an exposure dose for sterilization using ionizing/nonionizing radiations (e.g., gamma irradiation and UV light).

Cross-References

- [Bioburden](#)
- [Bioburden Reduction](#)
- [DHMR](#)
- [Microorganism](#)
- [Sterilization](#)

D/H ratio

► [Deuterium/Hydrogen Ratio](#)

D/L-Ratio

Uwe J. Meierhenrich

Institut de Chimie de Nice (ICN), Université Côte d'Azur, Nice, France

Keywords

Amino acids · Biomolecular asymmetry · Chirality · Homochirality · Sugars

Synonyms

[Enantiomeric ratio](#)

Definition

Chiral molecules such as amino acids and sugars are composed of enantiomers that occur in stereochemical D- or L-configurations or in a mixture of them. The D/L-ratio determines the fraction of a D-enantiomer over the corresponding L-enantiomer. Abiotically synthesized chiral molecules usually have a D/L-ratio of 1, or, in other words, they occur as a racemic mixture, as long as no enantiomerically enriched reactants or catalysts are used, or spontaneous symmetry breaking processes operate. In biology, however, amino acids and sugars show a D/L-ratio that is unequal to 1. The D/L-ratio of amino acids in ► [proteins](#) is nearly zero, whereas the D/L-ratio of ribofuranosyl sugar molecules in ► [DNA](#) is infinite.

Overview

A molecular structure that is non-superimposable with its mirror image is said to be chiral (see ► [chirality](#)). Similar to the right and the left hand, chiral molecules exhibit identical physico-chemical properties such as molecular weight,

size, and color. Corresponding chiral molecules are called enantiomers and their resolution in the laboratory is often challenging. In particular, for chiral amino acids and chiral sugars, the D, L nomenclature is still in use, which distinguishes between right-handed D-amino acids and left-handed L-amino acids or right-handed D-sugars and left-handed L-sugars. The synthesis of amino acids in the laboratory, via the Strecker mechanism or via the Miller-Urey experiment, leads to a racemic mixture of the amino acids with a D/L-ratio of exactly 1. Also, the foremost reaction produces sugar molecules in a racemic ratio, that is, the D/L-ratio equals 1. However, living organisms tend to prefer one conformation of the two possible enantiomers. Proteins are exclusively composed of L-amino acids (Meierhenrich 2008). The sugars occurring in RNA and DNA are exclusively of the D-configuration. The genetic material of biological organisms does not use their mirror-image L-sugar structures; thus, the molecular symmetry in living organisms is broken. Today it remains unknown how biomolecular asymmetry was triggered. Various hypothetical models exist to explain biomolecular asymmetry, among them (a) asymmetric photochemistry and the interaction of racemic organic molecules with circularly polarized light, (b) asymmetric phase transitions involving the precipitation of enantioenriched or enantiopure crystals or asymmetric adsorption processes, or (c) the weak nuclear interaction and the transfer of its inherent asymmetry to chiral organic molecules. The discussion of the validity of these hypotheses is influenced by the detection of D/L-ratios between 0.8 and 1 for different amino acids in various meteorites. Until now, L-enantiomeric excesses of up to 18.5% have been identified in the Murchison meteorite but an ► [amino acid](#) with a D/L-ratio larger than 1 has never been detected.

Cross-References

- [Amino Acid](#)
- [Asymmetric Reaction, Absolute](#)
- [Carbohydrate](#)

- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [DNA](#)
- [Homochirality](#)
- [Polarized Electron](#)
- [Polarized Light and Homochirality](#)
- [Protein](#)

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Dallol Geothermal Area

- [Dallol Geothermal System](#)

Dallol Geothermal System

Gian Gabriele Ori
Int'l Research School of Planetary Sciences,
Pescara, Italy
Ibn Battuta Centre, Université Cadi Ayyad,
Marrakech, Morocco

Keywords

Hydrothermal activity · Sebkhā · Dry lake ·
Archea · Habitability

Synonyms

[Dallol geothermal area](#); [Dallol volcano](#)

Definition

The Dallol geothermal system is located in the northern part of the Danakil Depression, Ethiopia (14° 14' 17" N 40° 17' 50" E, at about 120 m below sea level), and it is believed to be one of the most inhospitable environments on Earth. The area is part of the Afar Depression, a portion of a newly born ocean that hosts extreme

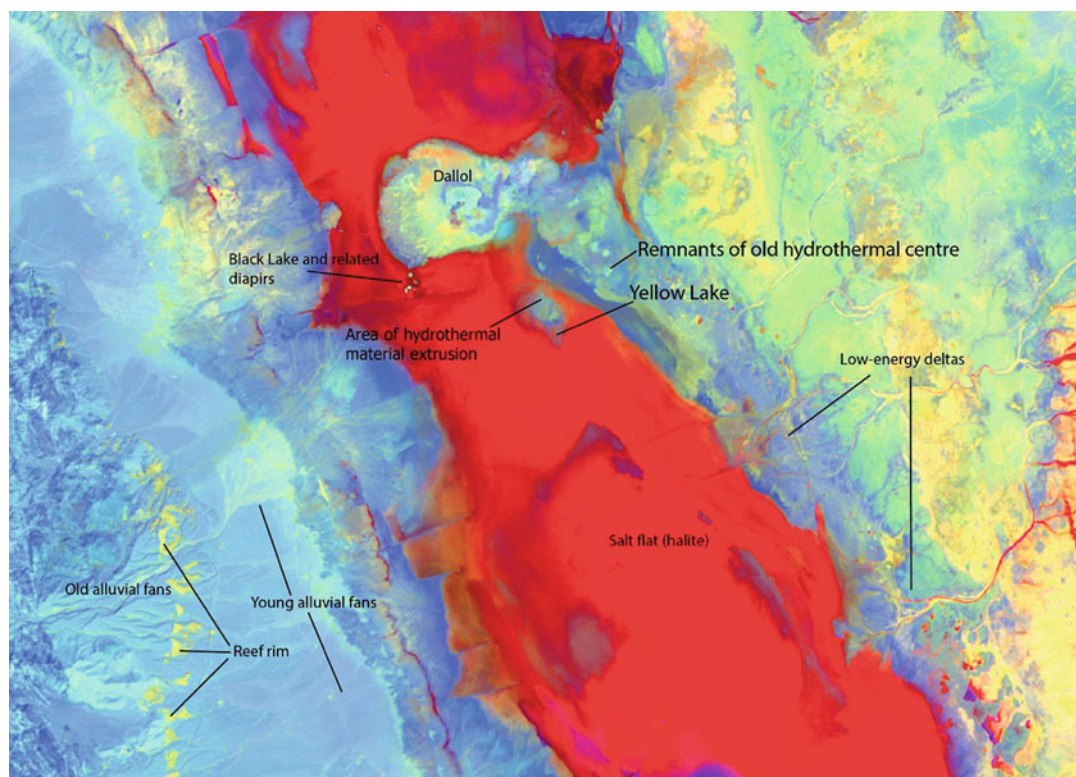
environments in term of physical and chemical conditions. Due to the extreme environmental conditions, Dallol and the surrounding areas are a compelling laboratory where habitability and limit of life can be investigated and compared with other planets.

History

The Northern Danakil is one of the most extreme areas in the World. The area is covered by a large salt flat (sebkhā in Arabic) that forms two dry lakes: Assale to the South of Dallol and Ghebrò to the North. Further South there are several large volcanic fields including the Erta Ale with a famous lava lake at the summit. Clearly, this remote geographical setting has left Danakil largely unexplored until the first half of the twentieth century. The Dallol has been almost unnoticed until potash deposits have been identified and their exploitation has been started (Vinassa de Regny 1938). However, the real scientific interest is relatively recent because it started in the 1970s with a few scattered expeditions, but it is only in the recent year that Dallol attracted geochemical, geophysical, and biological research. In recent time, Dallol has been a site visited by several number of scientists from universities and research centers. The Europlanet Research Infrastructure (a research program in planetary sciences financed by the European Commission) organized several multidisciplinary expeditions with the participation of more than 35 scientists.

Overview

The Dallol is a remarkable relief (40 m high), emerging from the large flat plain produced by evaporitic sedimentation (mostly halite and syl-vite) and water flooding (Cavalazzi et al. 2019; Lopez-Garcia et al. 2020). The current active cone is about 3.5 km in diameter and its summit consists in a sort of a few meters deep crater where the hydrothermal activity is concentrated. This *crater* contains of the entire series of features present in other hot springs produced by the



Dallol Geothermal System, Fig. 1 The main evaporitic basin surrounding Dallol. The red signature shows the vast sabkha plain principally made up of halite. Dark shadows indicate differences in humidity and the presence of fine grained (clay and wind-blown silt). To the east of the Yellow Lake, it is possible to observe the transition from halite flat to gypsum “contaminated” surface. The colors become dark blue and green/yellow. Hydrothermal

emission centers are shown in light blue. This can be compared with the brighter color at the center of Dallol representing active or rather recent hydrothermal activity. The area North of Yellow Lake consists of a polygonal evaporitic sabkha with hydrothermal material emitted by meagre but pervasive emissions. (Image: Principal Component Analysis from the multispectral Sentinel 1 data)

salt precipitation of over-saturated brines such as spring mounds, hot ponds, pools bordered by terraces, fumaroles, geysers exhibiting a large variety of colors in sediment and water. The water present in the Dallol *crater* reaches high temperature up to 112 °C. The water is, also, rather acidic with pH values quite below 1 (0–0.2) and, at places, it reaches values below 0, namely –0.74. The water is associated with gas releases of sulfur dioxide (SO₄), hydrogen chloride (HCl), carbon dioxide (CO₂), and hydrogen sulfide (H₂S).

The hydrothermal activity at the top of the Dallol is matched with a large number of different hot spring activities in the surrounding salt flat. One of the most impressive is the Gaet’ale (named also Yellow Lake) at about 4 km south-east of Dallol. The lake is about 60 m in diameter and contains yellowish bubbling water. The bubbling is due to the emission of CO₂. The water of the lake (containing calcium chloride, CaCl₂, and Magnesium Chloride, MgCl₂) is most saline water in the World reaching a concentration of 43% (Perez and Chebude 2017).



Dallol Geothermal System, Fig. 2 The hydrothermal activity features at the top of Dallol. Water ponds and gas emission chimneys are extensively present in the area. For scale: the chimney in the foreground is 1 m high

Southwest of Dallol at about 2 km apart a number of black domes, named Black Mountains, extrude from the plain and form a remarkable landmark in the landscape. These features are made up of black halite and are hydrothermally active with the formation of bischofite flows. An adjacent lake (Black Lake, 12 m in diameter and about 10 m deep) is acidic (about pH 3) with high temperature ranging around 70 °C. Bischofite and carnalite are common around the lake.

The geobiological setting exhibits extreme variables such as temperature, pH, salinity, sediment/rock composition, degassing mechanisms, and atmospheric pressure. This world of extremes is a compelling laboratory for the definition of the

limits of growth of life and, generally, for habitability. In a polyextreme environment such as the one of Dallol and its adjoining areas, it is possible to investigate the habitability by taking into consideration the multidimensional characteristic of this kind of setting. In fact, the environment is characterized by high atmospheric temperature (average 41.2 °C), high water temperature (up to 112 °C), low water pH (lower than -1), high saltwater content (up to 43%), and high content in water of Magnesium. The result is an arid environment with water and sediments limiting formation and growth of life (see Belilla et al. 2019 for discussion). It is possible that interaction among these limiting variables create several barriers to life. However, two inhibiting mechanisms



Dallol Geothermal System, Fig. 3 The hydrothermal activity features at the top of Dallol. Pools in the foreground are surrounded by terraces marked by the brine borders. Filled (inactive) ponds are present and the brine

deposits verge to an ochre/brown coloration. In the far background, an inactive (abandoned) area is getting altered (oxidation) and loses its bright coloration

are considered important limiting factors: the high chaotropicity and low water activity (a_w) due to high Mg content in brines and the association of hypersalinity and hyperacidity conditions. The water and sediment of Dallol and adjoining area are poor in living forms and their variability in physicochemical conditions strongly control the living factors (Belilla et al. 2019; Moors et al. 2020). The living forms basically consist of

Archea (Gómez et al. 2019; Belilla et al. 2019; Moors et al. 2020), and their occurrence is determined by the complex relationships of the interactions by the different constraints. The Dallol is a remarkable analogue to Mars (Fawdon et al. 2015; Kotopoulou et al. 2019) and probably to other Solar and extra-Solar planetary bodies. The analysis of this polyextreme geological environment is just at the beginning.



D

Dallol Geothermal System, Fig. 4 The Yellow Lake with the bubbling water due to carbon dioxide emission. In the background, the Dallol. The water salinity is 43%,

the highest salinity value on the Earth for a standing body of water. For scale: the lake is about 60 m wide



Dallol Geothermal System, Fig. 5 The Black Lake and in the background the western slope of Dallol. Note the thin layer of brine floating over the water surface. For scale: the lake is 12 m wide

Cross-References

- [Chaotrophicity](#)
- [Hydrothermal Environments](#)
- [Mars Analogue Sites](#)
- [Water Activity](#)

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Dallol Volcano

- [Dallol Geothermal System](#)

Dark Biosphere

C. Escudero

Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Keywords

Microorganisms · Subsurface ·
Geomicrobiology · SLiME

Synonyms

[Deep biosphere](#); [Deep subsurface microbiome](#)

Definition

The term dark biosphere encompasses those ecosystems that operate in the absence of sunlight and, therefore, their energy input to supporting life does not depend directly on photosynthesis. In these ecosystems, which include the deep continental and oceanic subsurface, life is mainly supported by the geosphere.

Overview

Dark biosphere, essentially, is the sum of underground ecosystems, both oceanic and continental. Deep subsurface ecosystems are oligotrophic extreme environments characterized by the absence of sunlight and oxygen where, in addition, pressure and temperature increase with depth (Kieft 2016; Escudero et al. 2018). Nonetheless, subterranean environments are full of life. Actually, it has been estimated that up to 90% of Earth’s prokaryotes belong to the dark biosphere (Kallmeyer et al. 2012; Magnabosco et al. 2018). Overall, as available organic matter is uncommon

in subsurface environments, minerals or abiotic processes that release energy from minerals are likely the main drivers of subterranean life.

Despite the fact that dark biosphere has been studied since the early 1920s, it is still not completely clear, however, if the available metabolic energy sources are 100% endogenous or, on the contrary, are partly dependent on products photosynthetically generated on the surface. In 1995, Steven and Mc Kinley described the first putative subsurface ecosystem completely independent of the surface in the Columbia River Basalt Group, where the primary producers were chemolithoautotrophic microorganisms. These ecosystems, which operate in the absence of any influence of photosynthesis, that is, organic matter produced on the surface, and which both electron donors and acceptors are renewed by geological processes, were named SLiMEs (Subsurface Lithoautotrophic Microbial Ecosystem) (Stevens and McKinley 1995; Nealson et al. 2005).

In SLiMEs, as the energy input from the surface is discarded, mineralogy and geochemistry define the availability of nutrients and the source of energy and, therefore, the operating metabolism at a given location and depth (Jones and Bennett 2017; Casar et al. 2020). Actually, some microorganisms are able to carry out external electron transfer, using minerals as direct electron donor or acceptors (Shi et al. 2016) or to dissolve minerals releasing compounds that can be used as substrate and contribute to the production of biomass (Torrentó et al. 2011; Shelobolina et al. 2012; Vera et al. 2013; Edwards et al. 2003). However, the direct or indirect use of minerals as energy source implies that extracellular agents such as nanowires or redox mediators need to be produced, which would increase the necessary energy to thrive in these oligotrophic environments. Therefore, energy released abiotically is crucial to sustaining dark biosphere (Hoehler 2004).

Different studies have shown that hydrogen (H_2) is one of the most abundant gases in subsurface environments. In addition, not only can H_2 be produced abiotically by processes such as water radiolysis or water-rock interaction (Apps and van de Kamp 1993) but also it is widely used as

electron donor by chemolithoautotrophic microorganisms. Thus, it is considered the main source of primary energy in SLiMEs (Stevens and McKinley 1995; Pedersen 1997).

However, not all subsurface locations produce enough H_2 to be considered a significant source of abiotic energy and it has been argued that dark biosphere might depend, partially, on the flow of organic matter and energy from the surface (Parkes et al. 2014). Some examples are petroleum deposits or sedimentary rocks, where the presence of organic matter photosynthetically produced is indisputable (Fredrickson and Balkwill 2006). On the other hand, the presence of pores and fractures in subsurface systems may interconnect surface and subsurface, which may lead to the percolation of organic matter rich water that can contribute in feeding the system (Lopez-Fernandez et al. 2018). In fact, heterotrophy is a widespread metabolism in the subsurface and the heterotrophic community is occasionally more diverse and numerous than the lithoautotrophic one (Breuker et al. 2011; Purkamo et al. 2015; Sanz et al. 2021). In these cases, fermenting and heterotrophic would be the main metabolisms that maintain the functioning of subsurface ecosystems.

Cross-References

- [Anaerobic Respiration](#)
- [Ecosystem](#)
- [Deep Biosphere](#)
- [Deep Subsurface Microbiology](#)
- [Extreme Environment](#)
- [Geomicrobiology](#)
- [Lithotroph](#)
- [Prokaryote](#)

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Further Reading

Ecosystem, Deep Biosphere, Deep Subsurface Microbiology, Extreme Environment, Lithotroph, Prokaryote

Dark Cloud

► [Dust Cloud, Interstellar](#)

Dark Fringe Interferometry

► [Nulling Interferometry](#)

Dark Reactions

► [Calvin-Benson Cycle](#)

Dark Streaks (Mars)

Alessandro Airo
Fachbereich Geowissenschaften, Institut für
Geologische Wissenschaften Tektonik und
Sedimentäre Geologie, Freie Universität Berlin,
Berlin, Germany

Definition

Dark streaks is a general term for temporarily darkened surface patches occurring on various slopes on Mars (e.g., crater walls or dune faces) that display a range of morphologies (e.g.,

conical, linear, or braided). The darkening of the surface is believed to be caused by the removal of the surficial dust cover due to dry grain flow, wetting of the soil, or fluvial activity. Over the course of months and years, the dark coloration fades away, which is presumably the result of the surficial accumulation of bright dust particles and/or drying of the soil.

Cross-References

- ▶ [Slope Lineae, Recurrent](#)
- ▶ [Slope Streaks \(Mars\)](#)

Darwin's Conception of the Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Keywords

Evolution · Natural selection · Variation

History

Charles Darwin (1807–1882) is the author of the principal evolutionary theory of the nineteenth century, which founded the most important part of the evolutionary thought of the twentieth century.

The son of a physician, he abandoned his own medical studies in Edinburgh after 2 years and went to Cambridge to study theology. There, he was initiated into botany and geology. In 1831, he embarked on the *Beagle* for a 5-year trip around the world. As the only geologist on board, he had to study the formation of the atoll island; moreover, he did the broad work of a naturalist, studying also animals and plants. He came back to England as an acknowledged geologist. However, he and his family settled in Down, in the south-west of London, where he prepared, for 20 years, a theory about the origin of species. In 1858, when

he received a letter from Wallace, a naturalist living in Malaysia, he decided to publish his book rapidly. *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* was published in 1859, and it expounded his theory based on the variation and selection of living beings.

In the first issue of his book, Darwin claimed that the tree of life came from a unique and simple ancestor. However, the lack of fossils from the oldest period of Earth led Darwin to be very careful on this topic. In the first edition of his book, he only wrote a few words about the origin of life in the last lines of the last chapter:

There is a grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

Doing some concessions on the social context, he changed these lines in the second edition, but he continued to assume that there was a very simple common ancestor to all the living beings.

However, Darwin never published any text about the process of the formation of the first living beings. He explained his position in a letter to his friend, the botanist Joseph Dalton Hooker (1817–1911):

It is often said that all the conditions for the first production of a living organism are now present, which could have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sort of ammonia and phosphoric salts, – light, heat, electricity &c. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured, or absorbed, which would not have been the case before living creatures were formed. (Calvin 1969)

In this quote, Darwin underlined several important points directly related to his evolution theory. Firstly, he claimed the possibility of a complexification of matter before the existence of life, and he indicated possible chemical ways. Secondly, he analyzed the particular case of the origin of life and suggested that life itself prevented a new formation of life. Therefore,

according to Darwin, the origin of life was the unique event in the history of life that could not repeat itself.

Cross-References

- [Huxley's Conception on Origins of Life](#)
- [Lamarck's Conception of Origins of Life](#)

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Daughter Molecule, Comet

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

A daughter molecule is a molecule produced from the photodissociation of a parent molecule which is directly outgassed from a cometary nucleus. The most abundant parent molecule is H_2O ; its dissociation products are H and OH. Other parent molecules include CO, CO_2 , CH_4 , NH_3 , HCN, H_2CO , and H_2S . Daughter molecules include CN, CS, and CO (which appears to be both a parent and a daughter molecule). Daughter molecules and radicals are mostly detected from their visible and ultraviolet spectra, while parent molecules are better observed with IR and millimeter spectroscopy.

Cross-References

- [Comet](#)
- [Parent Molecule, Comet](#)

De Duve, Christian

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

Christian de Duve was a Belgian medical doctor and biologist. In 1974, he was awarded with the Nobel Prize of medicine and physiology for his work and discoveries of lysosomes and peroxisomes.

Throughout his lifelong career, he develops a rich philosophical thought notably regarding the origin of life, publishing several number of books on that subject. He claimed that chemistry deals with deterministic phenomena and consequently that the origin of life depended on the initial conditions in which it arose. Therefore, he claimed that there are probably numerous cases of life in the universe.

Moreover, he distinguished two sorts of evolution: the horizontal evolution that is responsible of diversity of species and depends of environment and the vertical evolution that is responsible for the increase of complexity of organisms and does not depend of environment. For example, for him, the development of the brain is independent of the environmental conditions. For that reason, de Duve claimed that the emergence of the human species was not so improbable.

De Maillet's Conception of Origins of Life

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

History

At the end of the seventeenth century, Benoît de Maillet (1656–1738) wrote a book entitled *Telliamed, ou entretiens d'un philosophe indien*

avec un missionnaire français (La Haye chez Pierre Gosse) and signed under this pseudonym: *Telliamed*. This book was published in 1748 and 1755 after de Maillet's death. It presents an imaginary "entretien" between a missionary and an Indian man, who explains his conception of the world and of life. With this astucious rhetorical form, de Maillet presented his own view through the Indian man's mouth. According to him, life on earth came from a panspermic phenomenon. Life first developed itself in seas and then on continents. Therefore, the Indian man, in fact de Maillet, argues against the religious discourse.

Cross-References

- [Buffon's Conception of Origins of Life](#)
- [Spontaneous Generation, History of](#)

Dead Zone

- [Oxygen Minimum Zone](#)

Deamination

Matthew Levy

Michael F. Price Center, Albert Einstein College of Medicine, Bronx, NY, USA

Keywords

Ammonia · Degradation · Hydrolysis

Definition

Deamination describes the loss of an amine group from a molecule.

Overview

Deamination is likely to have played an important role in the availability of the biological building blocks of life. In the case of the nucleobases, the

components of ► [RNA](#) and ► [DNA](#), the dominant decomposition products of their exocyclic amine-bearing bases ► [adenine](#), ► [guanine](#), and ► [cytosine](#) are the deaminated products hypoxanthine, xanthine, and uracil, respectively. A calculation of the half-lives for the rates of decomposition of these bases shows that these compounds are not stable on a geologic timescale at temperatures much above 0 °C. This has led to the suggestion that life would be more likely to evolve under cold conditions, where biologically important material can accumulate, rather than at elevated temperatures such as hydrothermal vents, where they would be rapidly destroyed (Levy and Miller 1998).

Deamination is important for other biomolecules such as amino acids. In particular, the deamination of aspartic acid to fumaric acid and ► [ammonia](#) has been shown to have a half-life of 2.8×10^7 years at 0 °C and 96,000 years at 25 °C (Bada and Miller 1968). Equilibrium measurements for this deamination reaction have previously been utilized to estimate the concentration of ammonium ions on the early Earth (Bada and Miller 1968). Thus, deamination is not just a route to the destruction of biomolecules, but also a potential tool to ascertain conditions in the oceans of the early Earth or other environments.

In biology, one of the most critical deamination reactions is the hydrolysis of cytosine to uracil and ammonia. At neutral pH (~7) and 37 °C, the half-life of cytosine through deamination is 200 years in single-stranded DNA and ~30,000 year in double-stranded DNA (Lindahl and Nyberg 1974; Frederico et al. 1990). Measurements for the rate of deamination of free cytosine are similar, albeit slightly faster than those reported for single-stranded DNA (~60 years at 37 °C; Levy and Miller 1998). This deamination rate is sufficiently fast that biological systems must have evolved repair mechanisms fairly early in their history to prevent the resulting DNA damage.

Cross-References

- [Amino Acid](#)
- [Ammonia](#)
- [Nucleic Acids](#)

References and Further Reading

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Debris Disk

Paul Kalas

Astronomy Department, University of California, Berkeley, CA, USA

Institute of Astrophysics, FORTH and the University of Crete, Heraklion, Crete, Greece

Keywords

Extrasolar planetary systems · Interplanetary dust grains

Synonyms

[Planetary debris disks](#); [Protoplanetary disk of second generation](#)

Definition

A debris disk is a flattened distribution of dust surrounding a main sequence star that is continuously replenished by the collisional erosion of asteroids and comets. A debris disk may be present for much of the lifetime of a star, as is evident from the presence of the solar system's zodiacal dust cloud ([► \[Zodiacal Light\]\(#\)](#)).

History

Interplanetary dust particles were first observed as the naked-eye phenomenon of [► \[zodiacal light\]\(#\)](#) in

our own solar system. In 1983, the [► \[Infrared Astronomical Satellite \\(IRAS\\)\]\(#\)](#) began an all-sky imaging survey at 12, 25, 60, and 100 μm . Approximately 15% of bright main sequence stars revealed excess thermal emission, typically at 60 μm , that was attributed to thermal emission from circumstellar dust grains. Stellar coronagraphy and imaging resolved a relatively bright and extended dust *disk* surrounding the nearby A star Beta Pictoris (Smith and Terrile [1984](#)). An excess of infrared emission due to circumstellar dust was called the “Vega phenomenon” because the first IRAS discovery of such emission was made for the bright star Vega (Aumann et al. [1984](#)). The Vega phenomenon was attributed to the same dust replenishment mechanisms that create the zodiacal light – the collisional erosion of comets and asteroids that formed around other stars. The fundamental time-scale argument was that collisions, radiation pressure, and [► \[Poynting-Robertson drag\]\(#\)](#) limit the lifetime of circumstellar dust grains to less than 10^5 years (e.g., around luminous A stars such as Beta Pictoris, Vega, and Fomalhaut, grains smaller than 5–10 μm are ejected by radiation pressure), whereas the ages of the Vega phenomenon stars were all greater than ten million years.

The IRAS mission was succeeded by the launches of the [► \[Infrared Space Observatory\]\(#\)](#) (ISO 1995) and the Spitzer (2003) and Herschel (2009) space telescopes. Spatially resolved imaging was initially most successful at 350–850 μm wavelength from the ground, particularly with the SCUBA instrument on the 15-m James Clerk Maxwell Telescope on Mauna Kea, Hawaii. These data showed that circumstellar dust disks have various asymmetries along radial and azimuthal directions (Holland et al. [1998](#); Greaves et al. [1998](#)). At shorter, 1–10 μm wavelengths, the dust distribution around Beta Pictoris was shown to be asymmetric in the radial and vertical directions (Lagage and Pantin [1994](#); Kalas and Jewitt [1995](#); Burrows et al. [1995](#)). With its starlight suppression using coronagraphy and high angular resolution, the Hubble Space Telescope also produced new discoveries of debris disks seen in optical to near-infrared scattered light (Schneider et al. [1999](#)). These results were the basis of theoretical

investigations on how planetary companions could govern the structure of circumstellar dust disks (Roques et al. 1994; Ozernoy et al. 2000). Planetary companions were subsequently directly imaged around the debris disk stars Fomalhaut (Kalas et al. 2008), HR 8799 (Marois et al. 2008), and Beta Pictoris (Lagrange et al. 2009). Thus, the detection and characterization of debris disks are tightly connected to the search for exoplanets.

Overview

The study of debris disks aims to characterize the evolution of planetary systems with respect to the population of minor bodies such as comets and asteroids. Debris disks are distinct from primordial circumstellar disks that are located in star-forming regions such as Orion and Taurus/Aurigae. Debris disks are typically older than 10 Myrs and contain significantly less gas and total mass than primordial disks, and planets within a debris disk have finished forming and are in the process of evolving their atmospheres and surfaces. An external observer would also find that our planetary system has a debris disk in the inner solar system (zodiacal light and asteroid belt) and the outer solar system (see ► [Kuiper Belt](#)), corresponding to the locations where the collisional erosion of comets and asteroids replenishes interplanetary dust particles. Since the cumulative surface area of a planetary system is dominated by dust grains (the total mass is dominated by the largest planets), debris disks are the easiest component of a planetary system to directly detect in reflected light or thermal emission. One of the most important qualities of debris disks is that the gravitational influence of planets disturbs the overall structure of a disk. Therefore, debris disks can flag a system for the presence of planets long before the planets can be detected by other methods (Kuchner and Holman 2003).

Basic Methodology

The successful detection of solid objects next to bright stars is not only a question of angular

resolution but also one of contrast. Debris disks were first detected using thermal infrared techniques ($>3 \mu\text{m}$) because the contrast between the bright star and the faint disk is less in the infrared than at optical wavelengths: whereas a star has an energy spectrum that peaks in the optical and declines in the infrared, the energy spectrum of dust grains peaks at infrared wavelengths, due to the much cooler temperature of the dust. Therefore, infrared and submillimeter detectors are capable of separating the radiation emitted from the star from the radiation emitted by dust grains. The disadvantage is that since resolving power scales as the ratio of wavelength to telescope diameter, the longer the wavelength used, the larger the telescope required. This limitation has been overcome with ALMA which can achieve angular resolution at (sub)mm wavelengths comparable to optical and near-infrared telescopes.

At optical and near-infrared wavelengths, debris disks are detected by grains reflecting (scattering) light from the star, rather than by the dust's own thermal emission. Scattered light data also probe the polarization of scattered light which is a key diagnostic of grain properties such as size and porosity. Optical and near-infrared observations suppress bright starlight using coronagraphy and post-processing techniques that separate the residual point spread function of the star from the fainter astrophysical scene. Thermal observations at mid-infrared to millimeter wavelengths offer relatively good estimates of grain temperature, radial location, and total mass, with some inferences for grain size and composition. In contrast, scattered light observations give the radial, azimuthal, and vertical distribution of grains, as well as estimates of grain size, composition, and porosity by analyzing wavelength dependence and polarization.

A fundamental parameter in debris disk science is the ratio of the infrared luminosity of the dust relative to the total bolometric luminosity of the host star ($L_{\text{dust}}/L_{\text{star}}$). Since debris disks are optically thin, the fractional infrared luminosity is a measure of total dust mass. For scattered light images, the measured surface brightness as a function of distance from the star is proportional to the radial decrease of grain volume number density.

Other parameters often derived in the literature are the inner and outer radii of a debris disk, the grain temperature, the grain size distribution, and the vertical scale height.

Spectroscopy has been used to infer not only the composition of constituent grains but also their dynamics. Overall, spectra of debris disks reveal grain properties very similar to solar system comets, such as crystalline silicate and olivine emission features, as well as atomic gas such as neutral Fe and Ca^+ .

Another key component of debris disk science is estimating the ages of the host stars in order to understand the evolution of planetary systems. Stellar age indicators such as X-ray emission and the presence of lithium (destroyed as stars age) are particularly robust for the low-mass (late-type) stars. However, since main sequence stars have long departed from the cluster environment in which they formed, the method for physically associating the low-mass stars with the high-mass stars is by analyzing galactic space motions, thereby identifying groups of stars with common velocities, particularly in the azimuthal direction around the galaxy. Data from the ► [Hipparcos](#) mission were central in the identification of stellar “moving groups” or “kinematic groups.”

Key Research Findings

Approximately $15 \pm 5\%$ of stars have detectable debris disks, as suggested by the infrared surveys conducted with the IRAS, the ISO, the ► [Spitzer Space Telescope](#), and the Herschel Space Observatory (Matthews et al. 2014). The stellar age estimates indicate that stars with debris disks happen to be the younger (10–100 Myr) stars in the ► [solar neighborhood](#). For example, the Beta Pictoris moving group has several dozen candidate members (Song et al. 2003), and among these, there are at least four debris disks that have been imaged in scattered light, though with significantly different properties such as mass, suggesting that disk evolution is a stochastic process (Kalas et al. 2007). Several mechanisms have

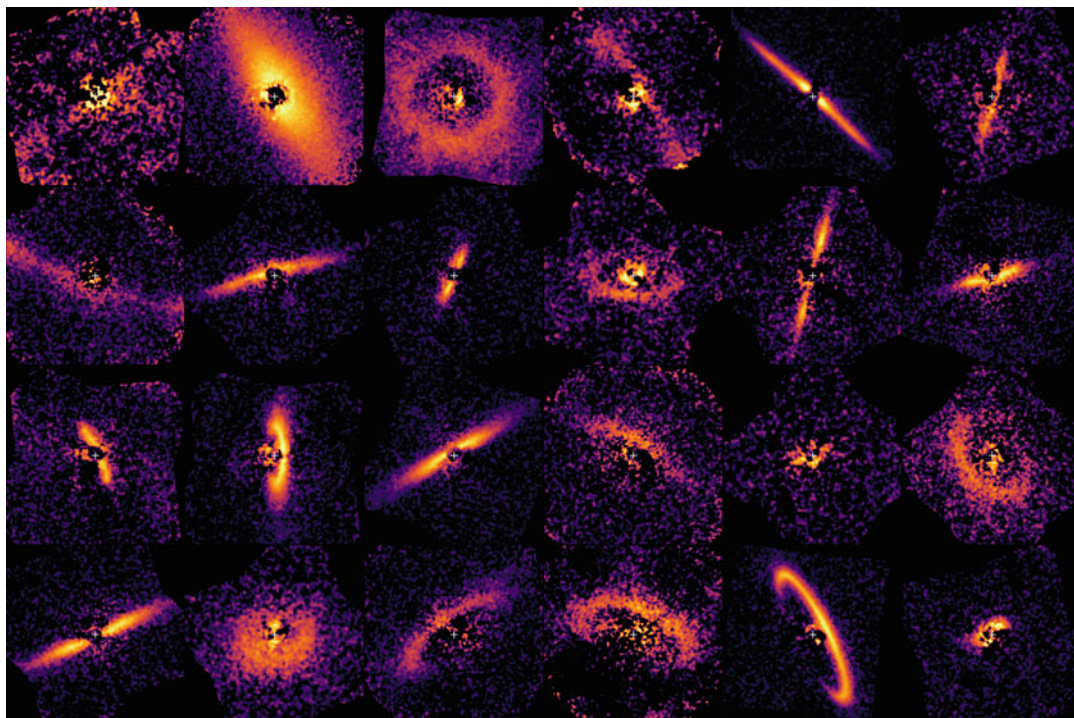
been proposed to explain the large variations in dust mass, such as stochastic collisions between large ► [planetesimals](#) and dynamical stirring as planets grow and dynamically evolve (Wyatt 2008). Despite a significant variation in debris disk properties at a given stellar age, the general finding is that debris disk dust mass varies approximately inversely with age or with age squared (Zuckerman 2001; Rieke et al. 2005).

Most debris disks have inner clearings of material approximately 10–100 AU in radius (Zuckerman and Song 2004; Kalas et al. 2006; Esposito et al. 2020; Fig. 1). In a few cases, this corresponds to the “ice line,” but in many other cases, the most likely explanation is dynamical clearing by a planetary system. For example, the debris disk surrounding Fomalhaut is a torus of dust beginning 133 AU from the star with a Jupiter-mass planet candidate imaged just 18 AU interior to the belt (Kalas et al. 2008).

In many cases, the far-infrared spectral energy distributions cannot be fit by single components of dust, but often require at least one warm inner component and one cold outer component with temperatures ranging from several hundred Kelvin to approximately 40 K, respectively (Hillenbrand et al. 2008). For example, the Epsilon Eridani debris disk can be separated into five components (Backman et al. 2009), and the HR 8799 disk has three components (a warm grain region interior to the three planets and two colder components exterior to the planets; Su et al. 2009). These results give further evidence that debris disk radial structure is governed by the dynamics of planets, with direct analogies to our own solar system.

Future Research Directions

New advances in instrumentation have substantially increased the number of well-resolved debris disks from optical to (sub)millimeter wavelengths, and some studies have probed the time domain as well. However, current methods to model the scattering and emission of dust grains



Debris Disk, Fig. 1 Twenty-four debris disks detected in polarized scattered light using the Gemini Planet Imager in *H*-band with a coronagraph (Esposito et al. 2020). North is up, east is left, and all panels have the same angular size (2.5 arcsec on a side). Nearly all have inner clearings 10–100 au in radius consistent with planet formation;

much like the inner edge of our Kuiper Belt is determined by the orbit of Neptune. With ages between 10 and 100 Myr, these systems are gas-poor, planet formation has finished, and the systems are dynamically evolving toward their final, stable, planetary architectures

struggle to simultaneously fit multiwavelength data for a given debris disk. Future work is needed to improve grain models, such as by simulating porous and fluffy aggregates that blend the physics of both small and large grains. On the observational front, the James Webb Space Telescope will provide unique images and spectra of debris disks in the mid-infrared that could discriminate between icy and refractory grain compositions. Large ground-based telescopes will have their adaptive optics systems and instrumentation upgraded to improve image fidelity closer to each star, ultimately increasing the number of cases where a planet is directly imaged interior to a debris disk. Multi-epoch imaging of already known and new exoplanets will more tightly constrain their orbit elements, offering a clearer

picture of how planets and disks coevolve. Reimaging of debris disks over time will test for time-variable phenomena, which have been recently discovered for the nearby AU Mic debris disk (Boccaletti et al. 2018) and remain difficult to explain.

Cross-References

- [Circumstellar Disk](#)
- [Coronagraphy](#)
- [Dust Grain](#)
- [Fomalhaut b](#)
- [Infrared Excess](#)
- [Interplanetary Dust Particle](#)
- [Late Heavy Bombardment](#)

- ▶ Planetesimals
- ▶ Protoplanetary Disk
- ▶ Protoplanetary Disk of Second Generation
- ▶ Snow Line
- ▶ Zodiacal Light

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Decarboxylation

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

Decarboxylation is a chemical reaction in which a carboxyl group (–COOH) is lost from a parent molecule as CO₂. Many carboxylic acids will

decarboxylate under even mild heating, and there are numerous decarboxylation reactions which are important in biochemistry, for example, in the Krebs cycle, and in the biosynthesis of many neurotransmitters such as dopamine and serotonin. It is also one of the important degradation mechanisms of amino acids and fatty acids in the environment.

Cross-References

- [Amino Acid](#)
- [Carboxylic Acid](#)
- [Krebs Cycle](#)

Decay Constant

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

The decay constant (symbol, λ and units, s^{-1} or a^{-1}) of a radioactive nuclide is its probability of decay per unit time. The number of parent nuclides P therefore decreases with time t as $dP/P dt = -\lambda$. The energies involved in the binding of protons and neutrons by the nuclear forces are ca. 1,000,000 times stronger than those of the electronic and molecular forces. Decay probabilities and λ s are insensitive not only to temperature and pressure but also to the strength of the bonds in which the radioactive element is held. The decay constant relates to the ► [half-life](#) of the nuclide $T_{1/2}$ through $T_{1/2} = \ln 2/\lambda$.

Cross-References

- [Earth, Age of](#)
- [Geochronology](#)
- [Half-Life](#)
- [Radioactivity](#)

Deccan Trapps

Nicholas Arndt¹ and Daniele L. Pinti²

¹ISTerre, University Grenoble Alpes, Grenoble, France

²Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

The Deccan Trapps (or Traps) are a volcanic plateau, or a large igneous province located in west-central India. It is generally believed that the traps formed through melting of a large mantle plume beneath the Indian continent. Deccan Trapps are a thick (500–3000 m) and large (1.5×10^6 km³) sequence of basaltic lava flows that erupted sub-aerially and rapidly onto the Indian continent about 67–64 Ma ago. The release of large amounts of sulfur gases during repeated cycles of volcanic eruptions that stand for at least 400,000 years has been at the center of a long-standing casual-link debate on the end of dinosaurs (Cretaceous-Tertiary or KT mass extinction). It has been suggested that Deccan Trapps volcanic activity triggered the mass extinction, independently or in concomitance with the impact of an asteroid in the Yucatan peninsula (the Chicxulub crater) while others suggest that only the Chicxulub impact triggered the mass extinction (e.g., Schulte et al. 2010; Chiarenza et al. 2020). Richard et al. (2015) suggested even that the Chicxulub impact triggered global ocean floor volcanism contributing to the Deccan Trapps initiation. This casual-link debate is mainly caused by an incomplete geochronological framework of the Deccan Trapps volcanic activity which initiated somewhere around the Chicxulub impact.

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Declination

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The declination is one of the two coordinates of the equatorial system of reference, used to locate a celestial object on the sky. It is the one coordinate measuring the angular distance north or south of the celestial equator, along a meridian passing through that object. Declination is measured positively (+) north or negatively (–) south of the celestial equator from 0° to 90°.

Cross-References

- [Coordinate Systems](#)
- [Right Ascension](#)

Deep Biosphere

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto
Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Biosphere refers to the sum of all Earth ecosystems, in contrast to deep biosphere which refers to the dark habitats physically located below the surface of continents and the bottom of the ocean. These hidden environments exist in permanent darkness with no possibility of light cycle for

metabolic activity. Those habitats are poorly understood due to the technological difficulties to reach them without contamination and to characterize them.

Cross-References

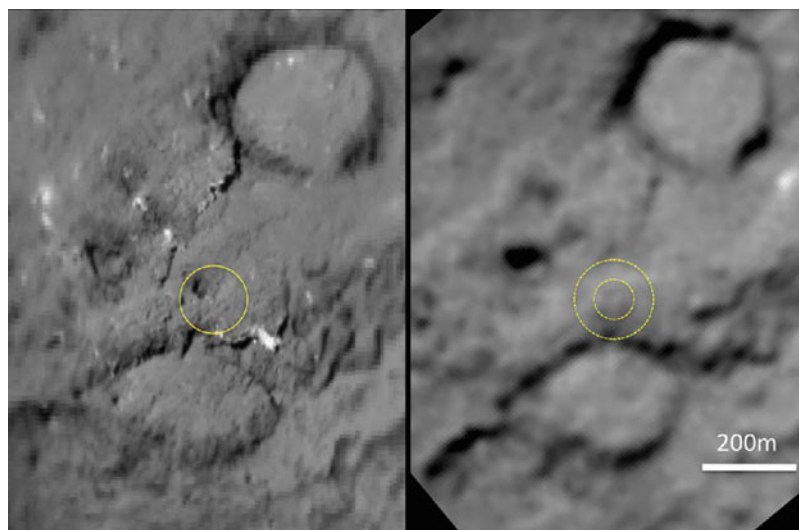
- [Dark Biosphere](#)

Deep Impact

Hervé Cottin
Laboratoire Interuniversitaire des Systèmes
Atmosphériques, Université Paris Est-Créteil,
Créteil, France

Definition

Deep Impact was a (NASA) mission launched on January 12, 2005, made of a space probe with limited instrumentation (optical imaging and infrared spectral mapping) and carrying a 370 kg impactor made mainly of copper. The impactor collided with the nucleus of comet 9P/Tempel on July 4, 2005, with a relative speed around 10 km/s. The observation of the resulting excavation should have allowed to measure inner properties of cometary nuclei. But, the unexpected large amount of dust released by the impact prevented any direct observation of the artificial crater. However, Deep Impact observations returned unprecedented images of a cometary nucleus and information about the nucleus structure and composition. Then, the Deep Impact spacecraft was redirected toward comet 103P/Hartley through an extended mission. The spacecraft keeps its original name of Deep Impact, while the next leg of the mission after the completion of the main objective is called EPOXI. The flyby occurred on November 4, 2010, and returned high-quality pictures of this comet. After a communication failure on August 8, 2013, and several unsuccessful attempts to restore the contact, the spacecraft was declared lost by NASA on September 19, 2013.



D

Deep Impact, Fig. 1 Tempel 1 impact site. This pair of images shows the area affected by the impactor released by NASA's Deep Impact spacecraft. On the *left*, the image from Deep Impact spacecraft shows a dark mound about 50 m in size (inside a *yellow circle* that shows the area hit by the impactor). The image on the *right*, obtained by

NASA's Stardust spacecraft, shows the impactor erased that dark mound and flattened the area. The *outer circle* annotated on the right-hand image shows the outer rim of the crater, and the *inner circle* shows the crater floor. The crater is estimated to be 150 m in diameter. (Credit: NASA/JPL-Caltech/University of Maryland/Cornel)

Follow-Up

In an attempt to see the crater created formerly, NASA rerouted the Stardust-NExT spacecraft which flew over the nucleus of comet 9P/Tempel on February 15, 2011 (Fig. 1).

Cross-References

- [Comet](#)
- [EPOXI Mission](#)
- [Star Dust](#)

Deep Subsurface Microbiology

Tullis C. Onstott

Department of Geosciences, Princeton University,
Princeton, NJ, USA

Keywords

Biogeochemistry · Ecohydrology · Enzymes · Genomics · Isotope geochemistry · Microbial metabolism

Synonyms

[Subsurface biota](#)

Definition

The science of deep subsurface microbiology involves the study of non-phototrophic microorganisms, ecosystems, and biogeochemical fluxes and cycles that occur beneath the soil zones, active layers, and lake beds of continents and the seafloor. Deep subsurface ecosystems are distinct from those that inhabit most surface soils or deep ocean environments in that they are primarily hypoxic to anoxic; the estimated microbial cell turnover times are on the order of decades to centuries (Phelps et al. 1994) and the principal energy sources originate from the geosphere (Parkes et al. 2007). Like surface ecosystems, the subsurface ► [bio-sphere](#) appears to control groundwater chemistry, mineral diagenesis, and organic degradation.

Overview

In June 1986, at the Savannah River Plant (SRP), South Carolina, the modern era of subsurface

microbiology was launched with a few hundred thousand dollars from a US Dept. of Energy (DOE), environmental monitoring program, savings from altering well completion designs. From this auspicious beginning, three wells were cored attaining depths of 200 m using chemical and physical tracers designed by Phelps to constrain microbial drilling contamination. Abundant and diverse microbial communities were observed in the subsurface aquifers, as discussed in a special issue of *Geomicrobiology Journal* in 1989. During the decade that followed, a wide range of environments and rock types were cored during seven field campaigns with a variety of fluids and tracers mostly to depths of several 100 m. By piggybacking on petroleum exploration drilling programs, microbial samples representative of their native subsurface environment were recovered from depths as great as 2.7 km for subsurface microbial and biogeochemical investigations. The teams of scientists that organized and executed these campaigns and examined the cores comprised microbiologists, geochemists, geologists, and hydrologists – some well seasoned and others young and ambitious, many from DOE laboratories and equally many from academia, all supported by DOE's Subsurface Science Program (SSP) and led, inspired, and motivated by the program's manager, Frank Wobber. Other groups formed quickly to explore the subsurface for life. Chapelle and Lovley at USGS began examining Atlantic Coastal Plain aquifers at the same time that DOE was working near SRP. In 1986 Whelan's group from WHOI and, later in 1992, Parkes' group from the Univ. of Bristol initiated studies of sub-seafloor sediments. In 1992, Pedersen from Gothenburg Univ. published his first results from a deep, fractured granite aquifer in Sweden. Other groups built upon earlier Russian studies and began examining the fluids associated with petroleum reservoirs. As summarized in Whitman et al. (1998), a substantial fraction of the Earth's living carbon biomass resides beneath the seafloor and soil zones, although just how massive remains uncertain.

Although the Whitman et al. (1998) review was thorough at its time, the uncertainties in

estimated global subsurface biomass remain large, and many subsurface environments had not been sampled and remain to this day unsampled. Studies of the marine deep sub-seafloor biosphere began later than those for terrestrial settings, but they now take the lead despite sampling challenges. Both deep hot, rift basin-related subsurface marine chemoautotrophic ecosystems and the not so hot, sub-seafloor sediments that represent vast, cold heterotrophic ecosystems functioning on old, buried photosynthate have been sampled. With respect to the latter, Lipp et al. (2008) reported a correlation between the biomass and the concentration of organic photosynthate in marine sediments that constrains the global marine subsurface biomass to lower values (Kallmeyer et al. 2012).

The continental deep subsurface biosphere contains what could be termed "warm," $<100\text{ }^{\circ}\text{C}$ ecosystems that are increasingly chemoautotrophic with depth. The rock-water interactions that fuel these continental subsurface ecosystems are not dependent upon localized magmatic heat input, for example, spreading centers or hot spots, but instead are influenced by regional, topographically driven meteoric fluid flow. In the case of the elevated plateaus and mountain ranges groundwater can penetrate to kilometer depths (Colwell et al. 1997). In the lower elevation granitic aquifers of the Fennoscandian Precambrian shield (Pedersen 1997) and Atlantic Coastal Plain aquifers, the regional flow is slower and shallower (Phelps et al. 1994).

Assuming a maximum temperature for life of $120\text{ }^{\circ}\text{C}$, mean annual surface temperatures that can range from -10 to $30\text{ }^{\circ}\text{C}$, and geothermal gradients ranging from 7 to $80\text{ }^{\circ}\text{C}/\text{km}$, the estimated depth to the base of the deep subsurface biosphere ranges from 1 to 20 km (see Zhang et al. 2005).

Metagenomes have been recovered from million-year-old ice (Bidle et al. 2007), tens of millions of years old, kilometers deep, saline fracture water (Chivian et al. 2008), and subseafloor sediment environments where fluid flux is negligible (Biddle et al. 2008; Chivian et al. 2008).

These studies revealed that in order to repair their DNA from radiation damage, subsurface organisms must metabolize extremely slowly without encountering entropic death. One long-term source of renewable chemical energy is radiolysis of water and serpentinization of mafic and ultramafic rock, which provide sustained sources of oxidants and reductants to these terrestrial and marine subsurface chemoautotrophic microbial ecosystems when organic carbon is scarce (Lin et al. 2005; Sherwood Lollar et al. 2014). Finally, subsurface microorganisms, and even the DNA fragments of deceased subsurface microorganisms, may represent a pool of ancient DNA or paleome (Inagaki et al. 2005), and the differences between their gene sequences and those of related surface organisms may be a direct evolutionary record (Lau et al. 2014).

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Biogeochemical Cycles](#)
- [Biosphere](#)
- [Chemolithotroph](#)
- [Energy Conservation](#)
- [Extreme Environment](#)
- [Lithotroph](#)
- [Prokaryote](#)
- [Thermophile](#)

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Deep Subsurface Microbiome

► [Dark Biosphere](#)

Deep-Sea Microbiology

Daniel Prieur

Université de Bretagne Occidentale (University of Western Brittany), Brest, France

Institut Universitaire Européen de la Mer (IUEM), Technopôle Brest–Iroise, Plouzané, France

Keywords

Archaea · Bacteria · Diversity · Extremophile · Hydrostatic pressure · Metabolic activity · Piezophiles

Definition

The deep-sea corresponds to depths of 1000 m and more. It is a dark (solar light does not penetrate beyond 100 or 200 m) and cold environment (about 2 °C), exposed to elevated hydrostatic pressure. There is no photosynthesis and the sparse deep-sea organisms that inhabit this environment depend on primary production occurring in the euphotic zone. However, in certain areas, such as cold seep areas or hydrothermal vents, fluids enriched with hydrogen sulfide or methane are discharged in deep waters. These chemicals serve as energy sources for symbiotic microorganisms that provide invertebrates (clams, tube

worms, shrimps) with organic matter produced by chemosynthesis.

History

Deep-sea microbiology began with the report of a French microbiologist Certes (1884) that microorganisms existed in waters and sediments collected at 5 km depth. A second start occurred with the pioneer work of US microbiologists C. Zobell and R. Morita in the 1950s. The availability of pressure-retaining sampling devices during the 1960s and 1970s of manned and robotic underwater vehicles renewed deep-sea microbiology, and several dedicated microbiology teams carried out extensive research particularly in the USA, Europe (Germany, France, the UK), and Japan.

Overview

For the early scientists involved in deep-sea microbiology, the first questions concerned the abundance and metabolic activities of bacteria under in situ conditions (cold temperature, oligotrophy, and elevated pressures). The first experiments concluded that abundant (10^6 cells ml⁻¹ of deep water, 10^9 cells g⁻¹ of deep sediment) deep-sea bacteria were not very active under in situ conditions, essentially because of elevated pressures. This view totally changed with the discovery of piezophilic bacteria living in the digestive tracts of deep-sea invertebrates. In the last decades, many piezophilic deep-sea bacteria have been isolated and described: all are heterotrophic, aerobes, or facultative anaerobes and belong to the phylum of ► [Proteobacteria](#). More recently, ► [Archaea](#) also have been reported from molecular studies, and although their abundance is about 10^4 cells ml⁻¹ in the deep layers, almost nothing is known about their physiology and metabolism. The discovery of hydrothermal vents in 1977 has considerably changed our views about deep-sea biology. At vents and cold seeps, animal communities are dense due to their

symbiotic associations with chemolithoautotrophic bacteria that obtain their energy from the oxidation of reduced compounds (hydrogen sulfide, methane) present in emitted fluids and provide invertebrates with this chemosynthetically produced organic matter. Also, various hyperthermophilic Bacteria and Archaea thrive in the black smokers that flow out of deep-sea vents. Among them are the most impressive extremophiles living on Earth, such as the anaerobic archaea *Pyrolobus fumarii*, which grows optimally at 106 °C (maximum 113 °C), or *Pyrococcus yayanosii*, which grows optimally at 95 °C with an optimal pressure of 52 MPa (maximum 120 MPa) and cannot grow under atmospheric pressure. Both organisms resist normally sterilizing conditions in an autoclave: they have survived for more than 24 h at 120 °C and up to 160 MPa for *P. yayanosii*.

During the last 20 years, deep-sea microbiologists have investigated an unexpected ecosystem: the deep biosphere, a term used to describe the enormous bacterial mass in the upper kilometers of the Earth's crust. J. Parkes first reported the existence of living bacterial cells in deep marine sediments, several hundred meters below the seafloor. They were recently reported at a depth of 1600 m in rocks deposited about 110 million years ago. These ecosystems represent the largest habitat for ► [prokaryotes](#) on Earth. Some organisms of the deep biosphere might be totally independent from solar energy (using abiotically produced carbon and energy sources). A parallel might exist between the emergence of the first life and the deepest parts of the biosphere.

Cross-References

- [Archaea](#)
- [Barophile](#)
- [Black Smoker](#)
- [Deep Subsurface Microbiology](#)
- [Extremophiles](#)
- [Hot Vent Microbiology](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Hyperthermophile](#)

- [Piezophile](#)
- [Psychrophile](#)

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Degassing

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Synonyms

[Outgassing](#)

Definition

The term “degassing” (or outgassing) refers to the process of releasing atmospheric gas present in the mantle or in magmas when its amount exceeds the solubility limit. The distribution of volatile elements, such as carbon dioxide (CO₂) or argon (Ar), between a solid (or a liquid) and a gas, reaches equilibrium when further transfer from one phase to another entails an overall increase of the system energy. Henry's law states that, at equilibrium, the amount of volatile element dissolved is

proportional to its partial pressure in the gas phase at a specific temperature. Outgassing of planetary mantles by volcanic activity is viewed as a major pathway to the formation of secondary atmospheres on telluric planets.

Cross-References

- ▶ [Earth, Formation, and Early Evolution](#)
- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Mantle Volatiles](#)
- ▶ [Noble Gases](#)

Degenerate Stars

- ▶ [White Dwarf](#)

Dehydration

- ▶ [Desiccation](#)

Deimos

Harald Hoffmann
DLR, Institute of Planetary Research, Berlin,
Germany

Definition

Deimos is the outer of the two Martian satellites that were discovered by Asaph Hall in 1877. It is in nearly circular synchronous orbits around ▶ [Mars](#) with an average distance of 23,458 km to the center of the ▶ [planet](#) and an orbital period of 1.26 days (IAU 2006). Deimos has an overall smooth surface and measures $15.0 \times 12.2 \times 10.4$ km; its bulk density is about 1.5 g/cm^3 . The heavily cratered surface indicates an old formation age. Two hypotheses are actually discussed to explain the origin of Deimos: capture of a D-type ▶ [asteroid](#) or reaccretion of Martian ejecta.

Cross-References

- ▶ [Asteroid](#)
- ▶ [Mars](#)
- ▶ [Phobos](#)
- ▶ [Planet](#)
- ▶ [Satellite or Moon](#)

Delta Deposit

- ▶ [Mars, Delta](#)

Delta Fan

- ▶ [Mars, Delta](#)

Delta, Isotopic

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Definition

The delta notation (symbol: δ) expresses the variation of the isotopic ratio “R” of an element (e.g., $^{18}\text{O}/^{16}\text{O}$), relative to the same ratio in a standard “R_{std}” and normalized to this standard ratio, or $(R - R_{\text{std}})/R_{\text{std}}$. The delta notation is usually expressed in per mil (parts per thousand, ‰) and it is obtained by multiplying the previous expression by 10^3 . Even if the delta notation represents the variation of an isotopic ratio of one element, the value after the “ δ ” symbol is usually presented as the isotope at the numerator of the ratio. As an example, the $\delta^{18}\text{O}$ (‰) = $[(^{18}\text{O}/^{16}\text{O})_{\text{sample}} / (^{18}\text{O}/^{16}\text{O})_{\text{std}}] / (^{18}\text{O}/^{16}\text{O})_{\text{std}} \times 1000$. This notation was proposed to express, in a convenient and readable way, the variability of isotopic ratios in natural systems in which the range is in the third to fifth decimal place (McKinney et al. 1950). It also removes the need to report absolute isotope

abundances and replaces them with relative deviations with respect to standards. The delta notation is usually applied to the stable isotopic ratios of elements, including sometimes the noble gases.

Cross-References

- [Boron Isotopes](#)
- [Chromium Isotopes](#)
- [Copper Isotopes](#)
- [Hydrogen Isotopes](#)
- [Iron Isotopes](#)
- [Nitrogen Isotopes](#)
- [Oxygen Isotopes](#)
- [Silicon Isotopes](#)
- [Stable Isotopes](#)
- [Sulfur Isotopes](#)
- [Zinc Isotopes](#)

Reference

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Denaturation

Henderson James CleavesII
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In biochemistry, denaturation is the process by which ► [proteins](#) or nucleic acids lose their native quaternary, tertiary, and/or secondary structure. Denaturation can be caused by conditions such as strong acid or base, concentrated salt, organic

solvents, or heat. Protein denaturation generally results in the loss of enzymatic activity. Denatured proteins may become insoluble or aggregate.

► [Nucleic acid](#) denaturation results in the separation of hydrogen-bonded complementary regions when the hydrogen bonds between the strands are broken. These bonds may be restored by annealing. Denaturation typically does not result in the breaking of the covalent bonds which hold a ► [polymer](#) together. Denaturation is often reversible in proteins and nucleic acids.

Cross-References

- [Nucleic Acids](#)
- [Polymer](#)
- [Protein](#)

Denitrification

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Nitrate reduction](#)

Definition

Denitrification is a microbial ► [anaerobic respiration](#) in which oxidized nitrogen compounds (e.g., NO_3^-) are used as ► [electron acceptors](#), which may ultimately produce molecular nitrogen (N_2) through a series of intermediate gaseous nitrogen oxide products. Inorganic nitrogen compounds are some of the most common electron acceptors used in anaerobic respiration. One of the most common electron acceptors for anaerobic respiration is nitrate, which can be reduced to NO_2^- , N_2O , NO , and N_2 . The process is the main means by which N_2 is formed biologically. Denitrification completes the nitrogen cycle, by

returning N_2 to the atmosphere. The process is performed primarily by heterotrophic bacteria (such as *Pseudomonads*), although autotrophic denitrifiers have also been identified (e.g., *Thiobacillus denitrificans*). Generally, several species of bacteria are involved in the complete ► [reduction](#) of nitrate to molecular nitrogen, and more than one enzymatic pathway has been identified in the reduction process. Denitrification is a widespread transduction system throughout the phylogenetic tree.

Cross-References

- [Anaerobic Respiration](#)
- [Electron Acceptor](#)
- [Energy Conservation](#)
- [Heterotroph](#)
- [Nitrogen Cycle, Biological](#)
- [Reduction](#)

Dense Cloud

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

In relation to the ► [interstellar medium](#), the term dense cloud is only vaguely defined. It is sometimes used to refer to that portion of ► [molecular clouds](#) with densities exceeding a few 100 atoms per cubic centimeter. Some authors use dense to refer to “dense cores,” those regions in molecular clouds with densities of 10^5 atoms per cc or greater, where stars may form or are forming. The gas phase of a dense interstellar cloud consists almost entirely of molecular hydrogen (H_2), with an admixture of ► [interstellar dust](#). Since molecular hydrogen lacks an electric dipole moment and hence has no allowed rotational transitions, the gas in dense clouds is usually traced by observing the millimeter-wavelength rotational

transitions of CO, the second most abundant gas phase constituent (typically about 1 part in 10,000 by number, relative to H_2).

Cross-References

- [Interstellar Dust](#)
- [Interstellar Medium](#)

Dense Core

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Star formation

Definition

Dense cores are the smallest and densest types of molecular clouds. They are particularly significant as being the birthplaces of both single and binary stars. A large fraction of dense cores, in fact, already contain young stars. Many of the rest exhibit a slow, inward contraction, which could be the prelude to the full collapse that results in star formation. Both types of dense cores have temperatures near 10 K. They are slowly rotating and appear elliptical when seen in projection onto the sky. In three-dimensional space, they are prolate spheroids or perhaps more complex, triaxial configurations.

Overview

The Milky Way, like other spiral galaxies, contains both stars and more rarefied, interstellar gas. About half the mass of this material is in molecular clouds, so called because they are chiefly made of hydrogen molecules. Molecular clouds have a wide range of sizes and masses. They are not

uniform, but contain nested substructures. The smallest coherent structures, about 0.1 pc in size and with masses a few times the solar value, are known as dense cores. They are of special importance, since they produce new stars. It is now believed that most binary stars are also created within dense cores.

Throughout most of the volume of molecular clouds, the gas has supersonic internal motion. The dynamical pressure associated with this motion helps to support the cloud for long periods of time against the force of self-gravity. The motion within dense cores, however, is subsonic. Thus, these entities are in balance between internal thermal pressure and self-gravity. They also contain a magnetic field, which aids in the support. The temperature of dense cores, like that of all molecular clouds, is very low, roughly 10 K. It is the combination of low temperature and relatively high density that renders dense cores susceptible to collapse and star formation.

Almost half of observed dense cores already enclose young stars. Since the cores contain solid dust grains along with gas, the embedded stars are highly obscured and can only be seen at infrared and longer wavelengths. The majority of dense cores have no internal stars. The bulk properties of these barren cores are similar to those containing stars. However, a high fraction of starless cores are undergoing inward contraction, as seen by Doppler-shifted emission lines from various trace molecules. This motion, which is subsonic, could be the prelude to the eventual collapse that forms a star or binary near the dense core's center.

Dense cores appear to have elliptical contours, when they are mapped in molecular lines. Each ellipse is a projection onto the sky of the objects' true, three-dimensional shape. This true shape has been difficult to ascertain, with some researchers favoring prolate spheroids (stubby cigars) and others more complicated, triaxial configurations. All agree, however, that the dense cores' shapes do not stem from their rotation. The latter has been observed, and the rate is too small to cause significant distortion of the cloud.

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Gravitational Collapse, Stellar](#)
- [Molecular Cloud](#)
- [Protostars](#)

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Deoxyribonucleic Acid

- [DNA](#)

Deoxyribose

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Deoxyribose is an aldopentose ($C_5H_{10}O_4$) found in the backbone of DNA. It exists in two stereoisomeric forms, D and L. The isomer used in DNA is the D-form. It is derived biologically from D-ribose by reduction of the C_2 hydroxyl group via a radical mechanism. It is typically found in deoxynucleotides in the pentofuranose form. In DNA, it is linked via the 3' and 5' hydroxyl groups

to connecting phosphate groups. When attached to a nitrogenous base, it becomes part of a deoxynucleoside.

Cross-References

- ▶ [Aldose](#)
- ▶ [Carbohydrate](#)
- ▶ [Nucleoside](#)
- ▶ [Nucleotide](#)

Depyrogenation

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

A pyrogen is a substance which causes, when in the blood flow of a homeothermic animal, a rise in the body or central temperature. The pyrogens can be synthetic molecules but often are toxins produced by pathogenic bacteria. Depyrogenation is the process of removing these pyrogens from a solution or compound. Depyrogenation has to be performed on containers and reactants to be used for some life detection tests.

Derivatization

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

Derivatization is the process by which an organic compound is reacted with a reagent, or reagents, to yield products suitable for analyses by various techniques. In many cases, the products are either a volatile adduct suitable for analysis by

▶ [gas chromatography](#) (GC) or a highly fluorescent product that can be separated by liquid
▶ [chromatography](#) and detected at very low levels (parts per billion) by its characteristic fluorescence at an optimal excitation wavelength. In the case of carboxylic acids, the reagents are usually alcohols in the presence of catalysts that convert the original molecules into esters for GC analyses. For the GC determination of amino acids, alcohols in the presence of catalysts are used to first convert the carboxyl groups to esters and reagents such as trifluoroacetic anhydride then used to add components to the primary amino groups to prevent their ionization. For the fluorescent analyses of amino acids, several reagents, such as fluorescamine or *ortho*-phthalaldehyde (OPA), are added to the primary amino group producing highly fluorescent products that can be analyzed using high-performance liquid chromatography.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Chromatography](#)
- ▶ [Fluorescence](#)
- ▶ [Gas Chromatography](#)
- ▶ [Liquid Chromatography-Mass Spectrometry](#)

Desiccation

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology,
Radiation Biology, Köln, Germany

Keywords

Anhydrobiosis · Cryptobiosis · Desiccation ·
Dehydration · Habitability of Mars · Survival

Synonyms

[Dehydration](#); [Desiccation effects](#)

Definition

Desiccation describes a process which causes loss of liquid water from a solid surface or from a porous medium (soil, food, ecosystems, individual organisms, etc.). This process leads to drying up of the matter. In biology, several organisms have developed strategies to tolerate desiccation imposed on them.

Overview

Water is one of the essentials for all forms of life on the Earth. Dehydration causes severe damage to various cell components: Lipid membranes may change from planar bilayers to cylindrical bilayers, and carbohydrates, proteins, and nucleic acids may undergo amino-carbonyl reactions (Maillard reactions) that result in cross-linking and finally polymerization of the biomolecules (Cox 1991, 1993). These structural changes can give rise to functional changes, such as inhibited or altered enzyme activity, changes in membrane permeability, and alteration of genetic information. The latter change is especially dramatic, because it may lead to cell death or mutagenesis (Munakata et al. 1997).

Certain organisms possess the ability to withstand extreme dryness, such as plants and animals living in arid or periodically arid environments (temporary rivers or ponds), where they may face the challenge of desiccation. In response to such extreme and unfavorable environmental conditions, organisms may resume a cryptobiotic state, which refers to a state of the organism that has no detectable metabolic activity. Anhydrobiosis refers to the state of an organism that survives the loss of (almost) all body water. In highly desiccation-resistant bacterial spores, the water content in the ► [spore](#) core is naturally reduced to 25–45% of their wet weight. As a consequence, proteins are immobile and enzymes inactive during the spore phase (Setlow 1994). This low water content is one of the reasons for the high resistance of bacterial spores to a variety of physical and chemical harmful agents. The bacterium *Deinococcus radiodurans* shows a

high radiation resistance and likewise a high resistance to desiccation. It has been suggested that the high radiation resistance is an evolutionary consequence of an earlier ► [adaptation](#) to prolonged periods of cellular desiccation (Mattimore and Battista 1996).

From the viewpoint of astrobiology, the ► [survival](#) of microorganisms in outer space is of interest, where they are exposed to a complex matrix of parameters, including the extremely dehydrating space vacuum. Space exposure experiments have shown that although a variety of microorganisms are known to be desiccation resistant, not many were able to cope with the mechanical stress of the high vacuum of space. The record of survival in space was reached by *Bacillus subtilis* spores, of which 70–90% survived after 6 years in space vacuum (Horneck et al. 2010).

► [Mars](#) is an important target of astrobiology, where the assessment of its habitability largely depends on the availability of liquid water. Because Mars is cold, but not always, and extremely dry, but perhaps not everywhere, the concept of a special region on Mars was developed as a way to refer to those places where the conditions on Mars might be conducive to microbial growth (Kminek et al. 2010). It was concluded that any region experiencing temperatures $>-25^{\circ}\text{C}$ for a few hours a year and a ► [water activity](#) >0.5 can potentially allow the replication of terrestrial microorganisms. Such special regions on Mars require special ► [planetary protection](#) measures for landers and rovers sent to the surface of Mars (COSPAR Planetary Protection Policy: <http://cosparhq.cnes.fr/Scistr/PPPolicy%2820-July-08%29.pdf>).

In biotechnology, freeze-drying or lyophilization is used as a method of preserving microorganisms or tissue without destroying their physical structure and viability (Morgan and Vesey 2009).

Cross-References

- [Adaptation](#)
- [Aerobiology](#)
- [Extreme Environment](#)
- [Mars](#)

- [Microorganism](#)
- [Planetary Protection](#)
- [Space Vacuum Effects](#)
- [Spore](#)
- [Survival](#)
- [Water Activity](#)

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Desiccation Effects

- [Desiccation](#)

Desorption

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Molecular desorption is the process whereby molecules are returned to the gas phase from the surfaces of interstellar ► [dust grains](#). This term is

especially used to describe desorption of material from the surfaces and bulk of ► [interstellar ices](#) in cold ► [molecular clouds](#). Possible desorption mechanisms include: thermal evaporation, ► [photodesorption](#), heavy particle ► [sputtering](#), cosmic rays ejection, and ejection of the products from highly exoenergetic surface reactions.

Cross-References

- [Dust Grain](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Photodesorption](#)
- [Sputtering](#)

Detergent

- [Amphiphile](#)

Deuterated Ammonium Ion

- [Ammonium \(NH₃D⁺\)](#)

Deuterium

Mark Dörr
University of Southern Denmark, Odense M,
Denmark

Keywords

Hydrogen · Isotope

Synonyms

[Diplogen](#); [Heavy hydrogen](#)

Definition

Deuterium (Symbol: ²H, earlier, D) (from the Greek: δεύτερος (*deúteros*) = “the second”) is

a stable ► [isotope](#) of ► [hydrogen](#) with a relative atomic mass of 2.01410222 mu and a nuclear spin of 1. Mass spectrometry and various scattering experiments reveal two elementary particles in its atomic nucleus, a positively charged proton and an uncharged neutron. These observations gave rise to its name. Other natural isotopes of hydrogen are *Protium* (^1H) (one proton, 1.00782519 mu, nuclear spin $\frac{1}{2}$) and *Tritium* (^3H) (one proton, two neutrons, 3.01610497 mu, nuclear spin $\frac{1}{2}$, radioactive) (Greenwood and Earnshaw 1984). Because of its mass, deuterium is also called “heavy hydrogen.”

History

Deuterium was discovered in 1931 by Harold C. Urey, who received the Nobel Prize in chemistry (1934) for this finding.

Overview

Hydrogen is the most abundant element in the universe (ca. 76% by mass). The average deuterium-to-hydrogen ratio in the universe is estimated to be ca. 20 ppm (Lellouch et al. 2001). Deuterium has a natural abundance in the Earth’s crust of $^2\text{H}/^1\text{H} = 145$ ppm. In the ocean, this ratio is 155.76 ± 0.1 ppm (a ratio of 1 part per approximately 6420 parts) according to the Vienna Standard Mean Ocean Water (VSMOW) (American Society of Limnology and Oceanography Inc 1995). Deuterium abundance in Jupiter’s atmosphere is about 22.5 ppm (ca. 15% of the terrestrial deuterium-to-hydrogen ratio); that of Saturn’s atmosphere is about 17 ppm (Lellouch et al. 2001). The Jupiter ratio presumably reflects the early solar nebular ratio as well as the one present during the early stages of the universe (Lellouch et al. 2001). Most of the deuterium in the universe is believed to have been produced during the nucleosynthesis era of the Big Bang (~ 10 s after t_0), since other

sources, such as rare cluster decays, and occasional absorption of naturally occurring neutrons by hydrogen do not account for the amount presently observed. If the de novo production rate of deuterium is very low, the amount of deuterium in the universe declines steadily since it is consumed in nuclear fusion reactions in stars. These fusion reactions are much faster than the proton-proton reactions that generate deuterium at very high temperatures in stars. Gamma radiation from ordinary nuclear fusion dissociates deuterium into protons and neutrons. Both reaction kinetics and gamma radiation make it improbable that the concentration of deuterium in the interior of the Sun and other stars is higher than the average universal abundance. In the outer solar atmosphere, however, deuterium is present in the same concentration as the one estimated on Jupiter. The natural deuterium abundance seems to be very similar wherever hydrogen is found.

Deuterium occurs in trace amounts naturally as deuterium gas ($^2\text{H}_2 = \text{D}_2$), but most of the deuterium in the universe is bound to a ^1H atom, forming a gas called hydrogen deuteride ($^1\text{H}^2\text{H}$ or HD). Deuterium exchanges rapidly with hydrogen in many compounds, like R-O-D and R-N-D, but slowly in many R-C-D compounds (R denotes a residue). This is the basis of important kinetic and mechanistic measurements in chemical reactions.

Hydrogen isotopic fractionation is very pronounced in cold interstellar clouds, so that the abundance ratio of (e.g.,) DCN/HCN can be much larger than the cosmic D/H ratio. In fact, doubly deuterated and even triply deuterated molecules are observed in the ► [interstellar medium](#), for example, D_2CO and ND_3 .

Cross-References

- [Deuterium/Hydrogen Ratio](#)
- [Hydrogen](#)
- [Hydrogen Isotopes](#)
- [Isotope](#)
- [Urey’s Conception of Origins of Life](#)

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Deuterium/Hydrogen Ratio

Daniele L. Pinti

Geotop, Research Centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Carbonaceous chondrites · Enstatite chondrites · Jupiter family comets · Long-period comets · Terrestrial oceans

Synonyms

[D/H ratio](#)

Definition

The deuterium/hydrogen ratio or D/H is the ratio of the hydrogen isotopes of mass 2 (2H or D, deuterium) and mass 1 (1H or protium). This ratio can be expressed as relative excess abundance of deuterium in per mil (‰) units. The reference is the terrestrial oceanic value of 155.5×10^{-6} (V-SMOW or Vienna-Standard Mean Oceanic Water). The ratio is measured in molecules and minerals, such as clays preserved in meteorites and comets. It can also be measured in mare basalts and highland rocks of the Moon, to determine the carrier of water in the Earth-Moon system but this requires correction for nuclear reactions between the solar wind, the galactic cosmic rays, and the lunar surface. The D/H

ratio shows a heliocentric distribution within the Solar system due to $\text{H}_2\text{--H}_2\text{O}$ vapor exchange, with the lowest value measured in the solar wind and giant planets (21×10^{-6}) and the highest in the HCN compounds in comets (2300×10^{-6}).

Overview

The D/H ratio supports a predominantly chondritic origin of terrestrial water and not a local origin in the Inner Solar system. The debate is still ongoing, but will hopefully be resolved in a near future by analyses of samples from Hayabusa 2 and OSIRIS-ReX return missions.

The water molecule has two elements: H and O, each of them having stable isotopes. The oxygen isotopic ratio, $^{18}\text{O}/^{16}\text{O}$ can be easily fractionated by low-temperature geological processes, such as weathering. The terrestrial water composition from oxygen isotopes cannot thus be compared with that of other cosmic reservoirs, such as the Sun, the asteroids, or the comets. Hydrogen is less fractionated by geological processes than oxygen, mainly because silicate rocks are rather dry and terrestrial isotopic variations are relatively small compared to those observed in different cosmic reservoirs. Deloule et al. (1991) estimated an average δD of $-150 \pm 30\%$ vs. V-SMOW for the primitive Earth, 110‰ depleted compared to the present-day bulk Earth ($\delta\text{D} = -43\%$; Lécuyer et al. 1998). These isotopic variations are relatively small when compared to the total isotopic variation in the Solar system, of 3200‰.

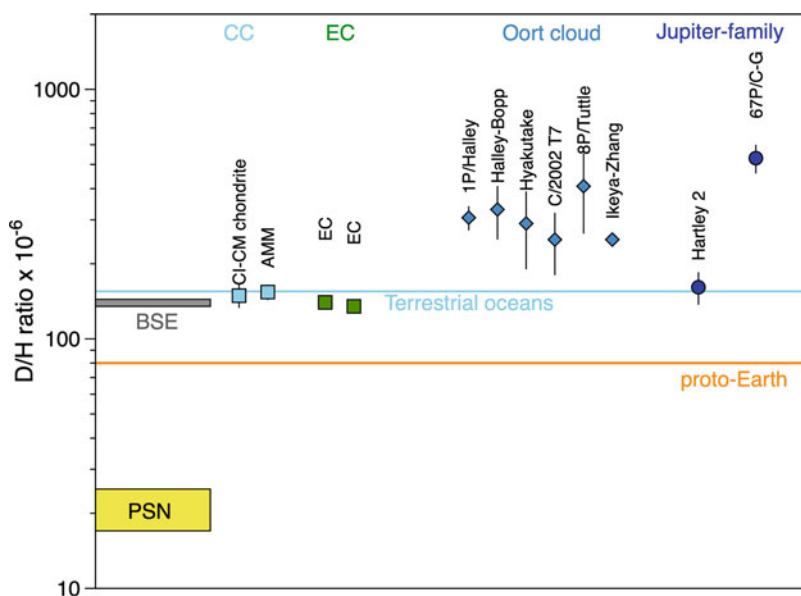
The major hydrogen reservoir in the universe is atomic or molecular hydrogen. The isotopic composition of water in several objects of our Solar system, such as comets, chondrites, or planets, shows a systematic enrichment in deuterium (Robert 2001a) due to the reaction $\text{HD} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{DHO}$. Models of the Proto Solar Nebula (or PSN) evolution indicate that once they had entered the nebula, interstellar ice grains vaporized, and the D/H ratio of the resulting deuterium-rich water vapor was lowered through isotopic exchange with molecular hydrogen. Water vapor successively condensed into

microscopic icy grains, with decreasing D/H ratios, the closer they were to the Sun. This heliocentric isotopic gradient reflects the fact that the closer to the Sun, the higher the temperature, and the faster the isotopic exchange between water and molecular hydrogen (Robert 2001a).

The D/H heliocentric gradient predicts that the D/H ratio for water condensed at Earth's distance (1 AU) from the Sun should be $\sim 80 \times 10^{-6}$ or $\delta D = -490\%$ depleted compared the global ocean (Fig. 1). The water isotopic composition of the bulk Earth is only slightly depleted compared to the global ocean ($149 \pm 3 \times 10^{-6}$ or $\delta D = -43\%$; Lécuyer et al. 1998) and is very different from the PSN value of $21 \pm 5 \times 10^{-6}$. Giant planets (which have primary atmospheres of solar composition) have D/H ratios ranging from 21 ± 8 to $65 \pm 2 \times 10^{-6}$ (δD from -865% to -580%), while long-period comets from the colder outer space of the Solar System, the Oort cloud, have D/H ratios much higher than bulk Earth (average D/H of $296 \pm 25 \times 10^{-6}$ or

$\delta D = +900\%$; Robert 2001a, b). Conversely, carbonaceous chondrites show an average D/H of $149 \pm 6 \times 10^{-6}$ ($\delta D = -43\%$; data compiled by Pinti (2005)), identical to the bulk Earth (Fig. 1). Antarctic micrometeorites (which have a CM-CR carbonaceous chondrite composition; Kurat et al. 1994) show an average value of $154 \pm 16 \times 10^{-6}$ or $\delta D = -11\%$ (Engrand et al. 1999, data compiled by Pinti 2005; Fig. 1).

The comparison of D/H ratios of water in the terrestrial oceans and meteorites supports the hypothesis that carbonaceous chondrites – likely Vesta family water-rich asteroids from the orbit of Mars-Jupiter – are the main carrier of water on Earth, although they make only 4% of the mass of Earth. Recently Piani et al. (2020) have measured the D/H in enstatite chondrites (EC), which are believed to be the main building material of the Earth, but previously assumed to be too dry for furnishing any water to the planet. Their results showed that up to 0.5 wt.% of water is contained in this class of meteorites against old data indicating



Deuterium/Hydrogen Ratio, Fig. 1 Variation of the D/H ratio in the Solar System. PSN stands for Proto Solar Nebula. BSE stands for Bulk Silicate Earth. Proto-Earth is the expected initial D/H ratio in the region where the Earth formed, based on isotopic exchange models between molecular H and water (Robert 2001a). D/H ratios measured in carbonaceous chondrites (CI-CM and AMM) and

in Enstatite Chondrites (EC) are compared with those measured in two distinct classes of comets, those from the external Oort Cloud and those supposed to have formed within the Jupiter orbit at the beginning of the Solar System (Hartogh et al. 2011; Altwegg et al. 2015). Note that one Jupiter-family comet has a D/H ratio very similar to that of terrestrial oceans (debated) (Hartogh et al. 2011)

less than 0.01 wt.%. The δD ratio of EC meteorites range between -103‰ and -127‰ vs. V-SMOW, less than that of the terrestrial oceans but close to that of the Bulk Silicate Earth (BSE; -130‰ to -75‰ ; Fig. 1), suggesting that EC could be an alternative carrier of water to Earth.

Cross-References

- [Carbonaceous Chondrite](#)
- [Chondrite](#)
- [Comet](#)
- [Hydrogen Isotopes](#)
- [Oceans, Origin of](#)
- [System Solar Formation, Chronology of](#)
- [Water, Delivery to Earth](#)

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Devon Island

Richard Léveillé

Natural Resource Sciences, McGill University, St. Anne de Bellevue, Québec, Canada

Definition

Devon Island (federal territory of Nunavut) is a large (66,800 km²), uninhabited island of the Canadian Arctic Archipelago. Situated in a polar desert, Devon Island is considered to be an analog to ► [Mars](#) because it is cold, dry, and largely non-vegetated, with a variety of analogous geological and geomorphologic features. These include the well-exposed and preserved Haughton impact crater and associated impact-induced hydrothermal deposits, as well as intracrater paleolake deposits, alteration minerals, valleys and gullies, and polygonal ground. In addition, the biological characteristics (e.g., endolithic and extremophilic microorganisms, little to no vegetation, low nutrients, and organic biomarkers in impacted rocks) are of particular interest to astrobiologists.

Cross-References

- [Crater, Impact](#)
- [Cryosphere](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [Hydrothermal Environments](#)
- [Impact Melt Rock](#)
- [Impactite](#)
- [Mars Analogue Sites](#)
- [Permafrost](#)
- [Terrestrial Analog](#)

Devon Island's Houghton Impact Structure

Gordon R. Osinski

University of Western Ontario, Department of Earth Sciences/Institute for Earth and Space Exploration, London, ON, Canada

Keywords

Impact crater · Impact cratering · Shock metamorphism · Impactites · Hydrothermal alteration · Microbial habitats · Endoliths · Thermophiles · Mars

Definition

A 23-km diameter, 31-million-year-old complex impact structure located on Devon Island in the Canadian Arctic.

History

The Houghton impact structure was first studied during Operation Franklin in the 1950s, where it was interpreted as a salt dome (Greiner et al. 1963), hence the original name Houghton Dome, a term that is still present on topographic maps of the region. It was subsequently confirmed as the product of a meteorite impact event by the discovery of shatter cones (Robertson and Mason 1975) and coesite (Frisch and Thorsteinsson 1978).

Overview

The Houghton impact structure is a well-preserved and well-exposed meteorite impact structure located on Devon Island in the Canadian High Arctic. With an apparent crater diameter of 23 km and a rim (final) crater diameter of 16 km (Osinski and Spray 2005), Houghton is classified as a midsize complex impact structure. This crater formed 31 million years ago (Erickson et al. 2021) when an asteroid or comet, likely between 1 and 2 km in diameter, struck what is now Devon

Island. It possesses a well-defined rim, featuring fault-bounded terraces, remnants of impact ejecta deposits, a well-preserved series of crater-fill impactites, and a subdued central uplift (Osinski et al. 2005b). The exceptional preservation of the Houghton impact structure is due to several factors, including the lack of other regional geological events since its formation, the cold-based glaciation in this part of the Arctic (which led to relatively little erosion), and the present-day polar desert environment. The latter also makes this crater an excellent analogue for Mars (Lee and Osinski 2005).

It has becoming increasingly clear over the past couple of decades that impact events, while initially destructive, also have beneficial effects for microbial life. As summarized in a recent review article (Osinski et al. 2020a), impact events can deliver and/or generate many of the necessary chemical ingredients for life and catalytic substrates, such as clays. They also create several habitats for life, including hydrothermal systems, crater lakes, highly shocked and porous rocks, and impact glasses. Studies of the Houghton impact structure contributed significantly to this realization that impact events are important astrobiological targets that may have played a central role in the origin of life on Earth, and possibly other planetary bodies. Two of the major astrobiological features of Houghton are the impact-generated hydrothermal system and the impact processing of crystalline rocks to create unique endolithic habitats.

Evidence for hydrothermal activity was first documented at Houghton by Osinski et al. (2001). Further studies resulted in the most comprehensive understanding of the 2D distribution of impact-generated hydrothermal alteration for any complex impact structure on Earth (Osinski et al. 2005a), with four distinct settings and styles of hydrothermal mineralization being recognized: (a) calcite and marcasite-dominated vugs and veins within the crater-fill impact melt rocks, with an increase in intensity of alteration toward the base; (b) quartz-cemented breccias in the interior of the central uplift; (c) intense calcite veining around the heavily faulted and fractured outer margin of the central uplift; and (d) mineralized

pipe structures interpreted as fossil hydrothermal vents around the faulted crater rim. Sulfur isotope data on hydrothermal products provides evidence that the hydrothermal system was colonized by thermophilic (heat-loving) microorganisms (Parnell et al. 2010). Other studies have shown that hydrothermal sulfate minerals continue to provide microbial habitats at the present day (Parnell et al. 2004). Izawa et al. (2011) also showed that the weathering of primary hydrothermal deposits and dissolution and reprecipitation of these products also create potential habitats for endolithic microbes.

Cockell et al. (2002) demonstrated that the impact event resulted in the increased porosity and enhanced translucence of Precambrian gneisses, enabling the colonization of a substrate by endolithic microorganisms that before the impact would have been uncolonizable. Subsequent studies explored the relationship of biomass with shock level and found that rocks shocked to pressures between 35 and 60 GPa provide the most ideal habitat for endolithic organisms (Pontefract et al. 2014) and, further, that microbial diversity is tied to the amount of porosity in the target substrate (Pontefract et al. 2016).

Cross-References

- Crater, Impact
- Crater Lakes (Mars)
- Hydrothermal Alteration
- Hydrothermal Environments
- Mars Analogue Sites
- Terrestrial Analog
- Thermophile

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Dewar Flask

► [Cryostat](#)

DHA

► [Dihydroxyacetone](#)

Dharwar Craton

Jean-François Moyen
Université de Lyon, LGL-TPE, UJM-UCLB-
ENSL-CNRS, Saint Etienne, France

Keywords

Archean · Craton · Geological province ·
Accretion

Synonyms

[South Indian shield](#)

Definition

The Dharwar craton is a part of southern India, underlain by Archean rocks, and extending

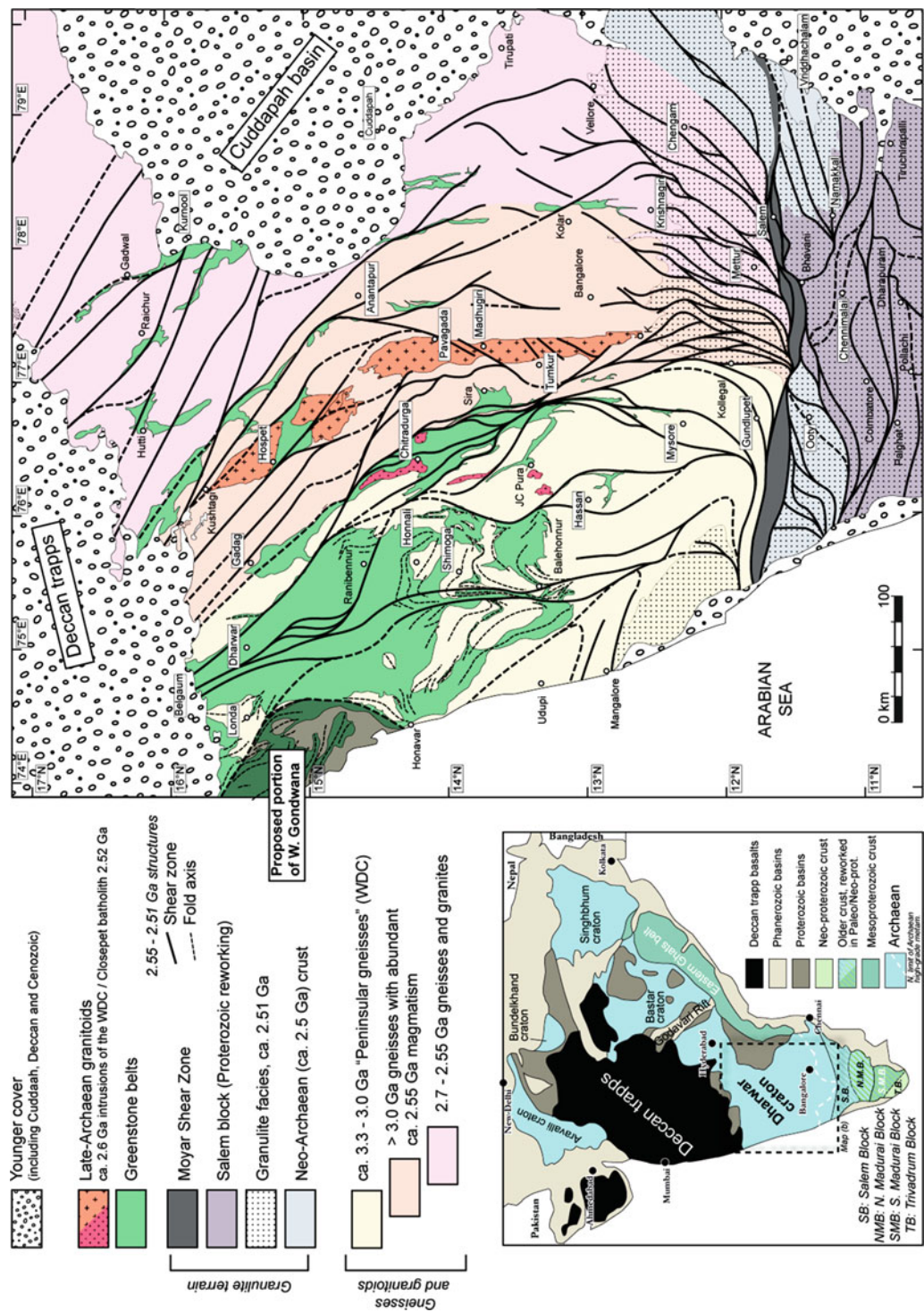
roughly between the cities of Goa, Hyderabad, Chennai, and Mangalore in Karnataka and Andhra Pradesh states.

Overview

The Dharwar craton is made of orthogneisses and greenstone belts, collectively formed between 3.3 and 2.6 Ga (Chadwick et al. 2000). It acquired its final structure between 2.56 and 2.51 Ga during a tectonic and metamorphic event that overprinted most previous structures and lithologies (Chardon and Jayananda 2008). This event was accompanied by the intrusion of voluminous granitoids (Chardon et al. 2011). Due to differential erosion and/or tilting, different crustal levels are exposed from south (granulite facies) to north (greenschist facies), allowing to reconstruct a three-dimensional section through the late Archean crust.

To the south, the Dharwar craton is cut by younger (Proterozoic) tectonic structures; various granulitic domains rework the Archean crust. It has also been suggested (Collins et al. 2014) that the northwestern corner of the Dharwar craton (Goa area) represents part of western Gondwana which docked in the Neoproterozoic against the Dharwar craton proper. The craton is covered by younger units to the north and east, including Proterozoic sediments of the Cuddapah basin and flood basalts of the Deccan traps (Fig. 1). Fragments of Archean crust are also found in the heavily reworked granulite terrain of Peninsular India, south of the craton (Collins et al. 2014).

The Dharwar craton is traditionally separated into two main geological domains (west and east) with contrasting ages and geological features. The **western Dharwar craton** is dominated by Mesoarchean rocks, including a ca. 3.3–3.0 Ga basement of TTG gneisses (the “Peninsular Gneisses”) and two successions of greenstone belts: an older, ca. 3.3 Ga Sargur Group, and a younger, 3.0–2.7 Ga Dharwar Group unconformably overlying the Peninsular Gneisses (Chadwick et al. 2000 and references therein). It is further intruded by several late Archean, ca. 2.61 Ga, plutons (Jayananda et al. 2006) of potassic granitoids. In contrast, the **eastern**



Dharwar Craton, Fig. 1 (a) Main crustal units forming the Indian shield. (b) Simplified geological map of the Dharwar craton. (Modified after Chardon et al. (2008))

Dharwar craton does contain only rare Mesoarchean remains; it is mostly made of Neoarchean juvenile granitoids that were emplaced ca. 2.55 Ga ago, concomitant with the main deformation phase (Jayananda et al. 2000; Chardon et al. 2002). However, recent fieldwork, mapping, and geochronology allowed to further subdivide the eastern Dharwar craton and identify a third, intervening domain with distinct features (Moyen et al. 2003; Chardon et al. 2011; Jayananda et al. 2019). Greenstone belts of the eastern Dharwar craton are 2.7–2.5 Ga old. The boundary between these domains has been interpreted as a tectonic suture, although it lacks many typical features of modern boundaries such as thrust-and-fold structures, HP/LT metamorphism, or ophiolites, and exemplifies the ambiguity of the Archean geological record.

The Dharwar craton has been pervasively affected by a ca. 2.55–2.51 Ga tectono-metamorphic event, involving (1) the emplacement of large volumes of mostly granitoids in the eastern Dharwar, (2) high-grade (granulite facies) metamorphism in the lower crust now exposed in the southern part of the craton (these granulites either correspond to modified old gneisses or to juvenile magmas emplaced in the lower crust), and (3) deformation represented by E-W bulk shortening of the crust, accommodated by transcurrent shear zones (in the western Dharwar) and sinking of the dense greenstone belts into the lighter gneissic basement (“sagduction”) (Chardon et al. 1996).

The Dharwar craton has been the focus of research for ancient traces of life, particularly in the western Dharwar craton which contains Archean sedimentary rocks, among others several units of banded iron formations (BIFs) (Manikyamba et al. 1993). In BIFs, Orberger et al. (2012) found spherules containing carbonaceous matter which might be derived from ancient microbial activity (Fig. 1). Stromatolites were also described (Sharma and Shukla 2004).

Cross-References

- Archean Eon
- Archean Tectonics

- Banded Iron Formation
- Craton
- Sagduction
- Shield
- TTG

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DHMR

J. Andy Spry

SETI Institute, Mountain View, CA, USA

Definition

Dry heat microbial reduction (DHMR) is a process for bioburden reduction. This process involves heating a spacecraft hardware element in an oven for a duration dependent on the set temperature and bioburden reduction required. It was originally developed for terminal sterilization of assembled spacecraft by NASA's Viking Project. In this case, each spacecraft was heated for 50 h at 111.7 °C including warm-up and cool-down periods. DHMR processes are approved by both NASA and ESA for use with spacecraft hardware over specified ranges of temperature and humidity.

Cross-References

- [Bioburden](#)
- [Bioburden Reduction](#)

- [Pasteurization](#)
- [Planetary Protection](#)
- [Sterilization](#)
- [Terminal Sterilization](#)

Diacetylene (C₄H₂)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

[Butadiyne](#); C₄H₂; HC₄H

Definition

The molecule diacetylene is the simplest polyyne, which is a hydrocarbon with alternating single and triple bonds; thus, diacetylene has the formula HC≡C-C≡CH. Diacetylene is found as a minor component in the atmospheres of the ► [giant planets](#), including Jupiter, Saturn, and Neptune, and in that of Saturn's satellite ► [Titan](#). In addition, it can be present in circumstellar environments, for example, in the envelope of the protoplanetary nebula CRL 618 (Cernicharo et al. [2001](#)).

Cross-References

- [Giant Planets](#)
- [Infrared Space Observatory](#)
- [Molecules in Space](#)
- [Planetary Nebula](#)
- [Titan](#)

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Diagenesis

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Diagenesis refers to all physical-, chemical-, and biological-related processes which bring sediments to be transformed into a ► [sedimentary rock](#) (lithification), exclusive of ► [weathering](#). Transformation of an unconsolidated sediment into solid rock is produced through a combination of compaction, recrystallization, dehydration, mineral replacement, dissolution, and cementation processes. Diagenesis begins when a detrital grain is sedimented and begins its interaction with the pore waters and overburden. Diagenesis ends when these processes grade into metamorphism, and sedimentary textures and structures (such as bedding, grading, bioturbation, etc.) are lost. Diagenetic processes thus take place at temperatures lower than 200 °C and pressures lower than 3 kbar: mostly result in minor to moderate changes in the rock's mineralogy and texture. Commonly, clays, silica minerals, evaporites, or carbonates replace or alter detrital grains, form cement, and fill pore spaces, thereby reducing the porosity and permeability of the rock. Organic carbon is also degraded during diagenesis through the metabolism of various heterotrophic bacteria. Diagenesis is an important process controlling the preservation of morphological, molecular, chemical, and biological signatures of life in older rocks.

Cross-References

- [Biomarkers](#)
- [Biomarkers, Morphological](#)
- [Metasediment](#)
- [Microbially Induced Sedimentary Structures](#)
- [Pseudofossil](#)
- [Sedimentary Rock](#)
- [Weathering](#)
- [Weathering Profile](#)

Diamictite/Diamicton

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Mixtite](#)

Definition

Diamicton is a poorly sorted terrigenous sediment. When lithified to sedimentary rock, it's called diamictite. Diamictite contains a wide range of particle sizes, from gravel to sand, dispersed in a clayey matrix. The nonlithified equivalent of diamictite is diamicton. Diamictite forms primarily in (sub)glacial environments (moraines) and in volcanic environments as *lahars* (debris flow composed of chaotically mixed pyroclastic material, rocky debris, and water). The astrobiological interest in diamictite is due to its possible significance as a climate indicator in suspected glacial sedimentary deposits, thus serving to identify similar processes in Martian polar caps. The fine material in diamictite is subject to rapid outwash during deglaciation. On Earth, it has been invoked to have caused excess alkalinity in the ocean (e.g., Huang et al. 2016) at the end of the Cryogenian global glaciation (20–635 Ma) which is related to a ► [Snowball Earth](#) episode.

Cross-References

- [Glaciation](#)
- [Polar Caps \(Mars\)](#)
- [Sedimentary Rock](#)
- [Snowball Earth](#)
- [Subglacial Environments](#)

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Diamino Acid

Uwe J. Meierhenrich

Institut de Chimie de Nice (ICN), Université Côte d'Azur, Nice, France

Keywords

Amino acids · Chirality · Murchison meteorite · Peptide nucleic acids

Synonyms

[Diamino carboxylic acid](#)

Definition

Diamino acids are diamino carboxylic acids. Diamino acids are molecules that contain at least one carboxylic acid group (COOH) and two amine functional groups (NH₂). Diamino acids belong to the chemical family of amino acids. Diamino acids often but not always contain a stereogenic center and can therefore be chiral. The protein ► [amino acid](#) lysine is a diamino acid.

Overview

In biochemistry, diamino acids, that is, amino acids containing a second amine functional group, are of particular interest. Lysine is a protein diamino acid. According to systematic studies on the recruitment order of amino acids and diamino acids in proteins, diamino acids were recruited in a relatively late stage of evolution. Ornithine and 2,6-diaminopimelic acid are nonprotein diamino acids that play important roles in the urea cycle and in bacteria cell walls.

Diamino acids are of particular interest in discussions of chemical evolution and the origin of life on Earth, since they can be used as monomers for the synthesis of peptide nucleic acids (PNAs), which some have suggested may have played a

role in the early evolution of life (Nelson et al 2000). There are numerous possible peptide nucleic acids. One type of PNA molecule is composed of N-aminoethylglycine leading to aegPNA, and others can be constructed from diamino acids (da) leading to daPNA. Peptide nucleic acids such as aegPNA and daPNA are capable of forming duplex structures with individual RNA and DNA strands. PNAs are nucleic acid analogs, and they are considered as candidates for the first genetic material on Earth. In this case, peptide nucleic acids may have transferred their genetic information to RNA and DNA (Meierhenrich 2008).

The diamino acids 2,3-diaminopropionic acid and 2,4-diaminobutanoic acid have been identified both in the Murchison meteorite and in the products of comet simulation experiments (artificial comets) (Munoz Caro et al. 2002; Meinert et al. 2012). PNA oligomers have never been detected in living organisms, in meteorites, or in artificial comets, although some research has suggested these may be prebiotic compounds.

In the context of the origin of biomolecular homochirality, the chiroptical properties of diamino acids have been studied. ► [Circular dichroism](#) spectra of zwitterionic L-diamino acids in solution show maxima at 200 nm (Bredehöft et al. 2007).

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Circular Dichroism](#)
- [Zwitterion](#)

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Diamino Carboxylic Acid

► [Diamino Acid](#)

(Z)-2,3-Diaminobut-2-enedinitrile

► [Diaminomaleonitrile](#)

2,3-Diaminomaleonitrile

► [Diaminomaleonitrile](#)

Diaminomaleonitrile

Martin Ferus

J. Heyrovsky Institute of Physical Chemistry,
Czech Academy of Sciences, Prague, Czech
Republic

Synonyms

[\(Z\)-2,3-Diaminobut-2-enedinitrile](#);
[2,3-Diaminomaleonitrile](#)

Chemical Formula

$\text{NCC}(\text{NH}_2)\text{C}(\text{NH}_2)\text{CN}$

Acronyms

DAMN

Definition

A stable intermediate in formamide- and hydrogen-cyanide-based prebiotic syntheses (Saladino et al. 2005; Hudson et al. 2012; Roy et al. 2007), DAMN, a HCN tetramer, forms needle-shaped pale yellow or colorless crystals, whose melting point is at 178–184 °C (Moser et al. 1967; Penfold and Lipscomb 1961). It is synthesized by a condensation from AMN (aminomalonitrile) in basic HCN solutions (Oró and Kimball 1962). In prebiotic synthesis of purines, it undergoes a photochemical interconversion to diaminofurmaronitrile (DAF), and conversion to 5-aminoimidazolecarbonitrile (AICN) or 4-amino-5-cyanoimidazole (ACI) (BECKER et al. 1973; Boulanger et al. 2013). Glycine is produced by its acidic hydrolysis (6 M HCl, 184 °C, 24 hod.); in basic environment it forms peptidic solids (Moser et al. 1968). DAMN is important to plausible prebiotic syntheses initiated by heat (Saladino et al. 2004), UV light (Saladino et al. 2004), or an impact event (Ferus et al. 2015).

History

After Miller experiment producing aminoacids (Miller 1953), the first example of the prebiotic synthesis of purines has reported Oró (Oró 1960) by refluxing a concentrated aqueous solution of ammonia and HCN (1.0–11 M solutions of HCN) for several days to give adenine (Oró 1960). The mechanism of formation of purines from HCN has been then studied in detail. Ferris and Orgel first recognized that AMN and DAMN were important intermediates for these transformations (see [Roy et al. 2007] and references therein).

Cross-References

- [Aminomaleonitrile](#)
- [Diaminomaleonitrile](#)
- [Formamide \(NH₂CHO\)](#)
- [Hydrogen Cyanide](#)

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Diaminovaleric Acid

► Ornithine

Diapirism

Nicholas Arndt

ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Diapirism refers to an upward migration of low-density material, commonly accompanied by a downward migration of denser diapirs nearby. A *diapir* is a teardrop-shaped body of solid but ductile, low-density rock that ascends through denser, more rigid rock. Examples are ice, mud (mud volcanism), and salt diapirs in sedimentary sequences and possibly dome-like intrusions of granitic gneiss in Archean cratons. Diapirism produces a characteristic dome-and-basin structure that may be characteristic of vertical tectonics in hot, ductile Archean continental crust (sagduction). The higher temperature results from the decay of radioactive elements, which were more abundant in the Archean continental crust than today. Salt diapirism is widespread in sedimentary basins that had seen the accumulation of thick evaporitic strata, such as Angola, Morocco, the northern Gulf of Mexico, Southern Iran, Western Kazakhstan, and Northern Germany.

Mud diapirism is observed in regions where overpressure develops in unconsolidated shale-rich strata, such as in pro-delta settings, in sabkhas where it is usually related to groundwater fluctuations, and in hydrocarbon systems. Mud diapirism may occur on Mars's surface and icy diapirism on Saturn's satellites such as Ganymede.

Cross-References

- [Archean Eon](#)
- [Cryovolcanism](#)
- [Ganymede](#)
- [Mud Volcanism](#)
- [Sagduction](#)

Diastereomers

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

Diastereomers are optically active ► [isomers](#) that are not ► [enantiomers](#). They are characterized by having more than one chiral center. A diastereomer with n chiral centers has 2^n possible ► [stereoisomers](#). Thus, for a diastereomer with two chiral centers, there are four possible stereoisomers: a pair of diastereomers with two pairs of enantiomers. One example is the diastereomers l-isoleucine and d-alloisoleucine. For isoleucine, the enantiomers are l- and d-isoleucine and for alloisoleucine the enantiomers are l- and d-alloisoleucine (see Fig. 3 in ► [Amino Acid](#)).

Diastereomers have different physical properties (different melting points, boiling points, solubilities, etc.). Their chemical properties also differ in that they react with reagents at different rates. Thus, they can be directly separated by chromatographic methods without the need for chiral reagents.

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Enantiomers](#)
- [Isomer](#)

Diazenylium (N_2H^+)

William M. Irvine
University of Massachusetts, Amherst,
MA, USA

Synonyms

N_2H^+

Definition

Protonated molecular nitrogen (protonated ► [dinitrogen](#)), N_2H^+ , is used by radio astronomers and astrochemists as a tracer of dense gas in ► [molecular clouds](#), since its large electric dipole moment requires relatively high densities to collisionally excite the pure rotational transitions at millimeter wavelengths. Since the presumed reservoir of most nitrogen in these clouds, molecular nitrogen (N_2), has no easily accessible transitions, N_2H^+ is an important indicator of the nitrogen chemistry in these regions. It is particularly useful, since it is one of the last gas phase species to freeze out onto the ► [interstellar dust](#) grains at the center of cold clouds.

History

The ion N_2H^+ was identified in interstellar molecular clouds by means of the characteristic hyperfine splitting pattern of the fundamental rotational transition ($J = 1-0$) at 93 GHz (Turner 1974), 2 years before this transition was measured in the laboratory, providing an interesting example of the ability to do fundamental molecular physics experiments in space. The interpretation of the emission from this species in molecular clouds has been recently revived by Daniel et al. (2013).

Cross-References

- [Dinitrogen](#)
- [Interstellar Dust](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

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Diazotrophy

Juli Peretó
 Institut Cavanilles de Biodiversitat i Biologia
 Evolutiva, Universitat de València, València,
 Spain

Synonyms

[Nitrogen fixation](#)

Definition

Diazotrophy is the metabolic ability to fix atmospheric nitrogen into a biologically useful form (i.e., ammonia).

Cross-References

- [Nitrogen Cycle, Biological](#)

DIBs

- [Diffuse Interstellar Bands](#)

Dicarboxylic Acid

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

Dicarboxylic acids are organic compounds containing two ► [carboxylic acid](#) functional groups. Dicarboxylic acids generally show the same chemical behavior and reactivity as monocarboxylic acids. The ionization of the second carboxyl group occurs less readily than the first one, because more energy is required to separate a positive hydrogen ion from the anion than from the neutral molecule.

Dicarboxylic acids are important metabolic products, for example, as Krebs cycle intermediates (e.g., α -ketoglutaric acid, $\text{HOOC}(\text{CH}_2)_2\text{-COCOOH}$) and the products of fatty acid oxidation. The simplest dicarboxylic acid is oxalic acid (HOOC-COOH); others important in biochemistry include malonic ($\text{HOOCCH}_2\text{COOH}$), succinic ($\text{HOOC}(\text{CH}_2)_2\text{COOH}$), and glutaric ($\text{HOOC}(\text{CH}_2)_3\text{COOH}$) acids. The protein ► [amino acids](#), aspartic ($\text{HOOCCH}_2\text{CH}(\text{NH}_2)\text{COOH}$) and glutamic ($\text{HOOC}(\text{CH}_2)_2\text{CH}(\text{NH}_2)\text{COOH}$) acids, are also dicarboxylic acids.

Cross-References

- [Amino Acid](#)
- [Carboxylic Acid](#)

Dichotomy, Planetary

Daniela Tirsch

German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Separation](#); [Split](#)

Definition

A dichotomy refers to the splitting of surface and other planetary features in two dissimilar, non-overlapping parts. On [▶ Mars](#), a dichotomy can be found in terms of crater density and topography with the highly cratered southern highlands and the less cratered northern lowlands. A further dichotomy is speculated to exist with respect to crustal thickness. The [▶ crust](#) of the northern lowlands could be much thinner (ca. 32 km) than the crust of the southern highlands (ca. 58 km). This has been derived from an interpretation of the gravity field assuming a constant crust density. The two competing formation hypotheses involve an exogenic cause (e.g., a giant impact) and an endogenic formation mechanism (e.g., degree-1 mantle convection). On the Moon, a dichotomy is known regarding the distribution of [▶ basalt](#), with the near side comprising about 90% whereas the far side only exhibits 10 % of the bulk basalt abundance. The reason for this is again a dichotomy in crustal thickness causing basalt plumes to easily reach the surface on the thinner near side (60 km) in contrast to the thicker far side (120 km). The Earth's hypsometric curve displays another dichotomy in surface elevation between the continents and the ocean basins.

Cross-References

- ▶ [Basalt](#)
- ▶ [Crater, Impact](#)

- ▶ [Crust](#)
- ▶ [Mars](#)
- ▶ [Moon, The](#)

Dicyan

- ▶ [Cyanogen](#)

Dicyanogen

- ▶ [Cyanogen](#)

Diderot's Conception of Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

History

The French philosopher Denis Diderot (1713–1884) wrote about life in several of his more famous texts, notably in his *Entretiens* (1776) and especially in *Le Rêve de d'Alambert* (from 1769, but published in 1830). Diderot was a partisan of spontaneous generation and of transformation of matter theories. In his *Elements de Physiologie* (published posthumously in 1875), he claimed that nature produced only a few living beings, perhaps only one, of which all the others would come from by combination, micturition, and dissolution and which would vary infinitely.

Cross-References

- ▶ [Buffon's Conception of Origins of Life](#)
- ▶ [Lamarck's Conception of Origins of Life](#)

Differentiation

► Fractionation

Differentiation, Planetary

Frank Sohl¹ and Doris Breuer²

¹Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

²German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Keywords

Accretion · Convective overturn · Core formation · Crust segregation · Degassing · Magma ocean · Partial melt

Definition

Planetary differentiation is the separation of different constituents of planetary materials resulting in the formation of distinct compositional layers. Denser material tends to sink into the center and less dense material rises toward the surface. If internal differentiation of a ► [terrestrial planet](#) has run to completion, the interior would be subdivided into an iron-rich metallic core and a silicate ► [mantle](#), overlain by a chemically distinct ► [crust](#) enriched in ► [basalt](#).

Overview

The accretion of the terrestrial bodies from planetesimals provides the initial source of energy for subsequent planetary evolution. The amount of kinetic energy converted to heat during accretion is not well known because it is strongly dependent on specific formation timescales and environmental conditions. Heat sources, other than deposition of impact energy during accretion, are the release of energy through gravitational separation of light and dense constituents, the decay of radioactive heat sources, and additional external heat sources

such as tidal heating (e.g., Schubert et al. 1986; see ► [Tides, Archean](#)). Provided that a sufficient amount of energy was retained during accretion, a near-surface magma ocean would have formed atop of the growing protoplanet. Chemical differentiation of the magma ocean would be affected by impact stirring, convective mixing, cooling, and solidification (e.g., Abe 1993). The solidification timescale of the magma ocean is determined by the balance between the heat flow entering from below, latent heat release upon crystallization, and heat loss at the surface. The crystallization of the magma ocean is thought to cause initial compositional layering in terms of unstable cumulate density stratification, thereby invoking gravitational overturn by convective instability (Elkins-Tanton et al. 2003). This may have led to the formation of an early basaltic crust and chemically distinct mantle reservoirs on terrestrial planets. Aqueous alteration involving chemical reactions between olivine-rich mantle ► [rock](#) and liquid water may have caused the release of a substantial amount of ► [hydrogen](#) (► [Serpentinization](#)). If the energy released by gravitational separation of light and dense constituents were sufficient to invoke melting of the remaining mantle material, the separation process would become energetically self-sustaining and will run to completion within a short period of time (tens of million years). The subdivision of terrestrial planet interiors into crust, mantle, and core (e.g., Sohl and Schubert 2007; see ► [Interior Structure, Planetary](#)) can be attributed to such intense differentiation events, commonly referred to as runaway differentiation.

Basic Methodology

The differentiation and associated chemical evolution of a terrestrial body is in general the consequence of partial melting in its interior. Density differences between the melt and the solid residuum would then result in their separation. For larger planets with increasing accretion time, the melting is caused by impact energy and results in the formation of a magma ocean close to the surface. In a magma ocean, the much denser iron

sinks and accumulates at its base. Iron parcels then settle further to the center of the solid or partly solid planet by Rayleigh-Taylor instability (Stevenson 1990). The larger the accumulated iron diapirs, the higher are the sinking velocities. The gravitational energy released by core formation is converted into thermal energy, which strongly heats the interior. As a consequence, the temperature profile is inverted to decrease from the center toward the surface. The total energy released by the differentiation of a homogeneous planet into an iron-rich core and a silicate mantle can be estimated from the difference between the potential energy stored in a homogeneous planet after accretion and the potential energy of the differentiated, two-layer planet (Schubert et al. 1986). If that amount of energy were distributed homogeneously within the interior, assuming thermal equilibrium between the mantle and the core, the mean temperature would rise about 1000 K for the Earth and about 300 K for Mars (Solomon 1979).

Further chemical differentiation of a planetary mantle is usually associated with crust formation. The process of crust formation can, in general, be divided into two phases: primary and secondary crust formation. A primary crust can be formed as a consequence of freezing of a magma ocean during an early state of planetary evolution. Whereas light minerals like plagioclase feldspar would rise toward the surface forming an anorthositic crust, heavy minerals such as olivine would sink to the bottom of the magma ocean. This gravitationally induced crystal differentiation will result in a chemically layered mantle.

Key Research Findings

The separation of the metal from the silicate particles is a common process in the ► [solar system](#). Prominent examples are the iron-rich cores of the terrestrial bodies and iron ► [meteorites](#) that consist of Fe-Ni alloys. The latter are assumed to be the fragments of the cores of larger ancient asteroids that have been shattered by impacts. Studies on short-lived radionuclides (e.g., ^{182}Hf) suggest

that the core formation process occurred during the first 5–30 million years of the solar system, prolonging with increasing size of the planetary body (e.g., Kleine et al. 2002). Thus, the differentiation event occurred most likely contemporaneously or shortly after completion of ► [asteroid](#) or planet accretion. The relatively rapid separation of silicate and iron implies that both components were fluid (Stevenson 1990). In case of small planetary bodies like the asteroids, the decay of short-lived radioactive isotopes like ^{26}Al and ^{60}Fe provides a sufficient amount of energy to melt the interior (e.g., MacPherson et al. 1995; Tachibana and Huss 2003). The presence of siderophile elements, i.e., elements such as S, Ni, and Co that are readily soluble in molten iron, would result in a significant melting-point depression (e.g., Braginsky 1964), thereby facilitating the segregation of iron alloys in the core. Once a metal core has formed, it may further differentiate as soon as an inner pure Fe core starts to solidify upon cooling. In turn, the fluid outer core then would be enriched in the low-melting-point components.

The formation of the secondary crust would deplete the mantle in radioactive elements and crust-forming minerals, as those are incompatible and enriched in the melt. In addition, the melt that forms the crust is enriched in volatiles that are released into the atmosphere by extrusive volcanism. Mantle degassing associated with crustal differentiation can play an important role for the evolution of planetary atmospheres. The mechanisms of crust formation differ between ► [plate tectonics](#) and one-plate planets. Plate tectonics provides for crust formation in a two-step fashion. Crust formation is most effective at divergent plate boundaries, where rising hot mantle material crosses the solidus near the surface. The corresponding pressure-release melting generates basaltic crust that is continuously recycled at convergent plate boundaries. More silicic crust is produced in a second differentiation step at convergent plate boundaries where basaltic crust is remelted (together with wet continental sediments and possibly mantle rock) to form new continental-like crust (e.g., Taylor and McLennan 1985). One important open question for the Earth with its plate tectonics is the timing of the

continental crust growth. Models range from rapid early crustal growth with crust production and recycling in equilibrium in the later evolution (Armstrong 1981), a continuous growth of the crust to its present size (Veizer and Jansen 1979), and an episodic growth with a peak at the Archaean-Proterozoic transition (Taylor and McLennan 1985). For one-plate planets in the ► [stagnant lid](#) convection regime, crust recycling is only possible in the form of crustal delamination for which the lower-dense crustal material (basalt that changes to eclogite at depth) sinks into the mantle and there is no two-stage differentiation. Instead, melt is formed underneath the lithosphere usually at greater depth as compared to planets with plate tectonics. The crust produced would predominately be composed of basaltic rock. Observations and thermochemical models show that for the Moon and ► [Mars](#), most of the basaltic crust is produced early in the planetary evolution (e.g., Nimmo and Tanaka 2005). ► [Venus](#) is distinct in that the surface has an average age of 300–800 Ma (Schaber et al. 1992). The uniform age distribution has been associated with a global resurfacing event, possibly associated with a change in the style of mantle convection (see Bougher et al. (1997) for a review). The relatively rapid global resurfacing of Venus may be questioned, since the cratering record allows a variety of interpretations in terms of volcanic resurfacing, including a global decrease in activity over time (Campbell et al. 1999).

Applications

The state of knowledge of planetary differentiation processes has important implications for the general understanding of the internal structure, thermochemical evolution, bulk composition, and atmosphere evolution of the terrestrial planets and terrestrial-type bodies like the Moon and several large outer-planet satellites. Even the interior of main-belt asteroid 4 Vesta (► [Vesta](#)) is likely differentiated (Ghosh and McSween 1998), as

suggested by the spectrally variegated surface of that accretional remnant.

Future Directions

To further our understanding of the internal differentiation and the associated volatile loss, new and improved techniques and methods will be developed and applied in the future. Among those are isotopic and trace element studies on planetary material, improved numerical techniques incorporating mantle melting and degassing in the frame of three-dimensional convection models, and also future missions applying new and improved measuring techniques.

Cross-References

- [Anorthosite](#)
- [Archean Eon](#)
- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [Basalt](#)
- [Core, Planetary](#)
- [Crust](#)
- [Diapirism](#)
- [Heat Flow, Planetary](#)
- [Hydrogen](#)
- [Interior Structure, Planetary](#)
- [Mantle](#)
- [Mars](#)
- [Meteorites](#)
- [Moon, The](#)
- [Planetesimals](#)
- [Plate Tectonics](#)
- [Primordial Heat](#)
- [Radioactive Heating](#)
- [Rock](#)
- [Satellite or Moon](#)
- [Serpentinization](#)
- [Solidus](#)
- [Stagnant Lid Convection](#)
- [System Solar Formation, Chronology of](#)
- [Terrestrial Planet](#)

- Tides, Planetary
- Venus
- Vesta

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Diffraction

Daniel Rouan

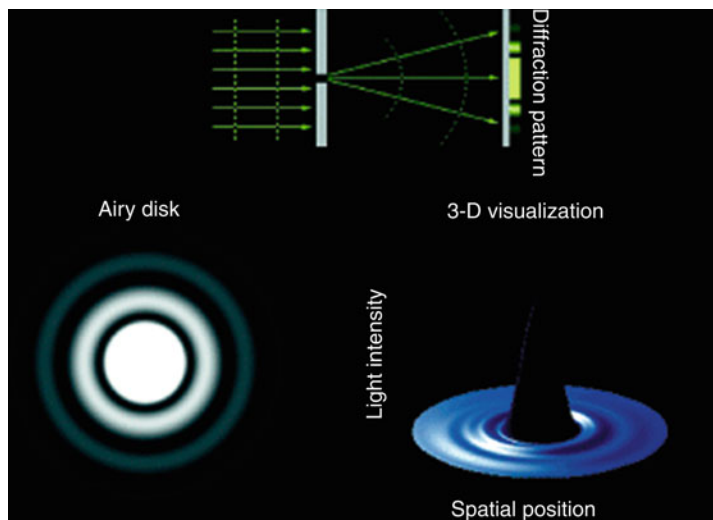
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Diffraction, in physics, is a phenomenon that occurs when a wave encounters an obstacle or travels through a medium with a varying refractive index. Secondary radial waves issued from the obstacle spread out, the more widely as the size of the obstacle becomes smaller and approaches the wavelength. Because the secondary waves may interfere, the diffraction pattern generally shows structures with fringes or rings (see Fig. 1). Diffraction of light in observational astronomy limits the ability of an imaging system to resolve the finest details. The larger the aperture of the telescope and the smaller the wavelength, the finer the angular resolution. A quantitative expression of this limit is given by the expression $\theta(\text{arcsec}) = 0.2 \lambda(\mu\text{m})/D(\text{m})$, where λ is the wavelength in μm and D the diameter of the telescope in meters. This effect provides one justification for telescopes having very large mirrors, the other justification being better collecting

Diffraction,

Fig. 1 Diffraction pattern generated by a small hole in a dark screen illuminated by a beam of light and seen at a certain distance. Note the rings that are characteristic of this figure called the Airy pattern



power. However, on the ground (as opposed to space), telescopes are hampered by atmospheric turbulence that blurs the image to a typical resolution of 1 arcsec, whatever the size of the telescope is. Only ► [adaptive optics](#) techniques allow to recover the diffraction limit of a telescope.

Cross-References

- [Adaptive Optics](#)
- [Coronagraphy](#)
- [Imaging](#)

Diffuse Bands

- [Diffuse Interstellar Bands](#)

Diffuse Cloud

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A diffuse cloud is that portion of an interstellar cloud with visual extinction (A_v) less than about

1 magnitude, corresponding typically to densities of a few tens of atoms per cubic centimeter or less, and column densities of order 10^{21} hydrogen atoms cm^{-2} . Hydrogen, the principal constituent of interstellar clouds, is predominantly in atomic form in diffuse clouds. The physics and chemistry of diffuse clouds may be studied by observing the absorption lines produced in the spectra of background stars. Trace constituents observed at visual and ultraviolet wavelengths include many atoms and diatomic molecules, including such simple molecules as CO, OH, CH, CH^+ , CN, and H_2 . At millimeter wavelengths, molecules such as C_2H and HCO^+ are observed. As the density increases, diffuse clouds grade gradually into those clouds referred to as translucent and then to those that are called dense. The Herschel satellite has recently discovered OH^+ , H_2O^+ , H_2Cl^+ , and HF as constituents of diffuse interstellar clouds (Neufeld et al. 2010; Gerin et al. 2010; Lis et al. 2010).

Cross-References

- [Dense Cloud](#)
- [Herschel Mission](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

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Diffuse Galactic Light

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

The diffuse galactic light is the weak background ultraviolet and visible radiation produced by ► [interstellar dust](#) grains scattering light from stars in the disk of the ► [Milky Way](#) galaxy. It is not easily separable observationally from the ► [zodiacal light](#) (sunlight scattered by dust in the solar system) and from airglow (emission from atoms and molecules in the Earth's upper atmosphere).

Cross-References

- [Background](#)
- [Interstellar Dust](#)
- [Zodiacal Light](#)

Diffuse Interstellar Bands

Martin A. Cordiner

NASA Goddard Space Flight Center,
Astrochemistry Laboratory, Greenbelt, MD, USA

Keywords

Astrochemistry · Interstellar medium · Interstellar dust · Optical spectroscopy · Large molecules

Synonyms

[DIBs](#); [Diffuse bands](#)

Definition

The Diffuse Interstellar Bands (DIBs) are broad spectroscopic absorption features, of predominantly unknown origin, which occur in the optical and near-infrared spectra of stars as their light passes through the interstellar medium. More than 400 DIBs have been detected to-date at different wavelengths, at least some of which are believed to be caused by large carbon-based molecules such as fullerenes, polycyclic aromatics, and carbon chain-bearing species.

History

In 1922, Mary Lea Heger discovered two prominent dark absorption bands in the spectra of hot (early spectral type) stars at wavelengths of 5780 and 5797 Å (Heger 1922). The cause of these features could not be established at the time, and their origin remains unknown to this date.

Due to the detailed studies of binary stars by Merrill and Sanford (1938), the unidentified bands were determined to originate in the interstellar medium (ISM), and four additional bands were discovered in the red region of the spectrum, at wavelengths of 6203, 6270, 6284, and 6614 Å. The bands were noted as being somewhat diffuse, as they have a broader width than other interstellar absorption lines that are known to be caused by common gas-phase atoms (such as sodium and calcium) or simple molecules (such as CH and CN). Henceforth, these and other unidentified, broad interstellar absorption features in optical spectra came to be known as diffuse interstellar bands (DIBs).

More than 400 different DIBs are now known (Hobbs et al. 2009) and more are found with each increase in survey sensitivity, but apart from the recent attribution of two near-infrared bands to ionized buckminsterfullerene (C_{60}^+ ; Ehrenfreund

and Foing 1997; Campbell et al. 2015; Cordiner et al. 2019), the vast majority of the DIB carriers are yet to be definitively assigned.

Overview

The diffuse interstellar band problem is among the longest-standing mysteries in astrophysics and has confounded the efforts of astronomers and chemists since the early twentieth century. At least some of the DIBs are probably attributable to large, carbon-based molecules. The resolution of this mystery is therefore likely to be of relevance to theories regarding the chemical composition of the interstellar medium, and the evolution of complex organic molecules in space, and may therefore be of relevance astrobiological studies. Due to their ubiquity in the dusty interstellar medium and their chemical stability in harsh environments, the DIB carriers constitute a possible source of cosmic carbon delivered to the early Earth and other planetary surfaces.

Basic Methodology

Diffuse interstellar bands are most readily detected and analyzed in high-resolution, high signal-to-noise optical spectra of hot stars (with spectral types O and B). The interstellar bands may be distinguished from stellar lines through multi-epoch observations of spectroscopic binary stars or by comparison with un-reddened standard stars. Variations in DIB spectra may be studied with respect to interstellar physical and chemical conditions in order to elucidate the nature of the carriers. The spectra are carefully compared with laboratory and theoretical data to test hypotheses regarding potential carriers. To assign a DIB carrier is very difficult because it requires a precise spectroscopic match between the DIB and the proposed carrier spectrum, at temperature, density, and radiation conditions matching those of the diffuse interstellar medium (ISM) where the carriers reside.

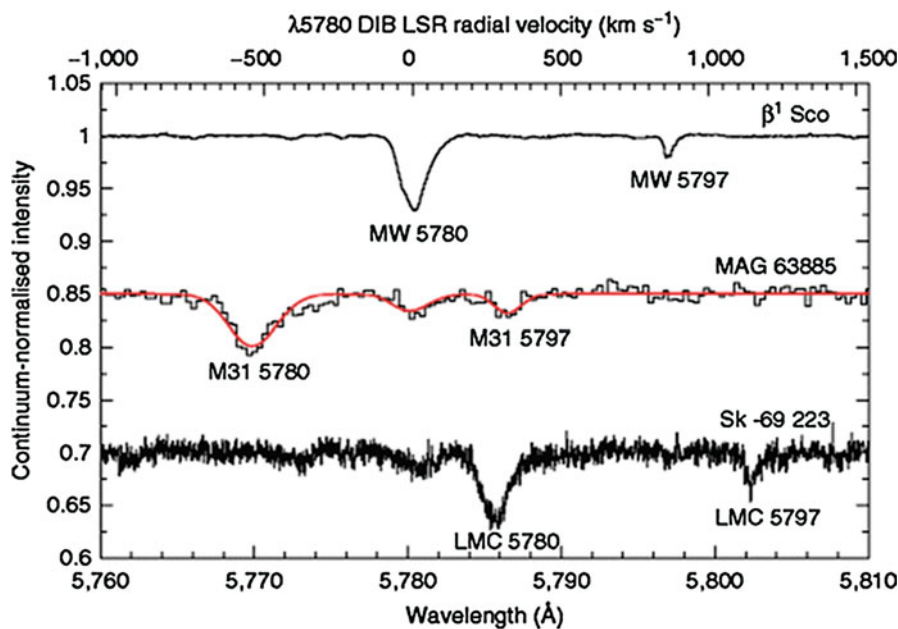
Key Research Findings

Observational Constraints on the DIB carriers

Throughout our Galaxy, the strengths of many of the diffuse interstellar bands are closely correlated with the amount of interstellar dust, which causes reddening of starlight. This suggests a possible origin in small solid particles that are known in the laboratory to exhibit broad optical absorption lines. Diffuse interstellar bands are observed in low-density regions of the interstellar medium whenever dust is present, and even in regions pervaded by intense, hard ultraviolet radiation that rapidly destroys all but the hardest molecular material. However, the correlation between DIB strengths and amount of dust is imperfect, with a scatter of about a factor of two about the mean for a given reddening (for the well-studied 5780 Å DIB; see Herbig 1993), which constitutes evidence against a solid-state carrier particle. In addition, the relative constancy of the DIB wavelengths across different astrophysical environments, the lack of any light polarization signature inside the DIB profiles and the lack of emission adjacent to the DIBs makes interstellar dust an unlikely carrier. Discussions on the viability of various carrier candidates are given by Herbig (1995), Snow (1995), and Sarre (2006).

Strong evidence that several DIBs are caused by gas-phase molecules is given by the observation of diffuse bands in emission in the Red Rectangle nebula (Sarre 1991; Fossey 1991). The wavelengths of these emission bands are close to those of a subset of relatively narrow diffuse interstellar bands, and the steep blue side and red-degraded tails are typical of electronic transitions in large, cold molecules.

Further evidence for large, carbonaceous carrier molecules is given by close examination of the shapes of many of the strongest diffuse interstellar bands, which reveal complex profiles with fine structure similar to that seen for various classes of large (gas-phase) molecules in the laboratory, including long carbon-chains, polycyclic aromatic hydrocarbons (PAHs) and fullerenes. The fine structure of these DIB profiles is observed to be variable, perhaps as a result of changes in the internal temperature, excitation,



Diffuse Interstellar Bands, Fig. 1 The 5780 and 5797 Å DIBs observed towards the Milky Way (MW) star β^1 Sco (top), the Andromeda (M31) star MAG 63885 (middle), and the Large Magellanic Cloud (LMC) star Sk -69,223 (bottom). Extragalactic DIBs are shifted from their

Galactic wavelengths due to the systemic Doppler motions of their host galaxies. (Data are from Cordiner et al. (2008); Cox et al. (2006). Spectra have been normalized and offset vertically for display. The MAG 63885 data have a fitted profile overlaid in red)

or isotopic composition of the carriers. DIB widths are consistent with carrier molecules containing at least about 20 atoms.

DIB strengths correlate well with the amount of neutral gas (such as H I and Na I), but not with the denser molecular gas traced by H_2 , as demonstrated by Herbig (1993). The DIB carriers are not, therefore, closely associated with the chemistry of those molecules that are typically most abundant in dense molecular environments where stars form and UV radiation fields are low. Indeed, various studies have shown that DIBs tend to be relatively weak inside dense molecular clouds (e.g., Adamson et al. 1991).

The fact that DIBs are observed most strongly in the relatively unshielded diffuse clouds with low extinction indicates that the carriers are resistant to destruction by UV radiation, so they cannot be small molecules, which tend to be easily photo-dissociated.

Observations of diffuse band properties in extreme environments may help elucidate the nature of the carrier. To that end, research into

the properties of diffuse interstellar bands outside the Milky Way is currently in progress (see for example, Cox et al. 2006; Cordiner et al. 2011), and although the DIB strengths show some deviation from the trends observed in the Milky Way (presumably as a result of the differing physical and chemical conditions in these environments, including the metallicity and interstellar radiation field strength), their overall spectrum is similar to that observed in our Galaxy. Two of the best-studied DIBs are found at rest wavelengths of 5780 and 5797 Å. Spectra of these DIBs are shown in Fig. 1, observed towards stars in the Milky Way, the Andromeda Galaxy, and the Large Magellanic Cloud.

DIB Carrier Candidates

Carbon is unique in its ability to form large, complex molecules. It is also one of the most abundant chemical species in the interstellar medium, where it exists in the form of neutral and ionized atoms, polyatomic molecules, aromatics, and dust grains. The fact that there are so many

different DIBs, each apparently caused by a different, large gas-phase molecule, is strongly suggestive that the molecular structures of at least some, and perhaps the majority of the carriers are composed predominantly of carbon.

Large, carbon-based molecules, such as polycyclic aromatic hydrocarbons (and the various classes of PAHs that have been modified, for example, by ionization, protonation, or dehydrogenation), are stable and resistant to destruction by UV radiation. Such aromatic molecules are believed to be abundant in the diffuse ISM where DIBs are strongest, and therefore represent an attractive class of possible carriers. This hypothesis has been reviewed by several authors (Crawford et al. 1985; Leger and D'Hendecourt 1985; Salama et al. 1999). Laboratory spectroscopy has shown that PAHs and their ions possess strong electronic transitions in the optical (e.g., Ruiterkamp et al. 2002; Tan and Salama 2006; Useli-Bacchitta et al. 2010). However, after extensive laboratory and theoretical studies of the spectroscopy of a plenitude of PAHs and related aromatics, no DIB has yet been assigned to any specific PAH-type molecule.

Following the suggestion of Kroto in the 1980s that C_{60} and other fullerenes might be present in the ISM (see Kroto and Jura 1992), Ehrenfreund and Foing (1997) examined the possibility of C_{60}^+ as the carrier of two DIBs in the near infrared. Thanks to recent advances in low-temperature laboratory spectroscopy, Campbell et al. (2015) confirmed a precise match between the laboratory and interstellar wavelengths of the two strongest (9577 and 9632 Å) C_{60}^+ bands. Detections of additional, weaker C_{60}^+ interstellar bands (at 9635 and 9428 Å) have also been claimed (Walker et al. 2015), so that the C_{60}^+ assignment now enjoys widespread acceptance. It should be emphasized, however, that obtaining a clean interstellar spectrum in this wavelength range is made difficult as a result of severe telluric contamination, as well as the presence of overlapping stellar features. The presence of the weaker C_{60}^+ bands was confirmed by Cordiner et al. (2019) using Hubble Space Telescope spectra of nine heavily-reddened Galactic sightlines. This places the assignment of interstellar C_{60}^+

beyond reasonable doubt, and confirms the chemical importance of fullerenes in diffuse environments. Other large, ionized, carbon-based molecules must now be considered as strong candidates to explain some of the remaining, unidentified DIBs.

Other related large molecules that have transitions in the optical include carbon nanotubes, “Bucky onions” and graphene sheets. Such stable, carbon-based molecules, which span the continuum of sizes from large molecules to small dust grains, may be injected into interstellar space in the outflows from dying stars, later to be incorporated into the next generation of star and planet-forming regions.

Theoretically, the addition or substitution of other atoms inside or at the periphery of aromatic carbon structures, either during the formation of the molecules or during their subsequent journey through the interstellar medium, results in molecules of biological relevance that may constitute potential DIB carriers. For example, the alkylation and oxidation of aromatic molecules in interstellar ice analogues (Elsila et al. 2006) results in the addition of methyl and hydroxyl side groups of the kind found in biomolecules. Heterocyclic aromatic organic compounds, including biologically important nitrogen heterocycles, are probably also present in the ISM and are theorized to be produced from reactions involving C_2H_2 and HCN in stellar outflows (Hudgins et al. 2005). Although they are less stable to UV degradation than PAHs, larger nitrogen heterocycles (containing at least 50 carbon atoms) should be able to survive in the diffuse ISM to act as possible DIB carriers.

Heteroatoms can also be added to large carbonaceous molecules in unusual ways to modify their optical properties. For example, iron atoms bond to the delocalized electron clouds above aromatic rings to form so-called organometallics. During the formation of fullerenes, metal atoms have a propensity to become trapped inside the carbon cage. Such species highlight the diversity of molecules that must be considered in the search for plausible DIB carrier candidates.

Some DIBs may be due to smaller organic molecules; close spectroscopic matches of the

8,037 Å DIB with CH_2CN^- and the 4,881 and 5,450 Å DIBs with $I\text{-C}_3\text{H}_2$ have been identified by Cordiner and Sarre (2007) and Maier et al. (2011), respectively. Radio astronomical absorption line studies of diffuse sightlines toward background quasars (Liszt et al. 2012, 2018) determined the presence of insufficient $I\text{-C}_3\text{H}_2$ for it to be a viable DIB carrier. However, the CH_2CN column density upper limit remains consistent with CH_2CN^- as a DIB carrier provided the anion-to-neutral ratio is in the range 17–50%.

Applications

Diffuse interstellar bands are clearly visible in reddened spectra of luminous objects throughout the universe. Once identified, the ubiquity of the DIBs will make them invaluable as probes of galactic interstellar chemistry and physics. Presently, their strengths are useful measures of the amount of interstellar dust in a sightline, and as tracers of a broad class of large organic molecules in space. The assignment of C_{60}^+ as carrier of two strong DIBs (and two weak DIBs) in the near infrared highlights the likely presence of a population of very large carbon-based molecules that have so far eluded detection, and thus sheds light on a previously unappreciated chemical complexity in the diffuse interstellar medium.

Future Directions

Further studies are required on how variations in interstellar physical and chemical conditions affect the DIB spectrum in order to further elucidate the properties of the carriers. In particular, the examination of peculiar or extreme interstellar environments in our Galaxy and beyond is likely to yield information in this regard. Continuing dedicated laboratory and theoretical efforts are necessary to determine the optical spectra of candidate carriers in order to make or rule out DIB assignments. Additional, detailed laboratory and theoretical studies of fullerenes and other

large molecules related to C_{60}^+ , are strongly justified to help unlock the remainder of the (still largely unsolved) DIB problem.

Cross-References

- [Aromatic Hydrocarbon](#)
- [Fullerene](#)
- [Interstellar Medium](#)
- [Interstellar Dust](#)
- [PAH](#)

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Diffusion

Sylvia Ekström

Observatoire Astronomique de l'Université de Genève, Faculté des Sciences, Université de Genève, Versoix, Switzerland

Definition

Diffusion refers to an irreversible transport process acting at the molecular scale and by which the density of a quantity X (e.g., the mass fraction of a chemical element) changes with time. The driving mechanism for the mixing is generally the density gradient ∇X , and the result is to homogenize the density throughout the considered region. The general form of the equation of diffusion can be written as

$$\frac{\partial}{\partial t}(\rho X) = \nabla \cdot (\rho D \nabla X)$$

with ρ the mass density of the medium (with units [mass length⁻³]) and D the diffusion coefficient (with units [length² time⁻¹]) or *diffusivity*. The characteristic timescale for diffusion is:

$$\tau_{\text{diff}} \propto \frac{\ell^2}{D}$$

with ℓ the characteristic size of the considered region.

Diffusion Potential

► [Membrane Potential](#)

3,7-Dihydropurine-2,6-dione

► [Xanthine](#)

Dihydroxyacetone

Didier Despois

Laboratoire d'Astrophysique de Bordeaux, CNRS-Université de Bordeaux, Bordeaux, France

Synonyms

[DHA](#); [HOCH₂COCH₂OH](#)

Definition

Dihydroxyacetone (IUPAC name 1,3-Dihydroxy-2-propanone) is one of the three simplest monosaccharides (“sugars”). Like the two others (L- and D-glyceraldehyde), it has three carbon atoms and is called a triose. But the molecule is symmetric and hence has no chiral center. It is present in cells where it plays a role in ATP production and

other biological pathways and is produced by ► [glycolysis](#). Dihydroxyacetone has been sought in the interstellar medium, but there is no convincing detection up to now.

Cross-References

- [Chirality](#)
- [Glycolaldehyde \(HOCH₂CHO\)](#)
- [Molecules in Space](#)

Diketopiperazine

Koichiro Matsuno
Nagaoka University of Technology, Nagaoka,
Japan

Keywords

Amino acids · Anhydride · Cyclic dimer ·
Oligopeptide

Synonyms

[Glycine anhydride](#)

Definition

A diketopiperazine is a cyclic dimer of two peptide-bonded ► [amino acid](#) molecules.

Overview

Amino acids, delivered via extraterrestrial delivery or synthesized by Miller-Urey-type chemistry, may have been available in abundance on the primitive Earth and may be abundant via these sources on other planets as well. Subsequent chemical evolution would require the synthesis of oligopeptides from the amino acid monomers. If a source of energy driving the formation of peptides is available in the form of geothermal heat exposed to the ocean as in hydrothermal

environments on Earth, diketopiperazines could quite easily be synthesized with the aid of the heat energy. The ease with which diketopiperazine is formed is a result of the presence of both a free amino group and a free carboxylic group residing in a single dipeptide once the latter is synthesized. A dipeptide having only one peptide bond linking its two units initially is unstable against transformation into a diketopiperazine with two peptide bonds in a closed-ring form.

At first sight, diketopiperazine may look like a dead end for chemical evolution since there is no room for making additional peptide bonds. However, this is a hasty conclusion. There is certainly a possibility for opening up the once-closed ring of peptide bonds when the surrounding conditions are changed. If the amount of diketopiperazine synthesized in the reaction solution becomes sufficiently high, the reaction of an amino acid molecule aminolyzing a diketopiperazine to form a tripeptide is actually confirmed experimentally (Nagayama et al. [1990](#)). The ring opening is due to the nucleophilic attack of an amino acid molecule's amino group on the diketopiperazine. The similar nucleophilic attack on diketopiperazine by an amino group of an oligopeptide is also possible, which results in an oligopeptide two amino acids longer.

Elongation of an oligopeptide through the aminolysis of diketopiperazine could play a significant role in the prebiotic evolution of oligopeptides, especially in the respect that the elongation could take place even in the absence of guiding templates. In other words, if there happens to appear a reaction environment in which both monomeric amino acids and diketopiperazines are supplied in abundance, a wide variety of oligopeptides could be synthesized. Some functional oligopeptides could be formed, even at the stage prior to the emergence of nucleotide or oligonucleotide molecules serving as reaction templates.

Cross-References

- [Amino Acid](#)
- [Hydrothermal Reaction](#)
- [Oligopeptide](#)
- [Origin of Life](#)

References and Further Reading

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Dimethyl Ether (CH₃OCH₃)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

CH₃OCH₃; Methoxymethane (IUPAC name)

Definition

Under standard conditions, dimethyl ether, the simplest ether, is a colorless gas. It is used in various chemical syntheses and as an aerosol propellant. Radio astronomers have found that dimethyl ether is commonly present in ► [hot cores](#), the dense and warm regions of ► [molecular clouds](#) where massive stars are forming.

Cross-References

- [Hot Core](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

Dinitrogen

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Keywords

Extreme UV · Photochemistry · Neutral atmosphere · Nitrogen (atomic) · Ammonia · Nitrogen cycle · Nitrogen fixation

Synonyms

[Molecular nitrogen](#); [N₂](#); [Nitrogen gas](#)

Definition

Dinitrogen is a chemical compound formed from the covalent bonding of two nitrogen atoms. It is a colorless, odorless gas at room temperature and pressure, which makes up approximately 78% of the Earth's atmosphere (by volume). It is also the major component of the atmosphere of ► [Titan](#) (one of Saturn's moons). Dinitrogen exhibits remarkable stability and is remarkably chemically inert. Liquid dinitrogen is widely used as a cryo-coolant (b.p. 196 °C at atmospheric pressure).

Overview

Dinitrogen (N₂) refers to ► [nitrogen](#) occurring in the diatomic form (its most stable form), also commonly called molecular nitrogen or nitrogen gas, in which two nitrogen atoms are linked by a triple covalent bond (which fills the Lewis electron rules; the two lone, nonbonding electron pairs, one on each N atom, lie at a quite low energy level). N₂ is commonly used as a laboratory or industrial cryo-coolant, as it has a boiling point of –196 °C and a melting point of –210 °C at atmospheric pressure.

Monoisotopic molecular nitrogen (N₂) is largely transparent to infrared and visible radiation because it is a homonuclear molecule and has no electric dipole moment to couple to electromagnetic radiation at these wavelengths. Significant absorption occurs in the extreme ultraviolet region, beginning around 100 nm. This absorption of UV light by N₂ is important in the Earth's upper atmosphere and the atmospheres of other planetary bodies.

Measurements of the energy required to form ► [ammonia](#) from N₂ and H₂ reveal that N₂ is unusually stabilized relative to its carbon analogue, ► [acetylene](#), because of the strength of the nitrogen-nitrogen triple covalent bond in N₂. This feature dominates the chemistry of dinitrogen, which is very unreactive at standard

temperature and pressure, thus making it (despite its abundance on Earth) a difficult-to-fix source of elemental nitrogen for living organisms.

The conversion of dinitrogen into biologically useful compounds (usually having N at an oxidation state other than zero) is called ► “[nitrogen fixation](#),” which is extremely important in both biological and abiological nitrogen cycling. Biological nitrogen fixation by bacteria in the root nodules of plants produces ammonia (Leigh and Dodsworth 2007). This N_2 to NH_3 reduction (which is by far the major natural nitrogen source for currently living organisms) is catalyzed by nitrogenase enzymes, the active sites of which contain Fe and Mo atoms, using energy derived from the hydrolysis of adenosine triphosphate and requiring anoxic conditions.

Abiotic nitrogen fixation occurs in nature through lightning in the atmosphere, which produces NO_x species (Hill et al. 1980), thanks to very high temperatures produced in the immediate vicinity of lightning bolts, followed by rapid thermal quenching that traps high-energy species, or through photocatalysis over various metal-oxide-containing minerals (Schrauzer et al. 1983). For comparison, uncatalyzed N_2 photochemistry in the Earth’s upper atmosphere is much less efficient. Precipitation often contains substantial quantities of ammonium and nitrate, much of it produced by lightning and other atmospheric electrical phenomena.

Decay of organisms and their waste products results in the formation of nitrate, which eventually may return to the atmosphere as dinitrogen through the microbial reduction of nitrate in a process known as “denitrification.”

Dinitrogen is thought to be a major reservoir of N in interstellar ► [molecular clouds](#), although it cannot be directly detected in these cold regions. Instead, its abundance is deduced from observations of its protonated derivative, N_2H^+ , which has strong pure rotational transitions in the 3-mm region of the spectrum. Besides the Earth, Saturn’s moon Titan is the only other known planetary body with a dense atmosphere mostly made of dinitrogen, the origin of which is not yet fully understood.

Cross-References

- [Ammonia](#)
- [Molecular Cloud](#)
- [Nitrogen](#)
- [Nitrogen Fixation](#)
- [Star Formation, Observations](#)

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Dione

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Dione, discovered in 1684 by Giovanni Domenico ► [Cassini](#), is an icy satellite of ► [Saturn](#). Its distance to Saturn is 377,000 km (or 6.2 planetary radii) and its diameter is 1,120 km. Its density is 1.5 g/cm^3 , which indicates a silicate and ice composition. Dione shows a large variety of structures, with cratered terrains, faults, and valleys, and albedo contrasts, indicating an early resurfacing and some internal past activity. The longest fissure, Palatine Chasma, is almost 400 km long and up to 8 km wide. A small satellite, Helene, is co-orbiting with Dione, located at its leading ► [Lagrangian point](#) (i.e., Helene is a Trojan moon with respect to Dione).

Cross-References

- [Saturn](#)

Dioxygen

Hiroshi Ohmoto

NASA Astrobiology Institute and Department of Geosciences, The Pennsylvania State University, University Park, PA, USA

Keywords

Atmospheric oxygen · Evolution of the atmosphere · Oxygen geochemical cycle · Oxygenic photosynthesis

Synonyms

Molecular oxygen; O₂; Oxygen (molecule)

Definition

Dioxygen is a molecule formed by the covalent binding of two oxygen atoms. At standard temperature and pressure, it occurs as a stable gas. O₂ condenses at 90.20 K and freezes at 54.36 K.

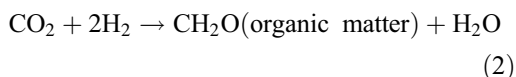
Overview

The present atmospheric level (PAL) of molecular oxygen (O₂) is 0.209 atm, corresponding to 3.7×10^{19} moles of O₂ in the atmosphere (Holland 1978). The dissociation of water (H₂O) in the atmosphere and shallow ►water by UV light is one source of atmospheric O₂:

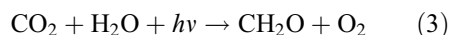


If hydrogen (H₂) can easily escape into space, such as on Mars where the gravity is much less than on Earth, O₂ can continue to accumulate in the atmosphere by Reaction (1) alone.

On Earth, a significant production of O₂ requires a continuous consumption of H₂ in the reduction of ►carbon dioxide (CO₂) by organisms:



When Reactions (1) and (2) occur simultaneously within cells of organisms in the photic zone, such as ►cyanobacteria, ►algae, and plants, it is better known as oxygenic ►photosynthesis:



Currently, terrestrial and marine organisms each produce about 3×10^{15} moles/year of O₂ (and also of organic C) (Holland 1978). Essentially, all of the organic carbon and O₂ produced by terrestrial organisms is converted back to CO₂ and H₂O by the reverse of Reaction (3). Thus, terrestrial organisms have not contributed to the long-term (>1000 year) accumulation of atmospheric O₂. The long-term input of O₂ to the atmosphere has been attributed mostly to the burial of organic matter (and some to the burial of pyrite) in marine sediments, which prevents the reverse Reaction (3) and causes the accumulation of O₂ in the atmosphere. About 0.3% of the total organic C produced in the oceans is buried in sediments to provide about 10^{13} moles/year of O₂ as the long-term atmospheric input (Holland 1978; Lasaga and Ohmoto 2002). The long-term output (consumption) of atmospheric O₂ has been carried out primarily by (a) the oxidation of reducing volcanic gases (e.g., H₂, ►carbon monoxide (CO), ►methane (CH₄), ►hydrogen sulfide (H₂S), and sulfur dioxide (SO₂)) and (b) the weathering of reduced compounds in rocks (e.g., organic C, ferrous ►iron, and reduced ►sulfur) (Lasaga and Ohmoto 2002; Kasting 1987). Today, the long-term fluxes of O₂ production and consumption appear to be balanced (Holland 1978; Lasaga and Ohmoto 2002).

The atmospheric *p*O₂ level before the emergence of cyanobacteria at time T₁ has been estimated to be $\sim 10^{-12}$ PAL, in which the reducing gases (H₂ and CH₄) were more abundant than O₂ (Kasting 1987). O₂ became more abundant than reduced gases at *p*O₂ > $\sim 10^{-5}$ PAL (Pavlov and Kasting 2002) at

Dioxygen, Table 1 Theories for the oxygenation of the atmosphere and oceans

Time	T ₁	T ₂	T ₃	T ₄
Atmospheric <i>p</i> O ₂ Level (PAL)	~10 ⁻¹²	~10 ⁻⁵	~5%	~50%
Oxygenic Photoautotrophs				➤
Oxic Atmosphere (<i>p</i> O ₂ > <i>p</i> H ₂)				➤
Oxic Photic Zone				➤
Oxic Deep Oceans				➤
Time before Present (Ga) (Theory 1)	~2.7	~2.4	~2.4	~0.6
Time before Present (Ga) (Theory 2)				>3.5

T₂, the photic zone became suitable environments for aerobic organisms and eukaryotes at *p*O₂ > ~5% PAL (Jahnke and Klein 1983) at T₃, and deep (as well as shallow) oceans became oxygenated at *p*O₂ > ~50% PAL (Kasting 1987; Sarmiento 1992) at T₄ (see Table 1).

The theory accepted by most astrobiologists postulates the ages of ~2.7 Ga (T₁), ~2.4 Ga (T₂ and T₃), and ~0.6 Ga (T₄), and a subsequent gradual rise of atmospheric *p*O₂ to the present level (Kasting 1987; Pavlov and Kasting 2002; Anbar and Knoll 2002). However, some mineralogical, geochemical, and paleontological observations (Ohmoto 2004; Hoashi et al. 2009) suggest that the placements of T₁–T₄ may have occurred before 3.5 Ga and that the atmospheric *p*O₂ level has been maintained within a range of 0.6–2 PAL since T₁ by a series of negative feedback mechanisms (Lasaga and Ohmoto 2002).

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Diphosphate

► Pyrophosphate

Diplogen

► [Deuterium](#)

Dirac, Paul

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Paul Adrien Maurice Dirac (1902–1984) was a British quantum physicist awarded in 1933 with the Nobel Prize (which he shared with Schrödinger) for the “discovery of new productive forms of atomic theory.”

Dirac established, independently of Fermi, the statistical laws (now called Fermi-Dirac statistics) that ruled fermions, particles systems subject to the Pauli exclusion principle. His scientific work led to introduce the concept of antimatter, which plays a central role in modern particle physics and cosmology.

In 1932 Dirac was appointed Lucasian professor of mathematics at the University of Cambridge, which was also Newton’s chair. Stephen Hawking was Dirac’s successor in the Lucasian chair.

Cross-References

► [Fermi, Enrico](#)

Directed Evolution

► [Evolution, In Vitro](#)
► [Evolution, Molecular](#)

Direct-Imaging, Planets

Marc Kuchner
Exoplanets and Stellar Astrophysics Laboratory,
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

Direct imaging of planets refers to the effort to detect and study exoplanets from the light emitted or scattered by the planets themselves, as opposed to inferring the existence and properties of planets from their effects on the images or spectra of the stars they orbit. Directly imaging an exoplanet, that is, collecting light from the planet and distinguishing it from light from the host star, which requires special instruments to overcome distortions caused by conventional telescope optics and the atmosphere. The challenge of developing these instruments – coronagraphs and interferometers with adaptive optics systems – has caused direct imaging to lag behind other exoplanet detection techniques. But direct imaging offers access to planets with host stars and orbital properties that make them unreachable by other techniques, and a means to find Earth-like planets around nearby stars and characterize their atmospheres. The few planets that have been detected by direct imaging so far tend to be hot, young giant planets, located far (>20 AU) from their host stars. The presence of such objects presents a challenge for some theories of planet formation.

History

In 2005, Chauvin et al. ([2005](#)) imaged a ~ 5 Jupiter-mass companion to a nearby brown dwarf using the VLT/NACO. Imaged planets have also been reported in the HR 8799 and Fomalhaut systems, though the masses of these objects remain uncertain and some of them may

turn out to be in the brown dwarf, rather than planet, mass range. The directly imaged planet with the closest orbit (8 AU) to its star has been reported in the Beta-Pic system by Lagrange et al. (2010).

Cross-References

- [Adaptive Optics](#)
- [Beta Pictoris b](#)
- [Brown Dwarf](#)
- [Coronagraphy](#)
- [Exoplanets, Discovery](#)
- [Interferometry](#)
- [VLT](#)

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Discovery of Extraterrestrial Life

Klara Anna Capova
Department of Anthropology, Durham University,
Durham, UK

Acronyms

- | | |
|------|--|
| METI | Messaging to Extraterrestrial Intelligence |
| SETI | Search for Extraterrestrial Intelligence |
| SETL | Search for Extraterrestrial Life |

Definition

The discovery of extraterrestrial life, a solid scientific evidence that either past or present life forms exist or have existed elsewhere in the

universe, is often referred to as one of the greatest discoveries of science. Such evidence for extraterrestrial life either within the Solar System or exoplanetary systems would answer the longstanding questions about whether or not we are alone in the universe, and about where we have come from. Given its philosophical, societal, and cultural importance, the anticipated global reach of and reaction to the discovery are profound and world-view changing.

Overview

Likely inspired by the historical accounts of the first contact between societies on Earth, the opinions about how the discovery of extraterrestrial life will unfold, tend to favor scenarios that involve a profound cultural shock, followed by an inevitable and irreversible societal change, and in some cases, even armed conflict. The explanation for such views is in the assumption that an intelligent, sentient, advanced life-form – a civilization similar to ours – will be discovered. Here, it plays an important part in the works of science fiction, most notably H. G. Well's novel "War of the Worlds" from 1897 (first published in 1898). Wells described the invasion of an alien, technologically superior race from Mars as a catastrophic event with global impact followed by a collapse of social order. This captivating story became a classic piece of literature and a landmark work of the science fiction genre. In 1939, when Orson Welles adapted the novel for a radio broadcast, the on-air dramatization of an alien attack caused a nationwide panic amongst at least one million of its listeners in the US (Cantril et al. 1966). To date, these fictional stories are reflected in the popular imaginations of what the discovery of extraterrestrial life could be like.

History of science shows us that the scientific search for life beyond Earth as a systematic activity dates to the second half of the twentieth century. Marking the era of "searches," the scientific community around American astronomers Carl Sagan and Frank Drake has undertaken the first

steps in active search for life beyond earth known as METI – Messaging to Extraterrestrial Intelligence. In 1972, NASA launched Pioneer 10 spacecraft carrying a small plate, now known as Pioneer Plaque, with engraved symbols intended for an intelligent receiver. In 1974, a radio transmission was sent from Arecibo radio telescope with the “1979 bits of information” carrying basic information about Earth and its inhabitants. The Voyager Golden Record (1977), a phonograph record containing a selection of photos, music, sounds, and greetings from Earth, was attached to Voyager 1 and Voyager 2 space probes that have since become the cultural icons of the Space Age. It should be noted that, historically, the first message sent to outer space was the “Message to Venus” in 1962 – composed of three Russian words in the Morse code sent from the former USSR. Gradually, METI has become an international activity.

Another method of the search for intelligent life-forms is SETI: Search for Extraterrestrial Intelligence that was formed in the 1980s (for more see SETI, History of, and SETI). Also called “passive search,” SETI activities involve coordinated effort to find technological civilizations that may exist elsewhere in the universe. By the use of radio technology, SETI’s activities focus on detecting the scientific evidence of past or present technology: techno-signatures. Both METI and SETI presume an intelligent, curious, advanced, scientifically literate, and possibly humanoid extraterrestrial life-forms, with technologies capable of intercepting (METI) or transmitting (SETI) a message.

Astrobiology, in contrast, operates with a distinctly different concept of extraterrestrial life and we have observed a paradigm change in the scientific search for life beyond Earth. The shift from searching for complex, sentient, intelligent life (METI, SETI) to searching for origins of life or life in its basics, as described by American anthropologist Helmreich: “No longer culture, but nature. No extraterrestrial messages but other-worldly organisms.” (Helmreich 2009). Such life – or even suitable conditions for it to emerge and evolve – could be found on Mars, other planets of the Solar System, or on exoplanets.

The new paradigm ushers in a different type of societal response to the discovery. Work entitled “Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH 84001” published in 1996 by David S. McKay is a recent example of how the discovery unfolds in a real-life situation. The chain structures revealed in the ALH 84001 meteorite originating from Mars led the scientific team to a conclusion that the structures might be the evidence for a primitive life on early Mars (McKay et al. 1996). Despite the nonconclusive evidence, the publication was followed by a keen interest by major news networks, public discussions, and recognition of its societal importance. This included the US President Clinton’s Statement regarding Mars meteorite discovery and potential far-reaching implications of the possibility of life elsewhere.

Given the immense cross-cultural differences within humankind, it is reasonable to assume that the societal response to the discovery of extraterrestrial life will not be globally uniform or universal. Rather, a variety of cultural, social, historical, religious, and even political factors would shape the short-term effects and long-term impacts. The deciding factors as to what the societal reaction will be like are in the very characteristics and attributes of the life-forms newly discovered.

Cross-References

- ▶ [ALH 84001](#)
- ▶ [Astrobiology](#)
- ▶ [Evidence in Astrobiology](#)
- ▶ [Exoplanets, Discovery](#)
- ▶ [Life, Definition of](#)
- ▶ [Sagan Carl](#)
- ▶ [SETI](#)
- ▶ [SETI, History of](#)

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Cross-References

- [Bioburden Reduction](#)
- [DHMR](#)
- [Inactivation](#)
- [Pasteurization](#)
- [Planetary Protection](#)
- [Sterilization](#)

Disk Instability, Model for Giant Planet Formation

Yann Alibert¹ and Ravit Helled²

¹Space Research and Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland

²Geophysical, Atmospheric and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

Keywords

Planet formation · Protoplanetary disk · Q (Toomre parameter)

Synonyms

[Gravitational instability \(Model for Giant Planet Formation\)](#)

Definition

The disk instability model suggests that ► [gas giant planets](#) form directly as a result of (local) gravitational instabilities in the ► [protoplanetary disk](#). Numerical simulations have shown that clumps of various masses can form in sufficiently gravitationally unstable disks. Protoplanetary disks can become gravitationally unstable if they are sufficiently cool and/or massive. The condition for gravitational instability can be determined from the value of the Toomre parameter Q . Protoplanetary disks will be unstable for $Q < \sim 1$. Once a local instability occurs, a gravitationally bound sub-condensation region (clump)

Disinfection

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

Disinfection is a process performed to reduce (by removal or inactivation) the number of viable microorganisms present in an environment (gas, liquid, surface, etc.). Typically, a disinfection approach is process-driven, rather than bioburden outcome-driven, and may use less precise process control parameters and bioburden reduction verification than Pasteurization or sterilization procedures. In planetary protection, disinfection may be a precursor process to a more controlled sterilization process.

is created. If the cooling time in this region of the disk is shorter than (or comparable to) the dynamical time, the fragment contracts, and eventually evolves to become a giant planet. The masses and survivability of clumps formed in the disk instability model are still being investigated. In addition, it is yet to be determined whether the forming objects significantly change their masses, compositions, and orbital locations after they form.

Cross-References

- [Gravitational Instability](#)
- [Planet Formation](#)
- [Q \(Toomre Parameter\)](#)

Dismutation

- [Disproportionation](#)

Disproportionation

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Synonyms

[Dismutation](#)

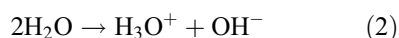
Definition

In chemistry, a disproportionation reaction is a type of chemical reaction in which two identical compounds react to form two or more new compounds of a dissimilar type. Usually, these involve reaction compounds containing an element in the same

oxidation state reacting to form two compounds containing that element, but with both higher and lower oxidation states, for example, in the Cannizzaro reaction with formaldehyde:



An example of a disproportionation reaction in which no redox chemistry takes place is the ionization of water:



Cross-References

- [Fractionation](#)
- [Redox Potential](#)

Dissimilative Metabolism

Juli Peretó
 Institut Cavanilles de Biodiversitat i Biologia
 Evolutiva, Universitat de València, València,
 Spain

Definition

Dissimilative ► [metabolism](#) is the process by which an inorganic compound (NO_3^- , SO_4^{2-} , Fe^{3+} , CO_2) is reduced because it is used as an ► [electron acceptor](#) for ► [anaerobic respiration](#). Dissimilative metabolism is conceptually very different from the ► [assimilative metabolism](#) by which the same compounds are reduced for its use as nutrient source. There are important differences between both types of metabolism. In the dissimilative metabolism, a large amount of electron acceptor must be reduced to guaranty the generation of sufficient energy, and the product is excreted into the environment, while in the ► [assimilative metabolism](#), only enough amount of the compound is reduced to satisfy the needs for cell growth, and the products are normally converted into cell material.

Cross-References

- ▶ [Anaerobic Respiration](#)
- ▶ [Assimilative Metabolism](#)
- ▶ [Electron Acceptor](#)
- ▶ [Metabolism](#)
- ▶ [Reduction](#)
- ▶ [Sulfate Reducers](#)

Dissimilatory Nitrate Reduction to Ammonium (DNRA)

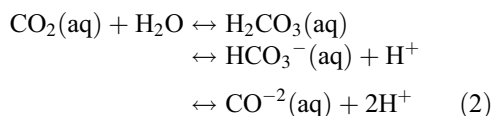
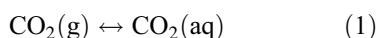
- ▶ [Nitrate Reduction](#)

Dissolved Inorganic Carbon Equilibrium

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

The dissolved inorganic carbon equilibrium is the equilibrium between CO_2 (g), HCO_3^- (aq), H_2CO_3 (aq), and CO_3^{2-} (aq) when CO_2 is dissolved in water. The equilibrium is dependent on the pressure of the gas, the overlying head-space and gas partial pressure, the solution temperature, the ▶ [pH](#) of the solution, and the concentration of various solutes such as electrolytes. It is significant because dissolved carbonate species may have a significant impact on the pH of natural waters:



Cross-References

- ▶ [pH](#)

Distal Impact Ejecta

- ▶ [Spherules](#)

Distillation, Rayleigh

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale
Supérieure de Lyon, Lyon Cedex 7, France

Definition

This term applies to chemical and isotopic ▶ [fractionation](#) during phase transformation when one phase progressively evolves from another of limited size and is continuously removed. Upon evaporation of an alcoholic solution, ethanol concentrates into the first vapor extracts and, as a result of the finite original supply, becomes depleted in the residual liquid. Distillation, which bears the name of “Rayleigh distillation” from Lord Rayleigh who provided the original equation, greatly enhances fractionation over exchange at equilibrium. Distillation as described for spirit amounts to fractional evaporation: changing phases leads to fractional condensation (rain), fractional crystallization (magmatic differentiation), fractional melting, etc.

Cross-References

- ▶ [Isotopic Fractionation \(Planetary Process\)](#)

Disulfide Bond

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogaya-ku, Yokohama, Japan

Synonyms

[SS-bond](#)

Definition

A disulfide bond is a covalent bond between two sulfur atoms (-S-S-) formed by the coupling of two ► [thiol](#) (-SH) groups. ► [Cysteine](#), one of the 20 protein amino acids, has a thiol group in its side chain and can easily be dimerized to ► [cysteine](#) in aqueous solution by forming a disulfide bond. In many protein molecules, disulfide bonds between cysteine residues are essential for protein folding. Disulfide bonds in proteins are cleaved by heating or by the addition of reducing reagents, which leads to protein denaturation.

Cross-References

- [Amino Acid](#)
- [Cysteine](#)
- [Cystine](#)
- [Protein](#)
- [Thiol](#)

Diversity of Life

- [Biodiversity](#)

Division

- [Phylum](#)

Dixon Island Formation, Western Australia

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The Dixon Island Formation is a 3.2-Ga-old sequence of lightly metamorphosed but highly silicified cherts, organic-rich black shales and tuffs belonging to the Cleaverville Group and located in the ► [Pilbara Craton](#), Western Australia. The unit is thought to have formed through shallow marine hydrothermal alteration of Archean ► [oceanic crust](#). Possible microbial mats and bacteria-like structures have been observed and are considered by some to be traces of early life. The sequence was the target of the Dixon Island-Cleaverville Drilling Project (DXCL-DP). The most important objective of the DXCL-DP was to understand the nature of the Middle Archean marine environment, influenced by hydrothermal activity, through detailed and systematic study of fresh drill core samples.

Cross-References

- [Archean Drilling Projects](#)
- [Biosignature](#)
- [Pilbara Craton](#)

DLR, Germany

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[German Aerospace Center](#)

Definition

The organization later called the DLR originated in 1969 as the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR; “German Test and Research Institute for Aviation and Space Flight”); it was formed from the merger of several previously existing institutions. In 1989, the DFVLR was renamed with the initials DLR and in 1997 was merged with the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) to create the present DLR, the Deutsches Zentrum für Luft- und Raumfahrt, referred to as the German Aerospace Center in English language publications.

History

DLR’s mission comprises research aimed at protecting the environment; development of environmentally friendly technologies; and exploration of the Earth, the Solar System, and space, which leads to new knowledge about the origin and development of the Solar System, its planets, and, hence, about the emergence of life. The space activities include Germany’s national space program, and Germany’s contributions to the ► [European Space Agency \(ESA\)](#) as well as the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Germany is a major contributor to the ESA mandatory program and also to the optional programs.

Over the years, Germany has been able to implement more than 100 space missions both nationally and within the framework of international cooperation. The DLR’s programs have involved planetary research, manned space flight, and related Earth-based research and development. The DLR has facilities at 14 locations in Germany: Augsburg, Berlin, Bonn, Braunschweig, Bremen, Cologne (headquarters), Goettingen, Hamburg, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Stuttgart, Trauen, and Weilheim.

Cross-References

► [ESA](#)

DNA

Irena Mamajanov and Nicholas V. Hud
School of Chemistry and Biochemistry, Georgia
Institute of Technology, Atlanta, GA, USA

Keywords

Adenine · Adenosine · Cytidine · Cytosine ·
Deoxyribose · DNA · Guanine · Guanosine ·
Phosphate · Purine · Pyrimidine · Ribose ·
RNA · Thymidine · Thymine

Synonyms

[Deoxyribonucleic acid](#); [Polydeoxyribonucleic acid](#)

Definition

DNA (deoxyribonucleic acid) is the polymer that stores the genetic information of all living cells and many viruses. DNA is a linear polymer of phosphodiester-linked 2′-deoxyribose sugars with heterocyclic bases (nucleobases) attached to the 1′ carbon of the 2′-deoxyribose sugars. The four nucleobases of DNA are adenine (A), guanine (G), cytosine (C), and ► [thymine \(T\)](#). DNA within a living cell primarily exists in the form of a double helix in which two polymer strands are held together by Watson-Crick base pairs (i.e., A-T and G-C base pairs).

Overview and Key Research Findings

DNA was discovered by Johann Friedrich Miescher in 1863. He separated the so-called nuclein from cells and showed that it was a previously uncharacterized phosphorus-containing material and hypothesized its involvement in heredity (Dahm 2005). It was not until 1944 that this hypothesis was confirmed, when Oswald Avery, Colin MacLeod, and Maclyn McCarty demonstrated that DNA taken from a disease-causing strain of the bacterium *Streptococcus*

pneumoniae permanently transformed a non-virulent form of the organism into a virulent one (Avery et al. 1944). Additional evidence was provided in 1951 by Alfred Hershey and Martha Chase, who demonstrated that when the bacteriophage T2 infects *Escherichia coli*, it is the DNA of the bacteriophage, not its protein coat, which enters the host cell and provides the genetic information for bacteriophage replication (Hershey and Chase 1951).

The double-helix structure of DNA was first proposed by James D. Watson and Francis Crick in 1953 (Watson and Crick 1953). The Watson-Crick model was largely based on X-ray fiber diffraction data of DNA obtained by Rosalind Franklin and Raymond Gosling (Franklin and Gosling 1953) and subsequent diffraction patterns obtained by Maurice Wilkins and coworkers (Wilkins et al. 1953). Biochemical information obtained by Erwin Chargaff regarding the 1:1 stoichiometry of G:C and A:T in DNA extracted from a wide range of organisms also facilitated Watson and Crick's elucidation of the double-helix structure (Elson and Chargaff 1954). Crick, Watson, and Wilkins shared the 1962 Nobel Prize in Physiology and Medicine for their contributions to determining the structure of the DNA double helix.

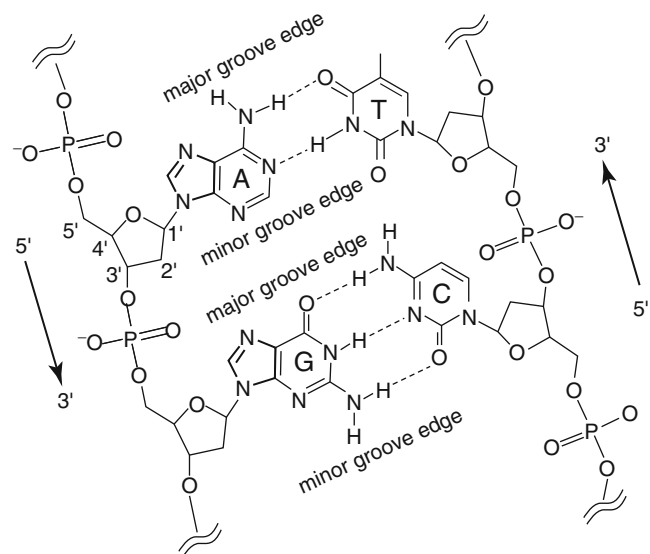
DNA Structure

The *primary structure* of DNA is generally described in terms of nucleotides, the molecular unit defined as a nucleobase connected by a glycosidic bond at the 1' position of a phosphorylated 2'-deoxyribose sugar. Along the backbone of a DNA polymer, or strand, nucleosides are connected to each other through the phosphate groups. A phosphodiester linkage exists between the 3' position of each ► nucleoside and the 5' position of the next nucleoside along a given DNA strand (Fig. 1). The order of deoxyribose nucleotides (dA, dG, dC, and dT) along a strand is the chemical basis for coding the genetic information contained within a DNA polymer. A single ► nucleotide that is not phosphorylated, that is, only the base connected to the sugar, is referred to as a nucleoside.

The repeating 3'-phosphate-5' linkages between nucleotides provide the polymer directionality for DNA that is inseparable from its synthesis and function. For example, DNA is synthesized by natural polymerases in the 5'-3' direction. That is, a DNA polymer being extended by a polymerase will have new nucleotides added to the terminal nucleotide at the free 3'-OH group.

The *secondary structure* of DNA within living organisms is predominantly a double helix formed by two strands with *complementary* nucleotide

DNA, Fig. 1 The chemical structure of DNA which illustrates Watson-Crick base pairing and the directionality of the deoxyribose-phosphodiester backbone



sequences, that is, sequences that support Watson-Crick base pairing along their entire lengths. The two strands of a Watson-Crick double helix run in opposite directions (as defined by the directionality of their polymer backbones) (Fig. 1). A Watson-Crick duplex is therefore said to have an antiparallel arrangement of its two strands. While complementary hydrogen bonding between nucleobases (i.e., A with T; G with C) provides specificity for base-pair formation, interstrand nucleobase stacking interactions apparently provide the most significant energetic contribution to helix stability (Yakovchuk et al. 2006).

The predominant helical structure of DNA within a cell and in vitro at high humidity (e.g., above 95% relative humidity) is known as the B-form helix (Fig. 2). The B-form helix is approximately 2 nm wide with a right-handed twist and a helical rise of around 3.4 nm per ten nucleotides. One complete turn of the B-form helix therefore consists of 10–10.5 base pairs. The B-form helix has two grooves that are of different widths and depths (Fig. 2). The wider groove is referred to as

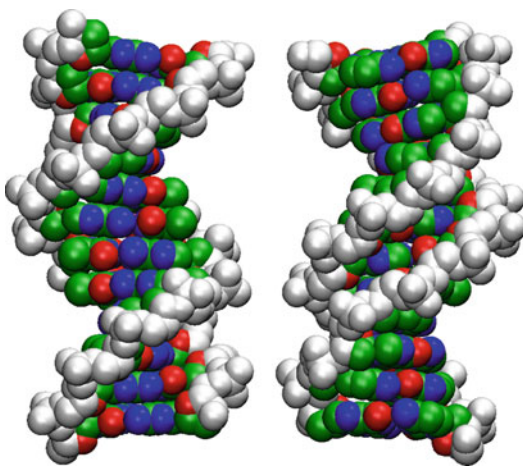
the *major groove* and the narrower one as the *minor groove*.

Under low humidity/dehydrating conditions, duplex DNA will undergo a structural transition from the B-form to the A-form helix (Saenger 1984), which is the same helical structure associated with duplex ► RNA. The A-form helix is also right handed but with a helical repeat of approximately 11 base pairs per helical turn. The width and depth of the major and minor grooves of the A-form helix also differ significantly from the B-form helix.

DNA Coding of Proteins

The genetic information that codes for the amino acid sequence of a particular protein is *transcribed* from a DNA polymer by a DNA-directed RNA polymerase into messenger RNA (or mRNA). The information contained in the mRNA is then *translated* into a protein by the ► ribosome, tRNA molecules, and other proteins necessary for protein synthesis and the overall process of translation (Kornberg 2007).

The transcription of many genes in eukaryotic cells and bacteria is regulated by the binding of proteins known as *activators* and *transcription factors* to specific DNA sequences that are located “upstream” from the protein-coding region of a gene (Kornberg 2007). These gene-regulating proteins often recognize their target sequence through complementary hydrogen-bonding interactions between amino acid side chains and the edges of the nucleobases that are accessible in the major and minor grooves of duplex DNA. The major groove appears to be the preferred groove for sequence recognition by DNA-binding proteins due to the greater dissimilarity between the pattern of hydrogen donor and acceptor groups of the major groove base edges, in comparison to the minor groove (Seeman et al. 1976). Some transcription factors are able to differentiate between similar DNA sequences without direct contact between the protein and the DNA bases that differ between two otherwise identical DNA sequences. Such protein-DNA recognition is referred to as *indirect readout* and can have its physical origins in the flexibility of a nucleic acid sequence, water-



DNA, Fig. 2 A space-filling model of a 12 base-pair duplex of B-form DNA. (*Left*) The model orientated such that reader is looking into the major groove at the midpoint of the duplex. (*Right*) The same model, but orientated such that the reader is looking into the minor groove at the midpoint of the duplex. Backbone atoms are shown in white, base carbon atoms in green, base nitrogen atoms in blue, and base oxygen atoms in red. For clarity, hydrogen atoms are not shown

mediated contacts, and sequence-specific cation localization (Watkins et al. 2010).

DNA Packaging and Supercoiling

The amount of DNA necessary for coding all aspects of a living organism has necessitated the evolution of highly efficient DNA packaging mechanisms. For example, the human **genome** contains almost three billion base pairs of DNA per haploid genome. If the DNA contained within the diploid genome of a human cell was fully extended, it would have a linear measurement of nearly 2 m. Given that the diameter of a typical human cell nucleus is around 2 μm , genomic DNA must be packaged in a highly condensed state. In eukaryotic cells, the packaging of DNA is accomplished by a group of evolutionarily conserved and positively charged proteins that form the histones, octomeric protein assemblies that are each wound by 145 base pairs of DNA (Luger et al. 1997).

The genomic DNA of bacterial cells is packaged by a combination of molecular and physical factors, including supercoiling, molecular crowding, polyamines, and protein binding (Zimmerman 2006). Supercoiling refers to the over twisting of a topologically constrained DNA duplex (a covalently closed circle of duplex DNA is the simplest example of a topologically constrained DNA molecule). Much like a rubber band that has been rolled and twisted, a supercoiled and topologically constrained DNA molecule will tend to collapse onto itself. Molecular crowding agents and positively charged polyamines also promote the collapse of DNA into a highly condensed state within bacterial cells by promoting the general phenomenon of DNA condensation (i.e., the propensity for DNA to interact with itself in preference to the surrounding solvent) (Bloomfield 1996). It appears that two highly covered bacterial proteins known as HU and IHF facilitate DNA packaging by promoting local bends in the DNA double helix (Sarkar et al. 2007).

DNA Triplexes and Quadruplexes

DNA double helix formed between a homopurine strand (i.e., only A and G nucleobases)

and a homopyrimidine strand (i.e., only T and C nucleobases) under certain conditions (e.g., high salt or solutions containing Mg^{2+}) can form a triplex secondary structure with a third strand bound in the major groove (Frank-Kamenetskii and Mirkin 1995). This third strand forms the so-called Hoogsteen pairs with the major groove edges of the **purine bases** of the Watson-Crick duplex. There are two possible triplexes: pyrimidine triplexes, in which the third strand is composed only of pyrimidine nucleobases, and purine triplexes, in which the third strand is composed only of purine nucleobases. In the case of pyrimidine triplexes, the C nucleobases require protonation in order to form a Hoogsteen pair with the G bases. Because the pK_a of the C nucleobase is around 4.5, pyrimidine triplexes are most stable under slightly acidic conditions. Triplex-forming nucleotides have been the object of intensive study as potential therapeutic agents for the modulation of gene expression activity in vivo (Frank-Kamenetskii and Mirkin 1995).

G-rich DNA sequences (e.g., TGGGGT) are capable of forming four-stranded secondary structures called G-quadruplexes that are held together by G-tetrads in which the G nucleobases are in a planar, cyclic Hoogsteen hydrogen-bonded arrangement (Davis 2004). These structures are further stabilized by cation coordination by the guanine O6 carbonyl groups in the center of the G-tetrad. G-quadruplexes are potentially formed in vivo by a large number of G-rich DNA sequences within the human genome (Huppert and Balasubramanian 2007), which has been taken as evidence that G-quadruplexes are involved gene regulation.

DNA Interactions with Water and Cations

DNA-water and DNA-cation interactions are intimately associated with DNA structure. The high dielectric constant of water and cations screen the electrostatic repulsions that would exist between phosphate groups across the major and minor grooves. The screening of these repulsions by cations is reflected by the observed dependence of DNA duplex stability on the concentration of

salt in a solution, as well as the valency of the cation (e.g., monovalent versus divalent). As mentioned above, the role that hydration plays in regulating DNA helical structure is illustrated by the B- to A-form structural transition that occurs below 95% relative humidity.

Although it had long been postulated that DNA secondary structures have an absolute requirement for water, recent studies show that water is not the only media able to sustain native DNA structures. A new class of water-free deep eutectic solvents has been reported to sustain duplex, triplex, and G-quadruplex structures (Mamajanov et al. 2010).

The Origin of DNA

The discovery of catalytic RNA molecules, or ribozymes, and the ever-increasing evidence that RNA is the central polymer of life have created great enthusiasm for the hypothesis that RNA once carried out both the information storage needs are now satisfied by DNA as well as the catalytic tasks now accomplished by protein enzymes. There are additional reasons to suspect that RNA preceded DNA (Dworkin et al. 2003), including the appearance of ► [ribose](#) in model prebiotic reactions and the presumed lack of a prebiotic route to deoxyribose; activated ribonucleotides polymerize more readily than activated deoxyribonucleotides; the biosynthesis of deoxyribonucleotides is through ribonucleotides in extant life. Ribosides are subunits of many coenzymes, some of which have prebiotic syntheses.

The much greater chemical stability of DNA under conditions of neutral and basic pH, as compared to RNA, would have provided a strong evolutionary advantage for any organism that developed a means to synthesize DNA for use in long-term information storage. In contemporary life, ► [ribonucleotide](#) reductases are responsible for converting ribonucleotides into deoxyribonucleotides through a free radical-mediated process. The lack of known ribozymes that can carry out such reactions has been suggested as evidence that DNA must have appeared only after coded proteins were part of life (Dworkin et al. 2003). However, it has more recently been argued that

RNA could have synthesized DNA by a non-reductive mechanism (e.g., via aldol condensation chemistry), which could have allowed DNA to appear before coded proteins (Burton and Lehman 2009).

Basic Methodology

See ► [Nucleic Acids](#)

Applications

Genetic engineering, the artificial manipulation of genetic material for the production of natural and novel proteins, is a major branch of biotechnology that would not exist without our fundamental understanding of DNA structure and its use within living cells. Examples of genetic engineering applications in medicine include bacteria that produce human insulin and proteins for viral vaccines. In addition, DNA research has given rise to bioinformatics, a field that utilizes information technology, from data storage to DNA sequence analysis, to provide insights regarding biological evolution, from recent events to the root of the tree of life (Garrett and Grisham 2004). Finally, DNA is now routinely used in forensic science, with the help of PCR and bioinformatics, to identify suspects, as well as victims, and to provide what can be the most critical evidence in support of a conviction or acquittal.

Future Directions

Nucleic acid research is constantly moving forward with deeper insights into the forces that govern DNA structure and how DNA functions within living cells, as well as refinement of biotechnological applications. From the astrobiological perspective, the discovery that DNA secondary structure can be maintained in an anhydrous solvent (Mamajanov et al. 2010) supports the proposal that nucleic acids might have first evolved in nonaqueous or mixed aqueous-organic media.

Cross-References

- Adenine
- Cytosine
- DNA Damage
- DNA Repair
- DNA Sequencing
- Double Helix
- Electrophoresis
- Extraterrestrial Delivery of Organic Compounds
- Genetics
- Genome
- Guanine
- Nucleic Acid Base
- Nucleic Acids
- Nucleoside
- Nucleotide
- Oligonucleotide
- Phylogenetic Tree
- Phylogeny
- Polymerase Chain Reaction
- Prebiotic Chemistry
- Purine Bases
- Pyrimidine Base
- Replication (Genetics)
- Ribonucleoside
- Ribonucleotide
- Ribose
- Ribosome
- RNA
- RNA World
- Sequence
- Thymine (T)
- Watson-Crick Pairing

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DNA- (or RNA-)Dependent DNA Polymerase

► DNA Polymerase

DNA (or RNA-)Dependent RNA Polymerase

► RNA Polymerase

DNA Damage

Thierry Douki¹ and Jean Cadet²

¹Univ. Grenoble Alpes, CEA, CNRS, Grenoble, France

²Département de Médecine Nucléaire et Radiobiologie, Faculté de Médecine et des Sciences de la Santé, Université de Sherbrooke, Sherbrooke, QC, Canada

Keywords

Bipyrimidine photoproducts · Cyclobutane pyrimidine dimers · DNA oxidation products · DNA strand breaks · 8-Oxo-7,8-dihydro-2'-deoxyguanosine · Pyrimidine (6-4) pyrimidone photoproducts · Spore photoproduct

Synonyms

Alteration

Definition

► **DNA** damage consists of chemical modifications of the deoxyribonucleic acid components that include alterations of the four main purine (adenine, guanine) and pyrimidine (cytosine, thymine) bases, the relatively minor 5-methylcytosine base and the 2-deoxyribose moiety. According to the damaging agents that may be endogenous

(reactive oxygen and nitrogen species such as hydroxyl radical, peroxynitrite, etc.) and exogenous (solar light, ionizing radiation, alkylating compounds, etc.), several classes of DNA lesions may be generated. These include single- and double-strand breaks, normal and oxidized abasic sites, single modified bases (oxidized lesions, alkylated adducts, addition products with reactive aldehyde arising from the breakdown of lipid peroxides, and 2-deoxyribose oxidation products), tandem modifications (intrastrand bipyrimidine photoproducts, vicinal oxidized bases), DNA-protein cross-links, interstrand cross-links, and clustered lesions (association of several oxidized bases, single- or double-strand breaks produced within one to two helix turns by several radiation-induced radical hits).

History

The discovery and characterization of *cis-syn* cyclobutane thymine dimer at the beginning of the 1960s, the main UVB- and UVA-mediated degradation product of isolated and cellular DNA, have provided a strong impetus to investigations in the fields of genotoxicity, mutagenesis, and ► **DNA repair**.

Overview

This entry focuses on the two main classes of DNA modifications that may be produced upon exposure of living systems to deleterious space conditions. These conditions comprise high vacuum, a wide range of temperature variations, and ionizing and UV radiations that have both galactic and solar origins (Nicholson et al. 2000). These effects include DNA photoproducts that are the main alterations generated upon exposure to solar extraterrestrial UV radiation of resistant microorganisms that may be carried in outer space. Under the latter conditions, the contribution of the second class of DNA damage that consists of radiation-induced degradation products involving mostly oxidative reactions is relatively minor.

However, the situation is different inside manned space vessels due to an efficient shielding against the UV radiation components involving the vacuum-UV ($140 < \lambda < 200$ nm), UVC ($200 < \lambda < 280$ nm), UVB ($280 < \lambda < 320$ nm), and UVA ($320 < \lambda < 400$ nm) photons. This protection is much more limited against high-charge (Z) and high-energy (E) (HZE) particles of galactic cosmic radiation (GCR) that, in addition to the HZE particles (1% of the nucleonic component), also include high-energy protons (87%) and α -particles (He ions) (12%) as well as electrons. Of concern are also solar particle radiations that are emitted during solar wind and erratic solar flares, consisting mostly of protons with very small amounts of α -particles and HZE ions (Durante and Cucinotta 2008).

Basic Methodology

Major progress has been made during the last two decades in the development of accurate and sensitive methods aimed at measuring photo- and radiation-induced damage to cellular DNA. This has benefited from the availability of new methodological approaches, including high-performance liquid chromatography coupled with electrospray ionization-tandem mass spectrometry detection (HPLC-ESI-MS/MS). Thus, the UV-induced DNA photoproducts that mostly consist of cyclobutane pyrimidine dimers (CPDs) and pyrimidine (6-4) pyrimidone photoproducts (6-4PPs) at the four main bipyrimidine sequences together with 5,6-dihydro-5-(α -thyminyl)-thymine, the so-called spore photoproduct (SP), can be measured by HPLC-MS/MS (Cadet and Douki 2010; Douki 2013). Polyclonal and monoclonal antibodies are also available for monitoring the formation of bipyrimidine photoproducts in cellular DNA and in tissue in a more semiquantitative way. HPLC-MS/MS is the method of choice for assessing the formation of single and clustered oxidatively generated base damage in cellular DNA at least under acute conditions of ionizing radiation exposure (Cadet et al. 2010). The modified version of the comet assay and the alkaline elution technique that both require the use of DNA

repair glycosylases to reveal classes of oxidatively generated damage such as oxidized bases and modified purine bases are suitable alternatives, although less specific than HPLC-MS/MS to deal with the detection of low amounts of radiation-induced DNA damage.

Key Research Findings

DNA Photoproducts

The UVC and UVB ► [photochemistry](#) of DNA that is triggered by the direct excitation of the bases is strongly dependent on the water content of the considered microorganisms, with two extreme situations that involve vegetative cells and bacterial spores.

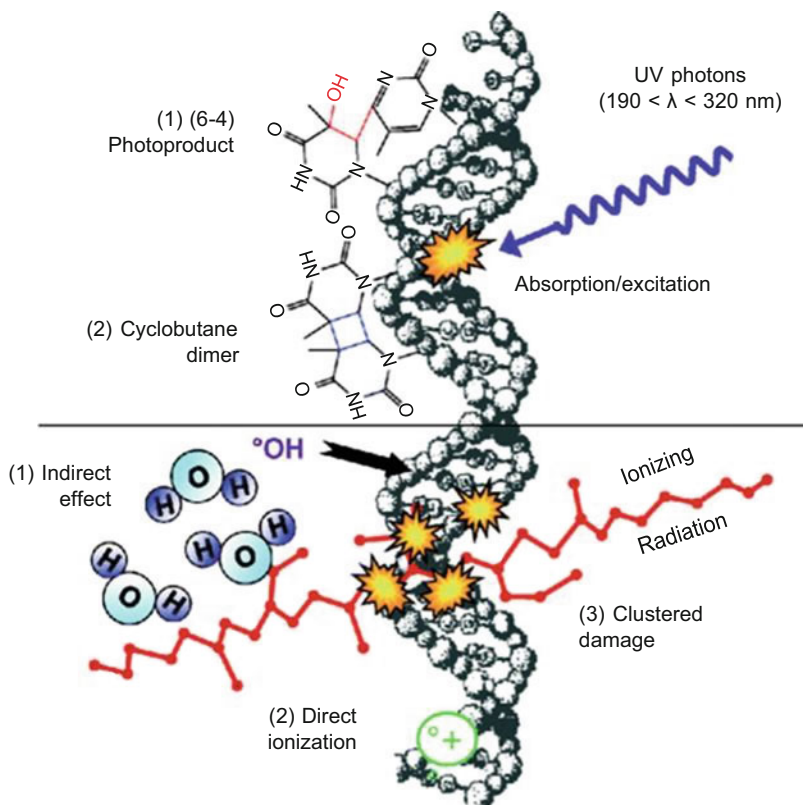
Vegetative Cells

Dimerization of two adjacent pyrimidine bases is the overwhelming reaction induced upon exposure of DNA of vegetative cells to UVC and UVB photons, thus giving rise to two main types of photoproducts, namely, *cis-syn* cyclobutane pyrimidine dimers (CPDs) and pyrimidine (6-4) pyrimidone photoproducts (6-4PPs) (Fig. 1). The formation of CPDs involves a $[2 + 2]$ cycloaddition between the C5–C6 double bonds of the two adjacent pyrimidine bases. The generation of 6-4PPs is rationalized in terms of $[2 + 2]$.

Paternò-Büchi cycloaddition between the C5–C6 double bond of the 5'-end pyrimidine to either the C4 carbonyl of a thymine or the imine group of a cytosine in a suitable tautomeric form (Cadet and Vigny 1990; Taylor 1994). The efficiency of bipyrimidine photoproduct formation and the relative yield of CPDs and 6-4PPs are strongly dependent on the primary DNA sequence. Another striking feature is the efficient hydrolytic deamination of cytosine residues in either CPDs or at the 5'-end of 6-4PPs that leads to the formation of mutagenic uracil derivatives. One may add that UVA is able to induce CPDs through a direct excitation mechanism (Banyasz et al. 2011) with an efficiency that is higher than the generation of 8-oxo-7,8-dihydro-2'-deoxyguanosine (8-oxodGuo) (Cadet et al. 2009) that mostly arises from singlet oxygen oxidation of 2'-deoxyguanosine (Cadet et al. 2017).

DNA Damage,

Fig. 1 Photo- and radiation-induced damage in DNA: UVB-induced bipyrimidine photoproducts upon photoexcitation and radiation-induced base and 2-deoxyribose degradation products by hydroxyl radical ($\cdot\text{OH}$) and one-electron oxidation (ionization)



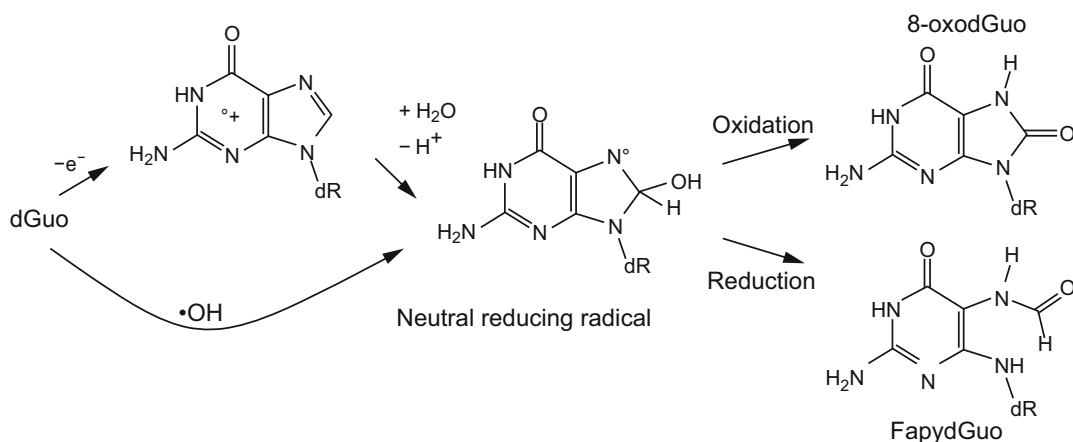
Bacterial Spores

The spectrum of DNA photoproducts in UVC- or UVB-irradiated bacterial spores is very different from what is observed in vegetative cells. Thus, the spore photoproduct (SP) that is another bithymine lesion is formed almost exclusively at the expense of CPDs and 6-4PPs in *Bacillus subtilis* spores (Cadet and Douki 2010). The pronounced changes in DNA photoreactivity have been accounted for by notable structural modifications of DNA molecules that were shown to adopt an A-like conformation. This was found to result from the binding of small acid-soluble proteins (SASP) in a dehydrated environment that is maintained by the presence of a high concentration of calcium dipicolinate (Ca-DPA). It was also shown that Ca-DPA is able to photosensitize the UVC-mediated formation of SP while protecting DNA against the damaging effects of UVB and UVA radiations (Cadet and Douki 2010). It may be added that CPDs and 6-4PPs are formed in significant amounts in spores that lack either

SASP or Ca-DPA, showing the major role played by the latter molecules in the generation of SP.

Radiation-Induced DNA Damage

The molecular effects of ionizing radiation on cellular DNA may be rationalized in terms of indirect effects through the generation of hydroxyl radical ($\cdot\text{OH}$), the product of water molecule radiolysis (Fig. 1), and direct interaction with the genetic material that leads to ionization of the bases and the 2-deoxyribose moiety (von Sonntag 1987). An important aspect to be considered in the mode of action of ionizing radiation is the multiplicity of radical and excitation hits that follow the energy deposition (Goodhead 1994). As a result, clustered damage, initially called “multiply damage,” consisting of several lesions (modified bases, abasic sites, single-, and double-strand breaks), may be generated within one or two helix turns. It may be added that the complexity of the clustered DNA damage increases with the ► **linear energy transfer (LET)** value of ionizing



DNA Damage, Fig. 2 Radiation-induced formation of 8-oxo-7,8-dihydro-2'-deoxyguanosine (8-oxodGuo) and *N*(2-deoxy- β -D-*erythro*-pentofuranosyl)-2,6-diamino-4-

hydroxy-5-formamidopyrimidine (FapydGuo) as the result of either $\cdot OH$ addition or electron abstraction

radiation and heavy particles. This is particularly of concern for space-ionizing radiation that consists of high-energy protons and densely ionizing high-LET HZE particles ranging from helium to uranium, whereas terrestrial radiation is represented mostly by low-LET photons (X-, β -, or γ -rays) (Durante and Cucinotta 2008).

$\cdot OH$ and One-Electron Oxidation Products as One-Hit Lesions

A large body of information is available on the $\cdot OH$ and one-electron oxidation of the purine and pyrimidine bases of DNA, thanks to comprehensive and detailed studies on model compounds Cadet et al. 2009; Wagner and Cadet 2010). Thus, the 4 *cis* and *trans* diastereomers of 5,6-dihydroxy-5,6-dihydrothymidine, 5-(hydroxymethyl)-2'-deoxyuridine, and 5-formyl-2'-deoxyuridine have been characterized as the main $\cdot OH$ -mediated degradation products of thymidine in cellular DNA (Cadet et al. 2008). Other pyrimidine base oxidation products including 5-hydroxy-5-methylhydantoin, 5-hydroxyhydantoin, 1-carbamoyl-4,5-dihydroxy-2-oxoimidazolidine, 5-hydroxymethylcytosine, and 5-formylcytosine have been identified in gamma-irradiated human cells (Madugundu et al. 2014). In addition, 8-oxo-7,8-dihydro-2'-deoxyguanosine (8-oxodGuo) and 2,6-diamino-4-hydroxy-5-formamidopyrimidine (Fig. 2) have been shown to arise from one-electron oxidation

and one-electron reduction, respectively, of 8-hydroxy-7,8-dihydroguanyl radical, the initial $\cdot OH$ addition product to guanine (Cadet et al. 2010). Similar degradation products are generated by $\cdot OH$ addition to adenine, however, with an efficiency that is about tenfold lower than for guanine degradation products. One-electron oxidation of nucleobases in cells gives rise to the same pattern of degradation products as those induced by $\cdot OH$. However, one may note a different product distribution since 8-oxodGuo is formed predominantly upon ionization of the bases as the result of the positive hole migration along the DNA chain with preferential trapping of the radical cation at guanine sites (Genereux and Barton 2010; Kanvah et al. 2010). It is well documented that DNA single-strand breaks (SSBs) are generated by $\cdot OH$ -mediated hydrogen abstraction from the 2-deoxyribose moiety (von Sonntag 2006; Dedon 2008). Ionization reactions are also likely to be involved in the formation of SSBs although there is still a lack of mechanistic information.

Specific Radiation-Induced Clustered Damage

DNA double-strand breaks (DSBs) that consist of two closely spaced and opposed single-strand breaks (SSBs) separated by less than 15 base pairs are the most representative radiation-induced DNA-clustered damage. It has been

predicted by Monte Carlo calculations that the frequency of complex DSBs that contain at least one additional nick/or modified base increases up to 70% for 2 MeV particles, while the proportion was only 20% for low-LET 4.5 keV electrons. Experimental support for the induction of a higher density of DSBs with the increase in LET of incident HZE particles was provided by the observation of a larger frequency of fluorescent γ -H2AX foci (i.e., 1 of the eukaryotic histones that become phosphorylated on serine 139 as a reaction to DNA DSBs formation). It has also been shown that the DSBs generated with high-LET radiation are more difficult to be repaired likely due to an increase in the complexity of the clustered lesions.

A second class of complex DNA damage consists of non-double-strand break-clustered damage that may comprise at least one-strand break together with one or several base lesions and/or apurinic sites on the two complementary DNA strands within one or two DNA helix turns (Hada and Georgakilas 2008). Attempts have been made using a DNA repair-based assay to monitor the formation of these lesions. However, it was found that the yield of clustered lesions, thus measured, is only slightly lower to those of single oxidized bases in irradiated cells, a rather surprising finding. At this point, it may be stressed that further work is required to better assess the formation of clustered DNA modifications.

Applications

The measurement of CPDs, 6-4PPS, and SP photoproducts has been made in the DNA of several microorganisms allowing detailed studies of their repair. The yields of bipyrimidine photoproducts vary according to the microorganisms due to the presence in some cases of photoprotective compounds and differences in the membrane composition. One may also note that the radiation-induced formation of 8-oxodGuo in cellular DNA was found to decrease with the increase in LET of the radiation. This is indirectly indicative of the major deleterious role played by complex clustered DNA damage in ► [radiation biology](#).

Future Directions

Efforts should be made to better ascertain the effects of vacuum-UV light on the DNA of resistant microorganisms including bacterial spores when exposed to outer space conditions in terms of photoproduct distribution. Another major topic to be further investigated concerns the detection and quantification of radiation-induced clustered damage, whose identification remains a challenging issue due to the complexity of the analytical problem thus addressed and the oneness of each of the damage.

Cross-References

- [Aerobiology](#)
- [Cosmic Rays in the Heliosphere](#)
- [DNA](#)
- [DNA Repair](#)
- [HZE Particle](#)
- [Ionizing Radiation, Biological Effects](#)
- [Linear Energy Transfer](#)
- [Mutation](#)
- [Nucleic Acid Base](#)
- [Nucleic Acids](#)
- [Photobiology](#)
- [Photochemistry](#)
- [Radiation Biology](#)
- [Solar Particle Events](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [Survival](#)
- [UV Climate](#)
- [UV Radiation, Biological Effects](#)
- [UV Radiation Dose](#)

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DNA Damage Correction

► DNA Repair

DNA Polymerase

Juli Peretó

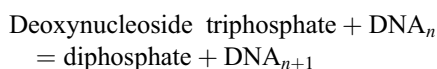
Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

DNA- (or RNA-)dependent DNA polymerase; DNA replicase; Klenow fragment

Definition

DNA polymerase is an enzyme which catalyzes the addition of a deoxynucleoside triphosphate to the 3' end of a DNA strand using a template. The systematic name of this enzymatic activity is deoxynucleoside-triphosphate:DNA deoxynucleotidyl transferase and the catalyzed reaction can be represented as



DNA-directed DNA polymerases (EC 2.7.7.7) use DNA templates, whereas RNA-directed DNA polymerases (EC 2.7.7.49), also known as reverse transcriptases, use RNA templates. These enzymes cannot initiate a chain de novo and require a primer, which may be DNA or RNA. Some DNA-directed DNA polymerases have acquired proofreading mechanisms through a 3'–5' exonuclease activity.

History

DNA polymerase I from *Escherichia coli* was discovered by Arthur Kornberg in 1956

(awarded with the Nobel Prize in Physiology or Medicine in 1959). Howard Temin and David Baltimore independently discovered viral reverse transcriptase in 1970 (both scientists shared the Nobel Prize in Physiology or Medicine in 1975).

Cross-References

- [DNA](#)
- [Replication \(Genetics\)](#)
- [Template](#)

DNA Recombination

- [Recombination](#)

DNA Repair

Wayne L. Nicholson^{1,2} and Ralf Moeller³

¹Space Life Sciences Laboratory, University of Florida, Merritt Island, FL, USA

²Space Life Sciences Laboratory, Kennedy Space Center, University of Florida, Gainesville, FL, USA

³German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Keywords

DNA damage · DNA, repair of damage

Synonyms

[DNA damage correction](#)

Definition

DNA repair refers to a collection of processes by which a cell identifies and corrects damage to the DNA molecule(s) that encode its genetic information.

History

The discovery and early history of DNA repair has been reviewed recently (Friedberg 2008 and references therein).

Overview

Deoxyribonucleic acid (DNA) is the molecule that stores the genetic instructions used by all known living organisms and some viruses (other viruses use ribonucleic acid – RNA – as their genetic material). Successful propagation of life is therefore dependent upon the faithful copying of the information encoded in the sequence of DNA bases in a process called replication.

In the context of astrobiology, DNA can be damaged by exposure to environmental factors such as heat, ultraviolet or ionizing radiation, extreme vacuum, desiccation, various toxic chemicals, or oxidizing agents. DNA can also be damaged as a result of normal metabolic processes occurring within cells. ► [DNA damage](#) can either: (1) block the progress of replication by the ► [enzyme](#) DNA polymerase, leading to cell death; or (2) lead to the incorporation of incorrect bases during replication, resulting in mutations.

In order to maintain the integrity of the structure and base sequence in DNA, the cell employs a number of enzymatic DNA repair processes to specifically recognize and correct damage to DNA or errors of base incorporation. Most of the DNA repair pathways described below have been shown to be important for microbial survival to exposure to outer space or other extreme environments such as the surface of Mars (Nicholson et al. 2005; Moeller et al. 2007):

- Certain types of DNA damage can be repaired by *direct reversal* using enzymes that recognize the specific type of damage. Photoreactivation is a light-dependent DNA repair mechanism, in which the UV-induced *cis-syn* cyclobutane pyrimidine dimers (CPDs) are enzymatically monomerized by a photolyase (Friedberg et al. 2006). UV-irradiated bacterial spores accumulate a spore-specific thymine

dimer, spore photoproduct (SP), that can be directly reversed to two thymines using the enzyme SP lyase (Nicholson et al. 2000).

- *Excision repair* pathways are used to correct a number of different types of damage occurring on only one of the two DNA strands. In general, damage-specific enzymes excise the damaged region and the correct sequence is restored by a specific repair DNA polymerase using the opposite, undamaged strand as a template. Examples are ► [nucleotide](#) excision repair, base excision repair, and methyl-directed mismatch repair (Friedberg et al. 2006).
- DNA damage can also be corrected by homologous ► [recombination](#) repair. In this pathway, when DNA is being actively replicated, pieces of damaged DNA can be swapped for undamaged DNA originating from the undamaged daughter strand, using a series of specific recombination (Rec) enzymes (Friedberg et al. 2006).
- Double strand breaks (DSB) can be formed in DNA by ionizing radiation or extreme desiccation. DSB are especially lethal because they disrupt the integrity of the DNA molecule. DSB are repaired in bacteria by a pathway called non-homologous end joining (NHEJ), in which the broken ends are rejoined by a specific DNA ligase. NHEJ has been shown to be important in the survival of spores to various types of ionizing radiation and high-energy particle bombardment (Moeller et al. 2007).

Cross-References

- [DNA](#)
- [DNA Damage](#)
- [Enzyme](#)
- [Error Rate](#)
- [Genetics](#)
- [Ionizing Radiation, Biological Effects](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Nucleotide](#)
- [Recombination](#)
- [Replication \(Genetics\)](#)
- [Solar UV Radiation, Biological Effects](#)

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DNA Replicase

- [DNA Polymerase](#)

DNA Sequencing

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Gene sequencing](#); [Sequencing](#)

Definition

- [DNA](#) sequencing is the process by which the order of ► [nucleotides](#) in a DNA molecule is determined. The first DNA sequencing method – set up by A. Maxam and W. Gilbert in the decade of the 1970s – was based on the controlled chemical breakage at one or two of the four

► [nucleotides](#). In parallel, F. Sanger developed an alternative system which relies on the abortive synthesis of complementary DNA strains, thanks to the use of dideoxynucleotide triphosphates – also called “dideoxys” – as chain terminators. In both methods, the fragments are separated and identified by ► [electrophoresis](#). The Sanger method for DNA sequencing gave rise to automatic DNA sequencers based on capillary electrophoresis, thus triggering the explosion of ► [genome](#) sequencing projects in the 1990s. Since 2005, a number of “next-generation” techniques have been released, producing a spectacular increase in sequencing speed together with a drastic reduction in the cost. They include the so-called pyrosequencing, sequencing by synthesis, and sequencing by ligation. Later on, the current “third-generation” techniques allow the fast and reliable sequencing of single DNA molecules. This is widely regarded as the future of sequencing, since single-molecule approaches do not require the DNA to be previously amplified.

Cross-References

- [Amplification \(Genetics\)](#)
- [DNA](#)
- [Electrophoresis](#)
- [Genetics](#)
- [Genome](#)
- [Mutation](#)
- [Nucleotide](#)
- [Sequence](#)

Domain (Taxonomy)

Purificación López-García
Unité d'Ecologie, Systématique et Evolution,
CNRS UMR8079 Université Paris-Sud 11, Paris,
Orsay Cedex, France

Keywords

Archaea · Bacteria · Eukarya

Synonyms

[Empire](#); [Primary kingdom](#); [Superkingdom](#)

Definition

Domain is the highest taxonomic rank in the hierarchical biological classification system, above the kingdom level. There are three domains of life, the ► [Archaea](#), the ► [Bacteria](#), and the ► [Eukarya](#). Organisms from Archaea and Bacteria have a prokaryotic ► [cell](#) structure, whereas organisms from the domain Eukarya (eukaryotes) encompass cells with a nucleus confining the genetic material from the cytoplasm.

Overview

The term “domain” was introduced by Carl R. Woese et al. (1990) together with the proposal of a natural classification system for all life on Earth, including microorganisms, which had previously escaped any attempt of classification based on evolutionary relationships (Woese et al. 1990). Woese’s proposal to class life in three major phylogenetic domains was an attempt to institutionalize the three major phylogenetic groupings of organisms that he had previously observed and defined (Woese and Fox 1977) based on differences in the small subunit ribosomal RNA, a macromolecule chosen as an ideal phylogenetic marker due to its universality, degree of conservation, and essential function. The three-domain classification system was proposed as an alternative to other life classification systems in use at that time, such as the traditional prokaryote-eukaryote division or the five-kingdom system (Monera, Protista, Fungi, Plantae, and Animalia) proposed by R. Whittaker in 1969. The three-domain classification based on ribosomal RNAs was received with skepticism by most biologists at that time, who were not ready to accept that the evolutionary information stored in one single macromolecule had more weight than other, phenotypic, characters. O. Kandler and his German school provided additional features that distinguished radically the two prokaryotic groups (Archaea and Bacteria)

including cell wall biochemistry and the presence of eukaryotic-like RNA polymerases in Archaea. The marked differences between archaea and bacteria have been widely demonstrated since then, thanks, among others, to the comparison of full genome sequences. The classification of life in three phylogenetic domains is well established today. It does not imply the demise of the prokaryote-eukaryote dichotomy at the structural level, which is an empirical reality. Therefore, there are two types of cells from a structural point of view, but three domains of life from a phylogenetic point of view.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Cell](#)
- [Eukarya](#)
- [Phylogeny](#)
- [Taxonomy](#)

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Doppler Shift,

Fig. 1 Diagram illustrating how the measured wavelength of a wave emitted by a moving source changes, depending on the direction of the movement with respect to the observer

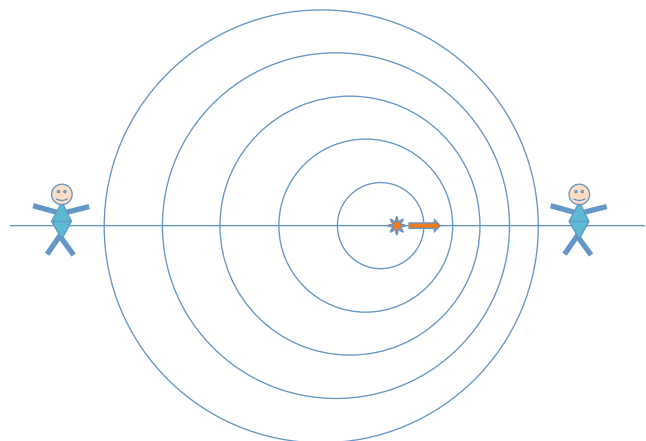
Doppler Shift

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The Doppler shift is the change in frequency and wavelength of a propagating wave (acoustic, electromagnetic, etc.), caused by the movement of the source emitting the wave relative to the observer. This effect is named after the Austrian physicist Christian Doppler who proposed it in 1842. In France, the effect is currently called Doppler–Fizeau, because the French physicist Hippolyte Fizeau proposed it for electromagnetic waves in 1848. If the source is moving away from the observer, the wavelength appears stretched while frequencies are shifted toward lower values, and if the source is approaching, the wavelength appears compressed and frequencies shifted toward higher values. In the case of light, the effect is called redshift (receding source) and blueshift (approaching source), respectively. This effect is of great importance in astronomy because it allows direct determination of the radial speed of celestial objects and of the distance of remote galaxies (because of the expansion of the Universe). It provides the basis for the most productive method for detection of exoplanets, the so-called ► [radial velocity](#) method. The relative amount of wavelength



change when the velocity is not close to the speed of light is given by the relation $\Delta\lambda/\lambda = v/c$, where v is the relative velocity, c is the velocity of the wave (e.g., speed of light), λ is the wavelength, and $\Delta\lambda$, the change in wavelength (Fig. 1).

Cross-References

- [Radial Velocity](#)
- [Radial-Velocity Planets](#)

Dormant State

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Dormant state refers to a reduced metabolic activity phase adopted as strategy to escape stressful conditions and/or save energy. It refers to a latent but capable to be active state. The adverse weather

conditions (low temperature in winter time, etc...) drive a plant or animal population to reduce their metabolic activity in order to preserve themselves avoiding frosting conditions. The spore state of sporulating Gram-positive bacteria is considered a dormant state of the bacterium.

Double Helix

Henderson James Cleaves II

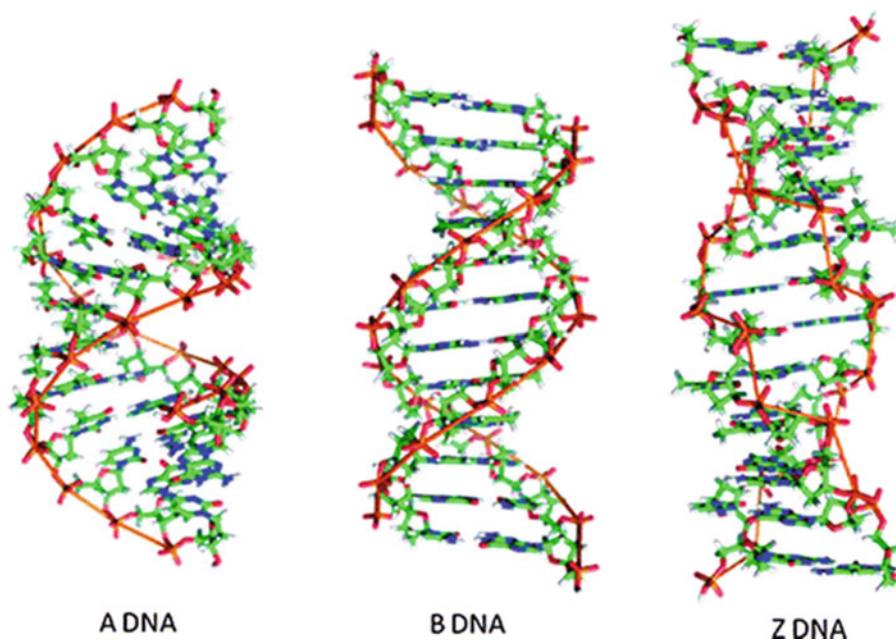
Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

A double helix consists of two congruent helices with the same axis, differing by their translation along the axis. In molecular biology, complementary double-stranded ► [DNA](#) typically adopts a double-helical structure. The DNA double helix



Double Helix, Fig. 1 Three double-helix structures adopted by double-stranded DNA under different physiological conditions

can be (from left to right in Fig. 1) of the A- or B-form, which are right-handed but differ from each other in the distance required to make a complete helical turn or of the Z-form, which is left-handed. The double-helix model of DNA structure was published in *Nature* by Watson and Crick in 1953. DNA is typically found in the B-form, while double-stranded ► **RNA** typically adopts the A-form.

Cross-References

- **Base Pair**
- **DNA**
- **Nucleic Acids**
- **Watson-Crick Pairing**

DPANN, Archaea

Ricardo Amils

Departamento de Biología Molecular, Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Definition

DPANN is a superphylum of the domain Archaea also named Nanoarchaea or ultrasmall archaea due to their small size. The name of the group is the acronym formed by the initials of the first discovered phyla: **D**iapherotrites, **P**arvarchaeota, **A**enigmarchaeota, **N**anoarchaeota, and **N**ano-haloarchaeota. More recently identified archaea have been placed within this superphylum. They are characterized by their small size ($<0.1 \mu\text{m}^3$) and small genome that limit their metabolic capacities. These are similar properties than the ultrasmall bacteria (CPR). Although many members of this group depend on symbiotic relationship with other organisms, some maintain a cell-free life status using mainly fermentation for the generation of cellular energy. Mostly they have been identified in anaerobic extreme environments at

high temperature, acidic pH, or high salt concentrations, although some members have been detected in less extreme environments like lake and marine sediments. The monophyletic status of DPANN is not well established yet and some phylogenetic analysis place them as members of the Euryarchaeota.

Cross-References

- **Acidophile**
- **Anaerobe**
- **Archaea**
- **Fermentation**
- **Genome**
- **Halophile**
- **Phylogeny**
- **Symbiosis**
- **Thermophile**

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Drake Equation

Leticia Carigi

Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Synonyms

Green bank equation

Definition

The Drake equation estimates the number of communicating extraterrestrial civilizations that might exist within the Milky Way today. This formula was proposed by Frank Drake in 1961 to organize the knowledge, at that time, about the formation and evolution of extraterrestrial life.

Overview

The original Drake equation gives the number (N) of civilizations in the Galaxy that are able to communicate through electromagnetic waves. That formula is written as the product of seven terms, as follows:

$$(N = R \times f_p \times n_e \times f_l \times f_i \times f_c \times L),$$

where (1) R is the rate of formation of stars suitable for life, that is, solar-type stars, in units of stars per year; (2) f_p is the fraction of suitable stars surrounded by planetary systems; (3) n_e is the number of planets suitable for life in a given planetary system, that is, the number of planets located within the habitable zone; (4) f_l is the fraction of habitable planets, within that zone, where basic life appears; (5) f_i is the fraction of planets on which basic life evolves into intelligent life; (6) f_c is the fraction of planets on which intelligent life develops a sufficiently high technology capability to broadcast signals of its existence out into the Galaxy; and (7) L is the lifetime of such a technological civilization emitting detectable signals into space.

The R factor is best understood in the equation due to the vast body of astronomical data available; f_p and n_e factors can be estimated with some degree of certainty using the properties of exoplanets detected so far. However, the remaining factors are unknown at present since we do not know any extraterrestrial life form or civilization. In particular, the L factor is the least known in the formula, because we have no idea even how long our civilization will last, and at the same time, is

the most determining factor in the Drake Equation. Thus, depending on whether one adopts the pessimistic or the optimistic point of view, a civilization may last 10 years or 100,000 years; he/she may obtain $N = 1$ or $N = 10,000$, respectively, indicating that we are either almost alone in the Milky Way (see Fermi Paradox) or, on the contrary, in the Galaxy there exist an abundance of extraterrestrial civilizations that are yet to be detected.

An important problem with the Drake equation is its incompleteness since the formula omits important factors such as possible interstellar colonization, the habitable planets or moons in stars unlike our Sun, the change of the habitable zone with the evolution of a star, the metallicity requirements for the formation of earthlike planets, etc. Since 1961, according to the new knowledge of Astrobiology, new factors have been added and the equation has been used as a basis for more general calculations of the possibility of detecting life in our galaxy.

Cross-References

- [Exoplanets, Discovery](#)
- [Fermi Paradox](#)
- [Galactic Habitable Zone](#)
- [Habitable Zone](#)
- [Search for Extraterrestrial Intelligence](#)
- [SETI](#)

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Dresser Formation, Traces of Life

Rogers C. C. Buntin and Nora Noffke
Old Dominion University, Norfolk, VA, USA

Keywords

Dresser Formation · Warrawoona Group · Pilbara · Archean · MISS · Microbial mat · Stromatolite · Microbialite · Biosignature, early life, extraterrestrial life, Mars

Acronyms

MISS Microbially induced sedimentary structures

Overview

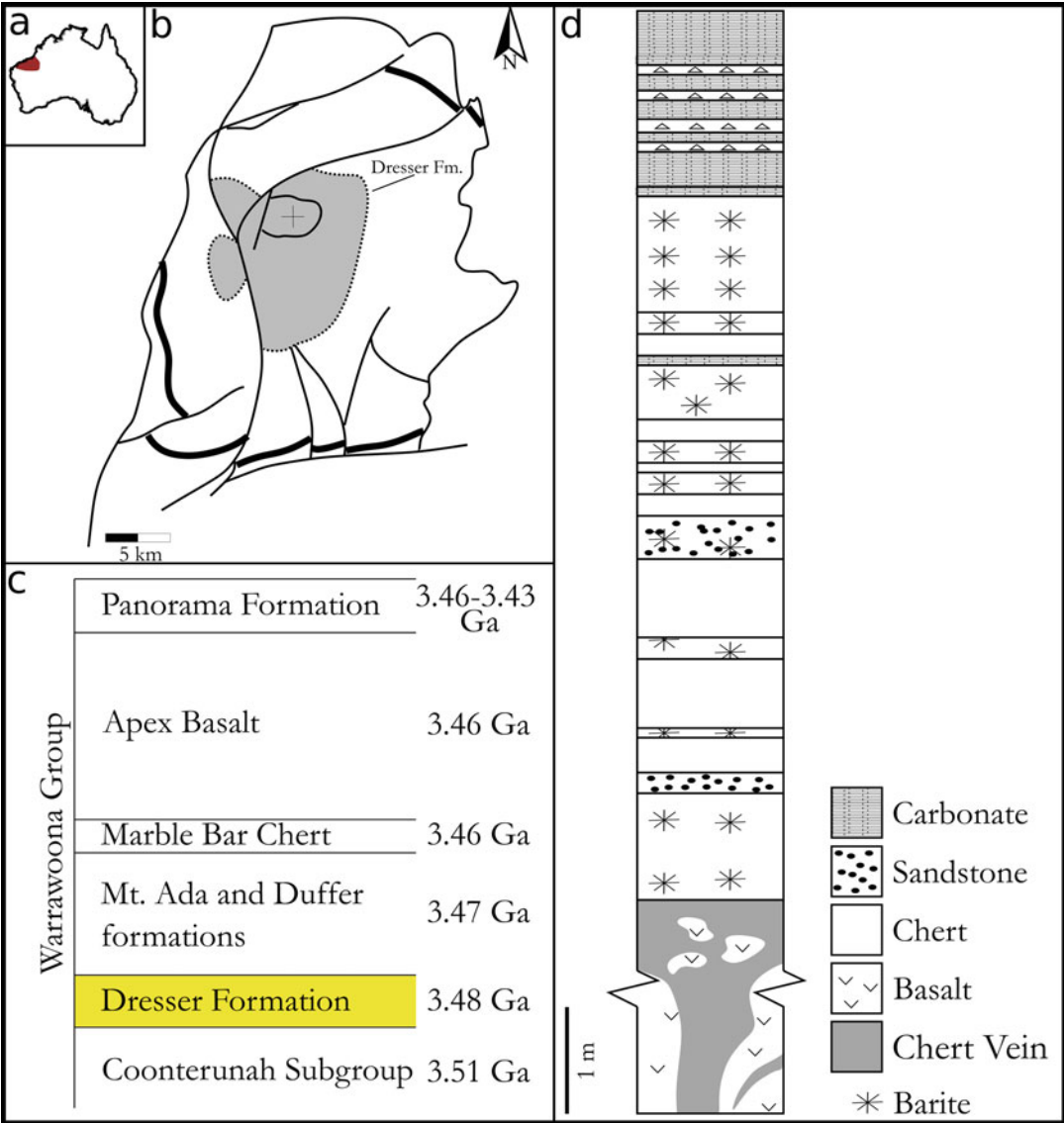
The Archean Dresser Formation (~3.48 Ga) crops out at several localities in the North Pole Dome, Pilbara, Western Australia (Fig. 1). A wide range of stromatolites, MISS, microfossils, mat fabrics, and biosignatures are preserved within hydrothermal dykes, barite mounds, siliciclastic deposits, and siliceous and ferruginous carbonates (Buick and Dunlop 1990) (Fig. 2). The spatial relation between stromatolites and biogenic carbon and sulfur isotopes suggests the presence of hyperthermophilic microbes (Ueno et al. 2008; Duda et al. 2018). Stromatolites and MISS aid reconstructions of the sedimentary setting because their morphologies are highly mediated by both biotic and environmental factors. The microbial structures also include abundant mat fabrics that allow insight into the evolutionary history of the Prokaryota. The Dresser Formation also offers the opportunity to study early Archean seawater chemistry. This review gives an overview on evidence of microbial life in the Dresser Formation.

Geologic setting The Dresser Formation (*ca.* 3.48 Ga) of the Warrawoona Group (Fig. 1c) is restricted to a ~25km² area in the North Pole

Dome of the East Pilbara granite greenstone terrane of Western Australia (Van Kranendonk et al. 2008; Noffke et al. 2013). The primary lithologies of the Dresser Formation (Fig. 1d) include: (i) komatiitic metabasalt transected by silica-rich veins; (ii) fossiliferous, interbedded chert and barite; and (iii) pillow basalts with interbedded cherts and diabase (Buick and Dunlop 1990; Philippot et al. 2009; Noffke et al. 2013). Chert-barite veins within the lowermost basal and komatiitic basalts are considered syngenetic, terminating at the chert-barite unit and occasionally found as allochthonous clasts in the overlying lithologies (Van Kranendonk 2006; Baumgartner et al. 2020). The fossiliferous chert-barite unit (North Pole Chert Member) ranges in thickness from 2–120 m and is a hydrothermally altered sedimentary succession composed of volcanoclastic sandstones and mudstones, as well as chemically derived carbonate-rich, banded and peloidal cherts, barite, and gypsiferous and dolomitic mudstones (Buick and Dunlop 1990; Baumgartner et al. 2020). Biosignatures found within the sedimentary succession include: stromatolites, MISS, ooids and peloids, a wide range of organic microfossils and mat fabrics, as well as fractionated carbon and sulfur isotopes (Dunlop et al. 1978; Buick and Dunlop 1990; Noffke et al. 2013; Djokic et al. 2017). Paleoenvironmental reconstructions of the chert-barite suggest deposition within either an enclosed volcanic caldera or an evaporitic lagoon, both influenced by syndepositional hydrothermal circulation (Groves et al. 1981; Buick and Dunlop 1990; Nijman et al. 1998; Van Kranendonk 2006; Van Kranendonk et al. 2008).

Basic Methodology

A geological field survey and stratigraphic logging gains an overview on the paleosetting recorded by the rock succession. Samples are collected, where permitted by the Geological Survey of Western Australia. Epoxy-hardened thin-sections are used to identify microscopic structures including organic microfossils and mat fabrics, as well as microsequences, sinoidal

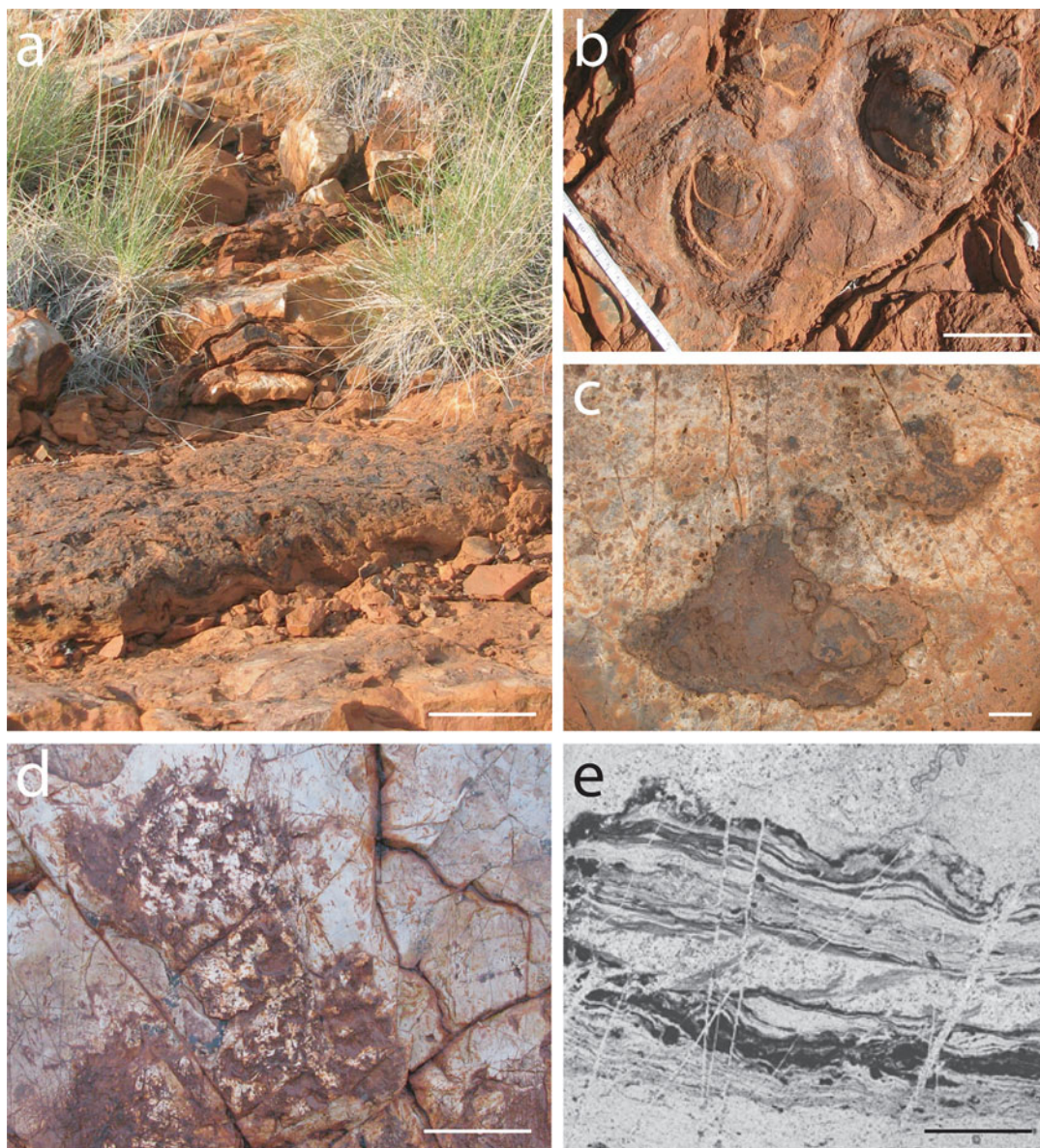


Dresser Formation, Traces of Life, Fig. 1 Location of the Dresser Formation: (a) The stratigraphic rock succession crops out in the Pilbara Craton, Western Australia. (b) The Dresser Formation forms a roughly circular structure

in the North Pole Dome Area. (c) Stratigraphy of the Warrawoona Group. (d) Simplified stratigraphic log of the Dresser Formation. (After Van Kranendonk 2006; Van Kranendonk et al. 2008)

structures, fenestrate porosity, and others. Mat fabrics includes fossilized coccoids, filaments, and extracellular polymeric substances (EPS), permineralized or replaced *in situ* (Amrawik 1992; Noffke 2010). Petrographic analyses of microbial structures allow statistical analyses of such micromorphologies (Noffke 2010) and the

classification of various microfossil morphology (Grey and Sugitani 2009; Baumgartner et al. 2020). Chemical etching of thin sections allows exposure of organic matter and prepares samples for analyses of organic matter and isotope mapping like Raman spectroscopy (Grey and Sugitani 2009; Baumgartner et al. 2020). Gas-



Dresser Formation, Traces of Life, Fig. 2 Microbially induced sedimentary structures in the 3.48 Ga Dresser Formation, Pilbara, Western Australia: (a) Classical site of wrinkly in situ preserved microbial mat and a stromatolite; scale 15 cm. (b) Stromatolites; scale 10 cm.

(c) Microbial mat chips; scale 1 cm. (d) Wrinkle structure; scale: 15 cm. (e) Vertical section through ca. 3.4 Ga old biofilms possibly of chemoautotrophic microbes, thin-section view. Image provided by Frances Westall; scale ca. 100 μm

chromatographic mass spectrometry and catalytic hydropyrolysis (HyPy) allows the liberation of non-extractable hydrocarbons (i.e., kerogen) to determine carbon fixation via microbial activity (Marshall et al. 2007; Duda et al. 2018; Lepot 2020).

Key Research Findings

Stromatolites Van Kranendonk (2006) and Van Kranendonk et al. (2008) and Hickman-Lewis et al. (2019) identified numerous stromatolites in the chert-barite unit including biolaminites,

domical, stratiform, and coniform morphologies (Fig. 2). Abundant biolaminites, domical stromatolites, and local stratiform morphologies are recognized in the lowermost chert and are associated with barite and interlaminated gray and white cherts (Van Kranendonk 2006). Layers including pyrite crystals occur directly above the lowermost metabasalt and are characterized by millimeter-scale laminae of FeS₂ and minor contributions of carbonate, chert, barite, and sphalerite (Van Kranendonk et al. 2008). Current rippled micrite higher in the stratigraphy include stratiform and conical stromatolites (Van Kranendonk 2006).

The biogenicity of laminites in the Dresser Formation is supported by their relationship to barite crystals. In hydrothermally derived cherts, laminates have no association with barite crystals. Avoidance of barite suggests growth occurred contemporaneous to hydrothermal fluid circulation. However, similar structures can form abiotically in hydrothermal vents as primary chemical precipitates (Hannington and Scott 1988; McLoughlin et al. 2008; Lepot 2020). If biogenic in origin, the morphologic diversities of stromatolites and their varying lithofacies associations suggest high diversity and niche exploitation by bacteria by 3.48 Ga. Van Kranendonk (2006) interpreted stratiform and domical stromatolites to have been produced by subaqueous chemoautotrophic extremophiles. Similar morphologies are associated with hydrothermal vents in modern shallow calderas, where laminated kerogen occurs in siliceous veins (Ueno et al. 2004). Photoautotrophic bacteria are interpreted to have produced domical stromatolites within a shallow marine carbonate platform setting (Van Kranendonk 2006).

Microbially induced sedimentary structures A great variety of MISS occurs in the Dresser stratification (Noffke et al. 2013). Sinoidal structures are drapes or laminations atop ripple cross-stratification. The laminae show regularly shaped and spaced tufts composed of pyrite with minor carbonaceous material preserved within a silica-rich rock bed. Sinoidal structures are identified alongside stromatolites described by Buick and Dunlop 1990 (e.g., by Van Kranendonk 2006;

Van Kranendonk et al. 2008) and interpreted to have formed in a subtidal environment.

Microbial mat chips and roll-up structures (Fig. 2) are also identified in two facies zones (Noffke et al. 2013). These chips are of 0.1–3.5 cm diameters and up to 0.4 cm thicknesses. Some chips are wavy or even rolled up, which documents their former ductile properties. This ductile behavior and the co-occurrence with biolaminites suggest biogenicity of these structures. Microbial mat chips and roll-ups are interpreted to occur in intertidal and lagoonal facies (Noffke et al. 2013).

Erosional remnants and pockets are well preserved on widely exposed bedding planes with 1–3 cm differences in elevation between remnants and pockets. Slope angles ranging between 15–90° yield modification index (MOD-I) values between 0.18–0.33. Index values produced by the MOD-I indicate the degree of microbial influence during formation of erosional pockets and remnants. Values are calculated by considering the area of a mat covered surface within a given area, the slope angle between the erosional pocket and remnant, and the thickness of a microbial mat over levelled ripple marks within ripple valleys. Continuous values between 0–1 indicate no microbial influence to maximum microbial influence, respectively.

Polygonal oscillation cracks described by Noffke et al. (2013) are 3–10 cm wide cracks defining polygons. Each polygon has a dent or hole at its center. Such a crack pattern derives from lateral shrinking and expanding of mat polygons responding to alternating humid and arid conditions in a seasonal climate (Noffke 2010). The holes in the polygon centers indicate rupturing of the ancient mat due to increasing gas pressure (Noffke et al. 2013).

A domical stromatolite described by Walter et al. (1980) from the Dresser Formation contains a hollow cavity that may reflect a preserved gas dome (Amrawik 1992). Given their modern distribution in sabkha-like settings along the mean high water line, polygonal oscillation cracks and gas domes are interpreted by Noffke et al. (2013) to have formed in an upper supratidal zone.

Microfossils Archean-age microfossils display simple morphologies and sizes typical of younger Precambrian microfossils (Schopf et al. 2007). Biogenicity can be ascertained when structures in question were rapidly permineralized or even found in association with stromatolites (Amrawik 1992; Schopf et al. 2007). Carbonaceous spheroids found in the Dresser Formation occur in silicified carbonates and were first described by Dunlop et al. (1978). The authors interpreted five unique microfossil morphologies including solitary spheroids, spheroids with splits, paired spheroids, and chains of spheroids. However, these carbonaceous spheroids were later argued to possibly be abiogenic in origin (Schopf and Walter 1983; Buick and Dunlop 1990). Four additional filamentous microfossils were described by Amrawik et al. (Awramik et al. 1983; Awramik et al. 1988). The location (Awramik Locality A) of the horizon from which additionally collected microfossils derived is uncertain. Uncertainty of the stratigraphic position of these fossils had led to some controversy about the biogenicity of these structures (Buick 1991; Amrawik 1992). Wacey et al. (2018) demonstrated the similarities between spheroidal microfossils and permineralized fragments of vesicular volcanic glass.

Chemical Biosignatures Geochemical evidence for early life is derived from isotopes (i.e., sulfur, iron, nitrogen, and carbon) reflecting an ancient spectrum of original microbial metabolism. Fractionation of carbon isotopes by primary production of organic matter and oxidation of iron and sulfur takes place via anoxygenic photosynthesis and chemolithotrophy (Lepot 2020). In anaerobic environments, CO₂ is reduced with H₂ (either from decaying organic matter, hydrothermally sourced, or atmospheric) to produce CH₄ or C₂H₃O₂ by methanogenic and acetogenic bacteria, respectively (Lepot 2020). Sulfur isotope fractionations (³²S/³³S/³⁴S/³⁶S) can be used as an indicator of microbial activity, because relatively large depletions in ³⁴S are a marker of microbial sulfate reduction (Philippot et al. 2007; Ueno et al. 2008; Wacey et al. 2015; Lepot 2020). Pyrite from

microbial mats in the Dresser Formation is heavily depleted in ³⁶S with a steep Δ³⁶S/Δ³⁶S slope, suggesting polysulfide pyrite precursors were formed by the mixing of mass independent fractionated sulfur and sulfur derived from microbial reduction of seawater sulfate (Wacey et al. 2015).

Kerogen containing significant amount of ¹³C-depleted carbon was described by Ueno et al. (2004) from silica-rich dikes intruding into pillow basalts. They argue organic matter was produced *in situ* along fissures and hydrothermal vents by chemoautotrophs, such as methanogenic bacteria. Catalytic hydropyrolysis of kerogens derived from chert from the komatiitic basalt yielded alkanes with a sharp decrease in homologues beyond C₁₈. Comparison with alkanes derived from modern cyanobacteria biomass suggests kerogen found in the Dresser Formation is biological in origin (Duda et al. 2018). Findings of Duda et al. (2018) are consistent with other alkane size-distributions yielded in analyses of Proterozoic kerogen (Ueno et al. 2001) and in cyanobacterial biomasses (Marshall et al. 2007).

Barite microspherules described by Baumgartner et al. (2020) are associated with stromatolites and pyrite laminations in the lowermost carbonate of the North Pole Member (Van Kranendonk et al. 2008). A biogenic origin for the barite precipitation is suggested by the porous internal textures produced in modern studies that demonstrate the precipitation of spherulitic barite around amorphous material (i.e., EPS and cellular surfaces; Stevens et al. 2015; Torres-Crespo et al. 2015; and Baumgartner et al. 2020). Additionally, framboidal and spherulitic barite aggregates precipitate at modern cold seeps rich in organic matter and in association with sulfur-reducing bacteria (Stevens et al. 2015; Baumgartner et al. 2020). Sulfur isotope analysis of the Dresser Formation chert-barite unit and chert veins supports the presence of local sulfate-reducing microbial communities (i.e., large δ³⁴S fractionations and I δ³³S/δ³⁴S slopes expected from microbial activity) (Philippot et al. 2007, 2009; Ueno et al. 2008).

Future Directions

The overall consensus is that the spectrum of stromatolites, MISS, microfossils, and chemical biosignatures in the Dresser Formation is witness to flourishing life of great diversity already in the early Archean. Studies in such old rocks on Earth deliver the criteria necessary for the exploration of extraterrestrial life in missions to Mars and other terrestrial planets.

Cross-References

- ▶ Abiotic
- ▶ Anoxygenic Photosynthesis
- ▶ Archean Environmental Conditions
- ▶ Archean Eon
- ▶ Bacteria
- ▶ Basalt
- ▶ Biogenicity
- ▶ Carbon
- ▶ Chemoautotroph
- ▶ Chemolithotroph
- ▶ Chert
- ▶ Cyanobacteria
- ▶ Environment
- ▶ Extremophiles
- ▶ Fossil
- ▶ Fractionation
- ▶ Fractionation, Mass Independent and Dependent
- ▶ Ga
- ▶ Gas Chromatography
- ▶ Hydrocarbons
- ▶ Hydrothermal Alteration
- ▶ Hyperthermophile
- ▶ Iron Oxidation
- ▶ Iron Oxides, Hydroxides, and Oxyhydroxides
- ▶ Isotope
- ▶ Isotope Biosignatures
- ▶ Kerogen
- ▶ Life
- ▶ Mars
- ▶ Mass Spectrometry
- ▶ Metabolism

- ▶ Microbial Mats
- ▶ Microbially Induced Sedimentary Structures
- ▶ Microfossils
- ▶ Oxidation
- ▶ Photosynthesis
- ▶ Pilbara Craton
- ▶ Precambrian
- ▶ Pyrite
- ▶ Raman Spectroscopy
- ▶ Reduction
- ▶ Stromatolites
- ▶ Sulfur
- ▶ Sulfate Reduction
- ▶ Sulfur Isotopes

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DTU Space, Denmark

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

- [Institut for Rumforskning og -teknologi](#);
- [National Space Institute, Denmark](#)

Definition

DTU Space, the conventional abbreviation for the National Space Institute at the Technical University of Denmark (DTU), was established in 2007 from the merger of several preexisting research groups and government laboratories, including the Danish Space Research Institute (DSRI). The DSRI had existed since the formation of the European Space Research Organization, which subsequently became the core of the European Space Agency (ESA). A key role for DTU Space is the development of instruments for the ESA Science Program, which enables Danish scientists to have access to scientific data from ESA missions. Another key national role is providing the research basis for a geodetic reference system for the kingdom of Denmark (Denmark itself, Greenland, and the Faroe Islands).

Cross-References

- [ESA](#)

Dual Status Objects

- [Active Asteroid](#)

Dubiofossil

Emmanuelle J. Javaux
Early Life Traces & Evolution-Astrobiology,
University of Liège, Liège, Belgium

Definition

A dubiofossil is a problematic structure that looks like a ► [fossil](#) but whose biological origin is uncertain or ambiguous. Several physical and chemical processes may produce structures resembling biological structures. In the recent literature, scientists also use the terms “putative,” “possible,” “probable” to designate an increasing confidence in the biological origin (biogenicity) of a structure, molecule, or pattern, while “pseudofossil” is used for an unambiguous abiotic structure, molecule, or pattern. Detailed analyses and criteria of ► [biogenicity](#) have to be applied on the dubiofossils to move them to the category of fossils (biogenic or biological structures) or ► [pseudofossils](#) (abiogenic or non-biological structures). This requires also a good understanding of the physico-chemical conditions of formation and preservation of the structure (the geological context and taphonomy), and observations at several scales. This is a crucial point when looking for early traces of life on Earth or for extraterrestrial life.

Cross-References

- [Biogenicity](#)
- [Biomarkers](#)
- [Fossil](#)
- [Microfossils](#)
- [Pseudofossil](#)

Dust Cloud, Interstellar

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Dark cloud](#)

Definition

Interstellar molecular clouds which lack obvious evidence of recent star formation, and hence which are observable because their dust grains block the light from background stars, are sometimes called dust clouds. Note that all ► [molecular clouds](#) do contain dust grains, whether or not they also contain stars.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)

Dust Devils

Barbara Stracke
Deutsches Zentrum für Luft- und Raumfahrt
(DLR), Institut für Planetenforschung, Berlin,
Germany

Definition

Dust Devils are meteorological phenomena that have been detected in the atmospheres of ► [Earth](#) and ► [Mars](#). They are thermally driven atmospheric vortices that are filled with loose materials such as dust and sand. The vertical velocity is predominantly upward. Their size ranges with heights from a few meters (on Earth and Mars) to several kilometers (only on Mars) and from a few meters to hundreds of meters in diameter. The first images of Dust Devils in the Martian atmosphere were taken by the ► [Viking](#) orbiter.

Cross-References

- [Earth](#)
- [Mars](#)
- [Viking](#)

Dust Grain

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Interstellar grain](#)

Definition

The small solid particles present in the interstellar medium are called dust grains or often simply either dust or grains. Most of them are only a few tenths of a μm in size. They consist of silicates and carbon compounds, coated in the coldest regions with icy mantles. They represent 1–2% of the mass of interstellar clouds. Their origin and composition are discussed in *interstellar dust*.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Ices](#)

Dwarf Planet

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

A dwarf planet according to the IAU (International Astronomical Union) Resolutions 5 and 6 (Resolution GA26-5-6, passed in 2006) is a celestial body of intermediate size, which orbits the Sun, is not a satellite, has not cleared the neighborhood around its orbit, and has sufficient mass for its self-gravity to maintain a nearly round shape. To date five dwarf planets have been

identified, namely, the asteroid ► [Ceres](#), ► [Pluto](#), Eris, Makemake, and Haumea, the latter three being ► [trans-Neptunian objects](#).

Cross-References

- [Ceres](#)
- [Pluto](#)
- [Satellite or Moon](#)
- [Sun \(and Young Sun\)](#)
- [Trans-Neptunian Object](#)

Dwarf Star

Jordi Isern
Institute for Space Sciences (ICE, CSIC),
Cerdanyola, Spain
Institute for Space Studies of Catalonia (IEEC),
Ed. Nexus, Barcelona, Spain
Fabra Observatory, Royal Academy of Sciences
and Arts of Barcelona (RACAB), Barcelona,
Spain

Definition

Ejnar Hertzsprung and Henry Norris Russell independently found the existence of stars with the same spectral type but different luminosities. Since the luminosity satisfies the relationship $L \sim R^2 T^4$, the most luminous ones must be larger than the dimmer ones and they coined the terms giant and dwarf stars. Based on the existing differences in the spectral features of stars with the same type, William W. Morgan and Phillip C. Keenan, from Yerkes Observatory, introduced the so-called “luminosity class” represented by a Roman number. One of these classes, the V one, was the Main-Sequence class, also known as dwarfs since normal stars at this stage have the minimum radius. However, since main-sequence blue stars have very large masses and radii, the term “dwarf star” is at present usually used to design main sequence stars with a mass equal or smaller than the Sun. For instance solar-like stars

are yellow dwarfs, and main-sequence M stars are red dwarfs. The term dwarf is also used in other stars having completely different properties but sharing a small size, like white dwarfs or brown dwarfs.

Cross-References

- [Brown Dwarf](#)
- [Hertzsprung-Russell Diagram](#)
- [Low Mass Star](#)
- [Main Sequence, Star](#)
- [Red Dwarf](#)
- [Spectral Type](#)
- [Stars](#)
- [Stellar Evolution](#)
- [White Dwarf](#)

Dynamic Kinetic Stability

Addy Pross
Ben Gurion University of the Negev, Be'er Sheva,
Israel

Keywords

Kinetic stability · Replicative stability · Kinetic irreversibility · Origin of life · Dissipative self-assembly · Persistence principle

Acronyms

DKS

Definition

A stability kind associated with physicochemical systems maintained in a cyclical nonequilibrium dynamic state through a continual supply of energy. Such cyclical nonequilibrium dynamic states are induced by kinetic, rather than thermodynamic factors, and their existence offers a kinetic perspective on the origin and nature of living systems.

Overview

Seeking a physicochemical characterization of the simplest living entity has long challenged the physical sciences. How can a simple living system be understood in physicochemical terms? How could such a system have emerged, and how can its unique biological characteristics, seemingly in defiance of conventional physical law, be explained? The recent discovery of the existence of a previously unknown kinetic dimension within chemical space (Boekhoven et al. 2015) has reaffirmed the existence of a stability kind in chemistry, dynamic kinetic stability, one applicable to energy-fuelled dynamic chemical systems (Pross and Khodorkovsky 2004; Pascal et al. 2013; Pross and Pascal 2013; Pross 2016, 2019; Pascal and Pross 2019). That stability kind allows the characterization of living systems in kinetic rather than thermodynamic terms, thereby offering new insights into the physical basis for life. Building on that kinetic base, together with established kinetic principles (Szathmáry and Gladkih 1989; Lifson 1997), suggests that a chemical replicative system, once activated into the DKS state, would be expected to evolve irreversibly toward increasing DKS (Pascal and Pross 2015; Danger et al. 2020). Accordingly, a strategy for the synthesis of dynamic nonequilibrium replicative systems, able to evolve and complexify – a model for simple protolife – now appears feasible (Pascal and Pross 2017; Yang et al. 2021). The existence of a kinetic dimension in chemical space, resting on the concept of dynamic kinetic stability, may help narrow the conceptual gap that has long divided the physical and biological sciences.

Cross-References

- Evolution, Chemical
- Free Energy
- Metabolism, Prebiotic
- Prebiotic Chemistry

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Dynamical Friction

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Dynamical friction is a force exerted by small objects that damps the random motions of large objects. This occurs via a gravitational “focusing” of small bodies behind the orbit of the large body. This is different than viscous stirring, which is simply an equipartition of energy between large

and small bodies. In the context of planet formation, dynamical friction from planetesimals acting on ► [planetary embryos](#) keeps the eccentricities and inclinations of the embryos relatively small such that collisions between embryos only occur once the planetesimal population is largely depleted.

Cross-References

- [Planetesimals](#)
- [Viscous Stirring](#)

References and Further Reading

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Dynamical Instability

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

A dynamical instability is a nonlinear response to a phenomenon that ultimately leads to a large-scale change in a system. This term may be applied to any type of dynamical system, such as orbits, atmospheres, interiors, etc. For example, during planet formation, the dust layer of a ► [protoplanetary disk](#) is compressed, increasing the density and ultimately coalescing the dust into ► [planetesimals](#). On a large scale, if the gas layer becomes cold enough and is massive enough, the gas can collapse into a ► [giant planet](#). After planet formation if two planets come close to each other, their orbits can be dramatically altered, perhaps even resulting in one being ejected from the system. In these examples, the particles (dust, gas, or planet) had been orbiting the star in the same way for a long time, but the orbit, or the particle itself,

was quickly (usually in just a few to a few thousand orbits) changed.

Cross-References

- [Ejection, Hyperbolic](#)

Dynamo, Planetary

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Keywords

Planetary magnetic field · Planetary magnetism

Synonyms

[Magnetic field generation](#)

Definition

A dynamo – generally – generates electric and magnetic energy from kinetic energy through the physical process of electromagnetic induction. A current will be induced in a closed wire moving through a magnetic field. The current by itself will generate a magnetic field. In planetary interiors, a similar although more involved mechanism can produce a global ► [magnetic field](#); convective flow of an electrically conducting material in a magnetic field will induce a current that will generate a magnetic field. If certain conditions are met, the magnetic field will maintain or amplify the original magnetic field.

Overview

Generation of a magnetic field requires an electrically conducting shell within a ► [planet](#), motion within that shell, and a “seed” magnetic field. For recent reviews on dynamo problems, see Busse

and Simitiev (2015), Christensen and Wicht (2015), and Roberts (2015). In the ► [terrestrial planets](#) and the satellites, this region is agreed to be the fluid iron-rich core at the center. In the ► [Giant Planets](#) ► [Jupiter](#) and ► [Saturn](#), the dynamo region is agreed to be the metallic ► [hydrogen](#) shell and in ► [Uranus](#) and ► [Neptune](#) a comparatively shallow layer of ionized fluid (see, e.g., Connerney 2015 for a review). In the terrestrial planets and satellites, there may be a solid inner core, the growth of which would provide a buoyancy flux that may drive the dynamo. This buoyancy then derives from a difference in composition between the solid inner core and the fluid outer core. Light alloying elements such as sulfur and oxygen tend to be expelled from the solidifying core and to form a buoyant layer above the inner core that tends to rise and mix with the outer core. In addition to (or instead of) a chemical buoyancy flux from the inner core, thermal buoyancy may drive the flow. The thermal buoyancy would result from a sufficiently large temperature difference between the core and the silicate rock ► [mantle](#) surrounding the core. Fluid cooled at the core-mantle boundary will tend to sink toward the center and thereby drive the convective flow. Thus, an entirely liquid core can support a thermal dynamo. There is a difference in efficiency between the thermal dynamo and the compositionally driven dynamo. While the thermal dynamo as a heat engine is subject to a Carnot efficiency (about 0.05, Gubbins et al. 2003), a compositionally driven dynamo is not as restricted. In the giant planets, thermal buoyancy is usually thought to drive the flow although helium droplets falling out of solution with hydrogen may provide a buoyancy flux (see Guillot and Gautier 2015 for a review). It should be mentioned that precession and tides have also been suggested to excite flow instabilities in the core and a dynamo (e.g., Tilgner 2015 for a review).

Convection in the dynamo region can be described by the field equations of fluid dynamics (e.g., Busse and Simitiev 2015). Because of the magnetic field, the electric currents, and the planetary rotation, the Lorentz and Coriolis force have to be included. The momentum equation then is

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} + 2\rho \mathbf{\Omega} \times \mathbf{v} = \nabla p + \rho \mathbf{g} + \mathbf{j} \times \mathbf{B} + \rho \mathbf{F}. \quad (1)$$

In Eq. 1, t denotes time, $\mathbf{v}$ is the fluid velocity, ρ is density, $\mathbf{\Omega}$ is the planet's rotational angular velocity vector, p is pressure, $\mathbf{g}$ is gravity, $\mathbf{j}$ is the electric current density, $\mathbf{B}$ is the magnetic induction vector, and $\mathbf{F}$ is the specific body force (buoyancy). Vector quantities are written in bold face. The first term on the left-hand side is the inertia term, and the second term denotes the Coriolis force. The first two terms on the right-hand side denote pressure variations and the hydrostatic pressure. The third term is the Lorentz force, where $\mu \mathbf{j} = \nabla \times \mathbf{B}$ with μ the magnetic permeability. The equation is supplemented by conservation of mass and entropy equations and by an equation of state.

The magnetic induction equation (written in a simplified form assuming a solenoidal velocity field and a constant magnetic diffusivity λ) is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \lambda \nabla^2 \mathbf{B}. \quad (2)$$

A sustained magnetic field can be generated by the flow if the production of field energy by shearing the field (first term on the right-hand side) overcomes the magnetic diffusion (second term on the right-hand side). The first term also shows that certain restrictions apply to the flow. A flow directed along the field lines, for instance, will not contribute to the dynamo. The relative weight of the two terms is measured by the magnetic Reynolds number

$$\text{Re} \equiv \frac{Ud}{\lambda}, \quad (3)$$

where U is a characteristic velocity and d a characteristic length (e.g., the core radius). The magnetic Reynolds number must be larger than 1 for the dynamo to operate. Other dimensionless parameter groups of relevance to the dynamo problem are the Rayleigh number that measures the vigor of the convection and the Ekman

number that measures the importance of the Coriolis force.

Numerical models of the dynamo driven by a buoyancy flux from below (a growing inner core) have been successful, but the models are still far from realistic values of both the Ekman and Rayleigh numbers. Nevertheless, a scaling law has been derived for the magnetic field strength at the surface of a core dynamo region (Christensen and Aubert 2006):

$$B \approx 0.9 \mu^{\frac{1}{2}} \rho^{\frac{1}{6}} \left(\frac{g Q_B d}{4\pi R_c R_i} \right)^{\frac{1}{3}}, \quad (4)$$

where Q_B is the buoyancy flux into the dynamo region (thermal and/or chemical) and R_c and R_i are the outer and inner radii of the core shell. The characteristic length d here is the thickness of the fluid core shell $R_c - R_i$. In this scaling, the magnetic field strength depends on the size of the core and the buoyancy flux but is independent of the electrical conductivity and of the rotation rate, although it is still required that the magnetic Reynolds number be larger than 1 and that in order to obtain a dipolar field, the Coriolis force must dominate over inertia. (The latter requirement is consistent with Cowling's theorem; see Roberts 2015.) The scaling is similar in conception to a scaling introduced by Stevenson et al. (1983), although the exponents in the power law differ. It is important to note that this scaling supersedes an older scaling law that was derived from a balance between the Lorentz force and the Coriolis force terms in Eq. 1. In the latter scaling – often used in the astrobiology literature when discussing the habitability of exoplanets – the magnetic field was considered proportional to the planetary rotation rate (see Hubbard and McFarlane 1980).

As Eq. 4 shows, the magnetic field strength depends on the rate of heat transfer through the mantle of a terrestrial planet or satellite. The buoyancy flux is directly related to the ► [heat flow](#) extracted by the planetary mantle from the core for a thermally driven dynamo. For a chemically driven dynamo, the rate of inner core growth and

therefore the rate of buoyancy release depend on the core cooling rate and therefore – again – on the heat flow from the core. The heat flow from the core can be calculated from thermal history models. This underlines an important property of terrestrial planets: A terrestrial planet may or may not have a magnetic field, and the existence of a field is not easily predicted from observations of bulk planetary parameters.

Cross-References

- [Core, Planetary](#)
- [Exoplanets, Discovery](#)
- [Giant Planets](#)
- [Heat Flow, Planetary](#)
- [Heat Transfer, Planetary](#)
- [Hydrogen](#)
- [Jupiter](#)
- [Magnetic Field, Planetary](#)
- [Mantle](#)
- [Neptune](#)
- [Planet](#)
- [Rotation Planet](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Terrestrial Planet](#)
- [Tides, Planetary](#)
- [Uranus](#)

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E

E

► [Redox Potential](#)

E_a

► [Activation Energy](#)

EADS

► [Venus Express](#)

EANA

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The European Astrobiology Network Association (EANA) was organized in Spring 2001 during the First European Workshop on Astrobiology co-organized with ► [ESA](#) at the ESRIN research facility in Frascati, Italy. Acknowledging that there are numerous centers of excellence in astrobiology in Europe, founders decided to promote their work by setting up this European Network to help the sharing of their expertise

and facilities. This network aims also to attract young scientists to participate practically in this evolving interdisciplinary field. Other goals are the promotion of astrobiology to European funding agencies (ESA, ESF) and political bodies such as the European Commission. Finally, individual members as national associations are invited to promote a public interest in astrobiology.

Up to 2010, scientists or organizations of 19 European countries are participating in this network: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Portugal, Spain, Sweden, Switzerland, The Netherlands, Poland, Romania, Russia, and the UK. EANA holds annual workshops alternately in the different member countries.

EANA was established as an affiliate partner of the NASA Astrobiology Institute in early 2002. EANA is also associated with the Commission of Astrobiology, Space Life Origin and Evolution at the Chinese Society of Space Research, and the Japanese Astrobiology Network.

For further information, visit <http://www.astrobiologia.pl/eana/>.

Early Earth

- [Archean Tectonics](#)
- [Cool Early Earth](#)
- [Hadean](#)

Earth

Daniele L. Pinti

GEOTOP Research Center for the Dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Definition

The Earth is the planet on which we live. It is the third planet from the Sun and one of the four telluric (or rocky) planets situated in the inner part of our ► [Solar system](#). It is a differentiated planetary body, which means that the elements composing the planet were redistributed based on their physical or chemical behavior (e.g., density and chemical affinities). The Earth is differentiated into the Fe-Ni metallic core, two silicate shells, the ► [mantle](#) and the ► [crust](#), the ocean, and the atmosphere. The crust is further differentiated in ► [oceanic crust](#), made essentially of ► [basalt](#), ► [gabbro](#), and ► [peridotite](#), and a ► [continental crust](#) essentially made of not only more felsic Al-rich silicate rocks such as igneous andesites and granites, but also sediments and metamorphic rocks. It is distinguished from other rocky planets of our Solar system by the near absence of old cratered surfaces – wiped off by more than 4 Gyrs of tectonic and ► [weathering](#) processes, by the presence of oceans and of a thick atmosphere. Earth is so far the only planet in the Universe where life is demonstrably present.

Overview

The Earth is the only easily accessible natural laboratory for astrobiologists to study planetary conditions which can favor the initiation of life. ► [Titan](#), the Saturn's moon, is considered the Earth at its prebiotic stage, i.e., when inorganic or organic chemical reactions took place producing some sort of ► [primordial soup](#) in a natural environment before the advent of life. Therefore, the geological conditions prevailing

at the surface and inside the Earth since its beginning are important in order to assess plausible scenarios of environmental conditions where life could have flourished. Here below, a very first-order and raw overview of the early evolution of Earth is reported. Specific entries of the Encyclopedia (several here suggested) are necessary to be read for having a larger vision of the several concepts here briefly introduced.

Earth has a mean radius of 6371 km and a mean density of 5.513 g cm^{-3} , the latter comparable to that of planet ► [Mercury](#) (5.43 g cm^{-3}). It is the largest of the rocky planets of the Solar system, with ► [Venus](#) slightly smaller (radius of 6052 km). Its distance from the Sun is around 149 million kilometers which corresponds to 1 ► [AU](#) (astronomical unit), for convenience. The Earth accreted in the inner Solar system, somewhere between the present-day orbits of Mercury and Venus and a few tenths of million years after the formation of the Solar system (e.g., Canup 2008; Yu and Jacobsen 2011), estimated at 4.57 Ga ago (e.g., Bouvier and Wadhwa 2010; Connelly et al. 2017). The Earth is differentiated, i.e., elements composing the accreted planet were redistributed according to their densities (gravitational differentiation: heavier metal down in the core, lighter silicates up in external shells, and volatiles outside) and chemical affinities (chemical differentiation). Planetary differentiation was triggered by melting caused by latent heat of accretion, heat from decay of long-lived and short-lived ► [\(extinct\) radionuclides](#). The timing of this differentiation is still a matter of debate, and mainly based on measurements of short-lived isotopic systems such as $^{144}\text{Nd}/^{142}\text{Nd}$ (Boyet and Carlson 2005) or $^{182}\text{Hf}-^{182}\text{W}$ (Kleine et al. 2009), which suggest differentiation took place somewhere between 30 and 200 Ma after the accretion of the Earth (Nimmo and Kleine 2015). The first protocrust of the Earth was likely mafic in nature and basaltic in lithological composition. More felsic continental crust developed at a later stage by remelting the felsic crust (*anatexis*) and production of granitoids. This process took a long time, and models suggest that continental crust had

reached a volume similar to its modern value by 3.0 Ga ago. Present-day composition (andesitic-granitic) of the continental crust could have been reached even later. The advent of plate tectonics, as we know it today, is not well dated. It may have appeared early and possibly operated with slightly different mechanisms. Some authors suggest, however, that it was not at work before 3.0 Ga ago or even later. This process is very important because it regulates any exchange of energy, heat, elements, and potential nutrients from the hot interior of the Earth to the surface and back to the mantle, and likely played a key role in favorizing development of life (e.g., Hall 2017). Primitive secondary atmosphere of the Earth, brought by asteroidal and cometary impacts, was likely composed dominantly by the CO₂ (>95% v/v) and N₂ (<5% v/v), as are the present-day residual primitive atmospheres of Venus and Mars (e.g., Pinti 2021). It is possible that other greenhouse gases such as CH₄ were present which compensated the weak luminosity of the Sun (► **Faint Young Sun Paradox**) and maintained the surface of the Earth above freezing (Pavlov et al. 2000). This atmosphere evolved toward an N₂-O₂-dominated atmosphere through eons, by progressively locking CO₂ into carbonates (CO₂ geological sequestration) and adding O₂ by a complex interplay of increasing sources (bacteria respiration) and reduction of sinks (reduced to oxidizing volcanic gases; organic matter preservation in sediments) (Catling 2015).

It is generally held that the planet Earth initially was an inhabitable inferno too hot for any kind of organism, including extremophiles, to survive. More clement climatic condition at the surface of the Earth (► **Cool Early Earth**) was nevertheless established within a few hundred million years. This was clearly established by oxygen isotopes in some of the Jack Hills zircons (Australia), a ubiquitous minor mineral of granites. Some of these zircons older than 4.1 Ga show excess ¹⁸O relative to mantle-derived rocks, which indicates that the source of their parent granites included low-temperature sediments and therefore that liquid water was undoubtedly present at the surface of the Earth.

Cross-References

- **Archean Eon**
- **Cool Early Earth**
- **Earth, Age of**
- **Earth's Atmosphere, Origin and Evolution of**
- **Earth, Formation, and Early Evolution**
- **Extinct Radionuclides**
- **Hadean**
- **Moon, The**
- **Oceans, Origin of**
- **Oxygenation of the Earth's Atmosphere**
- **Water, Delivery to Earth**

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Earth's Atmosphere, History of the Origins

Stéphane Le Gars

Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Ampère · Atmosphere · Kant-Laplace
cosmogonic hypothesis · Koene · Lavoisier ·
Rubey · Vernadsky

History

If the scientific investigation of the atmosphere really started in the seventeenth century, the problem of its origin was taken into account only two centuries later. It is indeed with the works of Galileo Galilei, Blaise Pascal, and Robert Boyle that the notion of pressure and temperature permitted to study in a quantitative way the atmosphere. John Mayow, Boyle's student, concluded, in an empirical way, that the air is a two-body mixture out of which one takes place at once in breathing and burning. In 1777, Antoine-Laurent de Lavoisier initiated an analysis and synthesis of air, and found out the "aerial nitrogen" and "oxygen" terms to name the two gases of the atmosphere. In his memoir "*Vues générales sur la formation et la constitution de l'atmosphère*," Lavoisier even thought of the possibility of the existence, at a high altitude, of a hydrogen film, which would sometimes be destroyed completely by combustion and would form again by the continual decomposition of plant and animal matters generated at the earth's surface.

In 1833, the French physicist André-Marie Ampère drew the conclusions from Laplace's hypothesis concerning the solar system origin and, taking up the Lavoisier's point of view and expressing the idea that the earth's atmosphere results from a reduction of bodies oxygenated by metals, leading to a nitrogen release originally combined to oxygen, explaining also the origin of oxygen in the atmosphere. As far back as 1856,

the Belgian chemist Cornille Jean Koene considered a link between oxygen and carbonic acid gas, inferring the lack of oxygen gas in the original terrestrial atmosphere because of a reducing medium due to the occurrence of metal or sulphide compounds. Finally, in the 1920s, the Russian Wladimir Vernadsky introduced, by his biosphere concept, the idea of a balance between atmosphere and human beings: for him, gases of the atmosphere are in an equilibrium state of dynamic and perpetual exchange with living matter.

It is only in 1951 that American geologist William Rubey in a seminal paper (Geologic history of sea water: An attempt to state the problem) that a modern theory of the origin of the atmosphere shaped up. Rubey proposed that the Earth's atmosphere did not originate from the weathering of the continental crust, a view that was popular among geologists at that time, but rather originated from volcanic degassing throughout geological times. The development of the noble gas geochemistry in that period supported this view. Von Weizsäcker (1937) clearly understood that the gaseous argon-40 was a product of degassing of the solid potassium-40 which resides in the crustal rocks. Analyses of radiogenic nuclides of neon, argon, and xenon in the 1980s (Allègre et al. 1986/1987) allowed quantifying a chronology of the degassing and demonstrated that majority of atmospheric gases did not derived from primordial gases from a primitive solar nebula but rather added shortly later the formation of the Earth by meteoritic and/or cometary material (Dauphas 2003).

Cross-References

► [Earth's Atmosphere, Origin and Evolution of](#)

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Earth's Atmosphere, Origin and Evolution of

Bernard Marty

Centre de Recherches Pétrographiques et
Géochimiques (CRPG), CNRS, Université de
Lorraine, Nancy, Cedex, France

Keywords

Atmosphere · Carbon · Comets · Mantle
volatiles · Meteorites · Nitrogen · Noble gases ·
Water

Definition

The Earth's atmosphere is a thin gaseous layer made of oxygen, ► **nitrogen**, and trace gases. It permits a mild temperature and provides a protection against cosmic rays, solar wind, and meteorite falls. It was stable enough through geological time to have nurtured the development of life.

Originally, the atmosphere consisted of water, carbon dioxide, nitrogen, sulfur, and ► **noble gases**, and it evolved by condensation of water to form the oceans, trapping of ► **carbon** in carbonates and organic matter, and biogenic production of oxygen. The Earth's atmosphere originated probably from the addition of bodies from the asteroid belt between Mars and Jupiter toward the end of terrestrial formation.

Overview

The Earth's atmosphere consists mainly of oxygen (20.95% O₂) and nitrogen (78.078% N₂), the other constituents making only 1% of the total volume: argon (0.934%), CO₂ (preindustrial: 280 ppm vol/vol), and noble gases. This composition is unique among planetary atmospheres: atmospheres of the giant planets (Jupiter, Saturn, Uranus, Neptune) are dominated by hydrogen and helium, reflecting the composition of the protosolar nebula, whereas the atmospheres of the inner planets, Venus and Mars (Mercury does not possess an atmosphere), are rich in CO₂, the concentration of N₂ being of the order of a few %. The high oxygen content of the terrestrial atmosphere is a byproduct of the development of life. Oxygen is produced by photosynthesis, a mechanism that uses solar photons to break down and oxidize organic molecules. Without life, oxygen would disappear in a few thousand years due to iron oxidation in terrestrial rocks. The very low CO₂ content of air is the result of trapping of carbon in rocks, either as carbonates or as organic matter buried in the crust. If carbonates were dissociated to release CO₂, the resulting atmospheric pressure would be around 27 bars, and the CO₂/N₂ ratio would be comparable to those of Venus and Mars atmospheres. Oceanic water, which is liquid under the Earth's surface conditions but was probably gaseous during the formation of the Earth, was part of the early atmosphere. If oceanic water was vaporized and oceanic halogens (components of salt) transformed into their gaseous forms (HCl, HF, HBr), then the atmospheric pressure would be 220 bar instead of 1.01 bar, and the Earth's surface would be an

inferno hostile to life. The reason why Earth escaped such hellish fate (while Venus kept CO₂-rich atmosphere with a pressure of 90 bar and a surface temperature of 450 °C) is unclear and is the focus of active research.

Origin of the Terrestrial Atmosphere

The “reconstructed” atmosphere’s composition, that is, the sum of volatile elements in the air, in the oceans, and in sedimentary rocks, consists of 86% water vapor, 12% CO₂, 1.4% HCl + HF, and 0.2% N₂. This composition is quite comparable to that of volcanic gases emitted by active volcanoes. This observation led Williams W. Rubey, a geologist at the US Geological Survey, to propose that the Earth’s atmosphere did not originate from weathering (chemical alteration) of the continental crust, a view that was popular among geologists at that time, but rather originated from volcano degassing throughout geological times (Rubey 1951). In support of this view was the discovery of the decay of ⁴⁰K (a rare isotope of potassium) producing ⁴⁰Ar, the most abundant isotope of the noble gas argon. In fact, the 0.934% abundance of Ar in the air is almost entirely due to ⁴⁰Ar, the other more abundant argon isotope, ³⁶Ar, having an atmospheric concentration of only 32 ppm vol. The discoverer of the ⁴⁰K decay, Von Weizsäcker, a German physicist in pre-World War II Germany, noted correctly that the high ⁴⁰Ar content of air was the result of the ► [degassing](#) of the “solid,” silicate-rich Earth, where potassium resides (Von Weizäcker 1937). This key observation led to the concept of atmospheric formation by degassing of volatile elements trapped in the mantle. This concept was refined using noble gases. Some of the isotopes of the chemically inert elements, now in the atmosphere, were produced by natural nuclear reactions like radioactive decay and spontaneous fission of parent elements contained in the mantle and crust, thus establishing a chronology of atmospheric formation. The terrestrial mantle also contains volatile elements including noble gases. A comparison of noble gas isotopic compositions between the mantle (which can be sampled in

basalts originating from mantle melting) and the atmosphere shows that the latter formed very early in the Earth’s history, within ~100 Ma after the start of solar system formation, 4.57 Ga ago (Ozima 1975; Staudacher and Allègre 1982).

There is evidence that a source other than mantle degassing contributed to atmospheric formation. On the one hand, models of ► [solar system](#) dynamics suggest that the Earth formed in a region of the nascent solar system that was too energetic to permit trapping of volatile elements into planetary embryos. Therefore, it has been proposed that terrestrial volatiles might have been contributed directly by impacting of bodies originating away from the present-day Earth radial location, in a region between Mars and Jupiter where volatile-rich meteorites, called the carbonaceous chondrites, originate. From dynamical reasons, these contributions might have happened toward the end of the terrestrial accretion once more than 90% of the Earth was formed (Morbidelli et al. 2000). On the other hand, the noble gas isotopic composition of ► [mantle volatiles](#) is significantly different from that of the atmosphere, which suggests either different cosmochemical sources for the mantle and the atmosphere (Marty 1989) or drastic atmospheric processing such as escape of volatiles to space that could have fractionated noble gas isotopes (Pepin 1991). In particular, the isotopic composition of mantle neon is close to that observed in the solar nebula (Sarda et al. 1988), which suggests that part of volatile elements originated from the nebular gas or from matter implanted by ions from the young Sun. This problem is not yet resolved, but some insight arises from the stable isotopes (i.e., the isotopes that are not produced or destroyed by nuclear reactions) of water and nitrogen. The ratios of the two hydrogen isotopes from the water molecule, D/H (where D stands for deuterium, or ²H, and H for ¹H), and of the two isotopes of atmospheric nitrogen, ¹⁵N/¹⁴N, are comparable to values found in primitive meteorites, also called chondrites (Marty 2012; Alexander et al. 2012). They are markedly different from the isotopic signatures of the cloud of gas and dust that collapsed to form the solar system and from isotopic ratios measured in comets

(another potential source of atmospheric volatiles, since comets, which come from the outer solar system beyond the orbit of Neptune, are very rich in volatile elements with water making up to 50%). Hence, major volatiles like water and nitrogen, and probably carbon too, seem to originate mostly from bodies within the inner solar system, akin of present-day asteroids between Mars and Jupiter. This scenario is consistent with dynamical models advocated above in which volatile-rich asteroidal bodies contributed to Earth toward the end of accretion. These bodies were not necessarily big, and gas-rich dust like interplanetary particles or micrometeorites could have played a significant role (Maurette et al. 2000). Mass balance considerations involving siderophile as well as lithophile elements indicate that the contribution in volatile-rich material at the end of accretion could have made only $\sim 0.3\%$ of the total terrestrial mass. However, the amount of terrestrial volatiles is equivalent to about 2% carbonaceous chondrites, which suggests that the supply of volatiles to the proto-Earth was a continuous process and was not restricted to the last stages of terrestrial accretion (Marty 2012). Recently, the in-situ analysis of noble gases in the coma of comet 67P/Churyumov-Gerasimenko by the ESA Rosetta mission established a genetic link between cometary volatiles and the terrestrial atmosphere, suggesting that about 20% atmospheric Xe and Kr could be cometary (Rubin et al. 2018).

Atmospheric noble gas isotopes indicate also that the early atmosphere had been escaping to space for prolonged periods of time of the order of several hundreds of million years, as a result of intense UV irradiation by the early Sun, which dissociated the water molecules (Hunten et al. 1987). Meanwhile, large bodies battered the Earth, resulting in large-scale melting and vaporization. Such high temperature episodes did not last for more than 1 or 2 Myr due to radiative heat loss into space, and, at some stage, the water vapor started to condensate to form the oceans. According to the isotopic record of some rare, very ancient, $\blacktriangleright$ [zircons](#), liquid water might have existed as soon as 4.37 Ga ago, that is, only ~ 150 Ma after the start of terrestrial accretion. Besides water, the Earth's surface needed to get

rid of CO_2 also: this species, the likely prevalent form of carbon in the early atmosphere, is a strong greenhouse gas that, if abundant, could have prevented cooling of the Earth's surface to the condensation temperature of water. How this took place is unclear: carbon might have been efficiently returned to the mantle by subduction (Zahnle 2006), or it could have formed carbonates, providing that liquid water was available and Ca^{2+} ions were removed by surface alteration of basalts.

It is probable that, before 3.8 Ga ago, large ocean volumes already existed, as indicated by the occurrence of sedimentary rocks in geological formations of this age. The carbon isotopic composition of graphitic inclusions, encapsulated in apatite in quartz from 3.86 Ga-old meta-sedimentary rocks from $\blacktriangleright$ [Akilia](#), West Greenland, suggests that life already existed (Mojzsis et al. 1996), but this record is still controversial. Around 3.8 Ga ago, a $\blacktriangleright$ [Late Heavy Bombardment](#) (LHB) of extraterrestrial material is recorded at the lunar surface by Maria craters dated at 3.85–3.85 Ga (Tera et al. 1974). Scaled to the Earth's dimensions, the LHB would have contributed an average thickness of about 200 m of extraterrestrial matter onto the whole Earth's surface. Modeling of solar system dynamics suggests that the LHB was due to a large-scale perturbation of the outer solar system and that both comets and asteroidal bodies were involved (Gomes et al. 2005). This episode had certainly significant impact on the atmospheric composition (and on the survival of living matter, if any), but such effect is presently unknown.

The composition of the early atmosphere is constrained by the rock record. The composition of ancient lavas called $\blacktriangleright$ [komatiites](#) indicates that their oxygen fugacity (a measure of the oxidation state of a mineral assemblage) was close to that of modern lavas (Canil 2002). The gas phase in equilibrium with such a molten magma contains water vapor, CO_2 , and N_2 as the main species of H, C, and N. Hence, the early atmosphere of the Earth in the Hadean (4.4–3.8 Ga) was probably oxidizing and not reducing as proposed from experiments aimed to produce amino acids in a reduced gas mixture upon electric discharges

(Miller 1953). How oxidizing the atmosphere was during the first 1–2 Ga is not clear yet. Sulfur in sedimentary rocks of the Archean eon (the geological eon between 3.8 Ga ago and 2.5 Ga ago) contains isotopic anomalies that are best explained by interactions between atmospheric species and ultraviolet irradiation of the Sun. At present and presumably since 2.4 Ga, most of solar UV irradiation is absorbed in the higher atmosphere by oxygen species, notably ozone. Hence, the evidence from sulfur isotopes that UV photons could penetrate deep in the atmosphere has been taken as evidence that free oxygen was not present in the atmosphere until 2.4 Ga ago (Farquhar et al. 2000).

During the first half of the Earth's history, the Sun was less luminous, and the energy reaching the terrestrial surface was ~25% smaller than the present-day one (Kasting 1993). However, no glaciation took place in the Archean eon (the so-called ► [faint young Sun paradox](#)), and there is evidence that the oceans were hotter, up to 70 °C on average, than the present-day oceans (Robert and Chaussidon 2006; ► [Precambrian Oceans, Temperature of](#)). More CO₂ in the Archean atmosphere might have helped in keeping the Earth's surface warm, but the required level is beyond what the sedimentary record from this time has preserved in terms of CO₂ partial pressure (e.g., Shaw 2008). The existence of methane in the Archean atmosphere requires a strong source, and the only significant one could be CH₄-producing bacteria. Alternatively, it has been proposed that more N₂ in the atmosphere would have helped to preserve a significant greenhouse effect in the Archean, by increasing Rayleigh backscattering (Goldblatt et al. 2009). However, the fossil record of the Archean atmospheric N₂ pressure is not consistent with a high partial pressure of N₂ in the Archean atmosphere (Som et al. 2012; Marty et al. 2013) and even suggests a much lower pressure than today. Hence the faint Sun paradox requires another type of explanation, which is still discussed. There is no consensus about the time of appearance of free oxygen in the atmosphere, a strong indication of colonization of the Earth's surface by living matter. Different lines of evidence point

to a (geologically) brutal increase of the partial pressure of O₂ around 2.35 Ga ago, the Great Oxygenation Event when life-related sources of oxygen took over oxygen consumption by basalts (Holland 2002), and the isotopic signature of sulfur in sedimentary rocks discussed above seems to support this view.

Future Directions

There is no doubt that significant advances in our understanding of the origin and evolution of the atmosphere will arise in the near future. First, several planetary missions are documenting potential extraterrestrial sources of volatile elements to terrestrial planets. The NASA Genesis mission has sampled solar wind ions for 27 months with the aim to analyze the isotopic composition of the Sun. The ► [Stardust mission](#) has sampled cometary grains, and one of the objectives of the mission is to investigate possible links between cometary matter and volatile elements of the terrestrial planets, and missions are on the way or under development to sample and analyze in situ comets and asteroids. The analysis of other planetary atmospheres has allowed better insight in the origin of atmospheres of giant and inner planets. The in-situ analysis of the Martian atmosphere has allowed exceptional insight into the evolution of the atmosphere of the red planet (Conrad et al. 2016), and several missions are now targeting the composition of Venus and its atmosphere. In parallel, the analysis of ancient sedimentary rocks with low metamorphic grade will help to better constrain the composition and thermal state of the atmosphere and oceans in the past, and several drilling projects in ancient terranes ► [Archean drilling projects](#) are sampling unaltered rocks for this purpose.

Cross-References

- [Carbon](#)
- [Faint Young Sun Paradox](#)
- [Great Oxidation Event](#)
- [Mantle Volatiles](#)

- [Nitrogen](#)
- [Nitrogen Isotopes](#)
- [Noble Gases](#)
- [Oceans, Chemical Evolution of](#)
- [Oceans, Origin of](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Stardust Mission](#)

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Earth, Age of

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Keywords

Accretion (planetary) · CAIs · Chondrules · Decay constant · Geochronology · Meteorite · Radioactivity · Radiogenic isotopes

Definition

The age at which material condensed from the ► [Solar Nebula](#) ceased to significantly add to the Earth.

History

Around 1850, British physicist Lord Kelvin (William Thomson) elaborated on the theory of heat conduction formulated by the French physicist and mathematician Joseph Fourier and concluded that the Earth was no more than a few tens of Ma old. Kelvin also fiercely opposed the geologists who guessed from modern sedimentation rates that the Earth was older than a billion years. However, by World War II, the general agreement among scientists was that the Earth was older than 3 billion years. It is often incorrectly stated that Kelvin's mistake, one of the most devastating in the history of modern physics, was due to his ignorance of radioactive heating. It was British geologist Arthur Holmes who pointed out that the loss of heat from the interior of the Earth is largely controlled by mantle convection. In 1954, American geochemist Clair Patterson brought the controversy to an end by showing that meteorites and the Solar System are some 4.55 Ga old and that the age of the Earth cannot be very different.

Overview

Even though the age of our planet is occasionally presented as controversial, mostly on religious grounds, all scientists agree that it started forming some 4567 million years ago. Two real issues cloud the discussion. First, there is no original rock sample of that age left on our planet: the oldest crustal segment is 3.8 Ga old (Isua Supracrustal Belt, West Greenland), the oldest rock is some 4.1 Ga old (Acasta gneiss, Canada), while the oldest undisputable mineral ages are 4.3 Ga old detrital zircons (Jack Hills, Western Australia). The problem of the age of the Earth is therefore best addressed by dating the earliest objects of the Solar System, the calcium-aluminum-rich refractory inclusions (► [CAIs](#)) found in some chondritic meteorites and applying a comparative chronology based on extinct radionuclides to both terrestrial samples and meteorites in order to date the Earth's formation. The U-Pb age of CAIs is rather well established at 4568.0 ± 0.5 Ma. The small glass blebs found in

chondrites, which are known as ► [chondrules](#), are 1–3 Ma younger than the CAIs. The ► [radioactivity](#) of the extinct ^{182}Hf nuclide ($T_{1/2} = 8.5$ Ma) requires that the terrestrial core segregated 30 Ma after the formation of CAIs, which places a strong constraint on the age of the planet itself. Similar, but less tight constraints are placed by other extinct nuclides (^{129}I , ^{244}Pu) and by ^{235}U . The early Solar System evolved by condensation of the nebular gas followed by dust agglomeration and then by coalescence of asteroid-sized bodies and their merging into a few tens of protoplanets. A second issue therefore is a matter of definition: how long did the accretion stage last? Astronomical evidence indicates that UV and X-rays emitted by proto-(T-Tauri)-stars similar to the Sun had blown off the nebular gas and that the disk of debris was swept clean in less than 5 Ma. Dynamic models suggest that the period during which protoplanets merged to form planets as we know them today may have lasted for a few extra tens of Ma.

Cross-References

- [Earth's Atmosphere, History of the Origins](#)
- [Geochronology](#)
- [Radioactivity](#)

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Earth, Formation, and Early Evolution

Stephen Mojzsis
University of Colorado, Boulder, CO, USA

Keywords

Acasta · Akilia · Basalt · Continents · Core (planetary) · Cosmochemistry · Crust · Early

Earth · Earth's atmosphere (origin and evolution of) · Geochronology · Granite · Hadean · Impact processes · Isotopes · Isua · Jack Hills · Late heavy bombardment · Moon-forming impact · Oceans (origin of) · Solar system · Zircon · Biopoesis · Geochemistry · Lithosphere · Protolith

Definition

Earth formed as a silicate- and metal-rich body in the same context of the other inner Solar System “terrestrial” worlds. In its early evolution, it separated into layers (core, ► [mantle](#), ► [crust](#)) because of the chemical and mechanical properties of the materials that accreted to the Earth. The surface zone stabilized within the first 100 million years of Earth's existence and has hosted geochemical cycles modulated in whole or in part by the presence of liquid water and an atmosphere since about 4.4 Ga ago.

Overview

Introduction

Earth is a natural and accessible planetary-scale laboratory to test ideas to be used in the search for life elsewhere in the solar system and beyond. An understanding of Earth's origin is essential to the discipline of astrobiology, at least for the reason that this planet is the singular known repository of Life. Studies of the origin and early evolution of Earth have undergone dramatic shifts in recent years and have radically changed our knowledge of its formative time and how early events led to a habitable planet. This knowledge logically forms the basis of ongoing searches for other habitable solar system's exoplanets in the galactic neighborhood. More than 4000 planets around other stars have been documented by various methods, mostly within a sphere of space around $3 \times 10^9 \text{ ly}^3$ (ly = light years). Yet it remains to be seen whether the specific orbital architecture of our solar system that includes habitable rocky ► [“terrestrial planets”](#) with liquid water within a few

astronomical units of a G-type star is exceptional or commonplace.

Early Earth was a vastly different planet from the one we are so familiar with today. The surface was heated from below by radioactivity, thermal conduction through the ► [crust](#), and vigorous small-scale convection cells of ► [magma](#) and mainly from above by the muted radiation of a faint young Sun and by occasional meteoritic impacts. At first glance, it should have been uninhabitable. However, if there were liquid water, organic chemicals, and energy – all of which were present on this primeval surface – it is not unreasonable to suppose that the primordial chilled crust was the first platform in which processes of prebiotic chemistry, leading to the emergence of life (► [origin of life](#)) could have taken hold. Whatever the composition of the first crust was, the surface zone remained under a super-greenhouse atmosphere that kept temperatures within the stability field of liquid water.

The early terrestrial hydrous surface was continuously reworked by volcanic eruptions and meteoritic impacts that mitigated its long-term survival, which may be the reason why the oldest surviving terrestrial rocks or minerals date from 150 Myr after accretion (Harrison 2009). The long residence times of the oldest rocks in the crust means that almost any geological process could have been experienced by them. Over the intervening several billion years, ► [weathering](#), denudation, erosion, ► [metamorphism](#) (thermal, chemical, pressure induced, or all of the above), plate tectonics' subduction, remelting, reworking, and other crustal recycling processes had been at work to consume all but a minute fraction of what once existed from the first billion years of geologic time. Investigations focused on the origin of the hydrosphere and on when the crust evolved into the current basaltic (oceanic) and granitic (continental) dichotomy rely almost completely on information gleaned from a few outcrops or isolated minerals within much younger rocks from the oldest surviving terranes (Blichert-Toft and Albarède 2008).

That by 4.0 Ga the basaltic and the granitic crust was established on Earth and oceans as well as a rock cycle and the generation of

sediments is directly supported by the existence of metamorphosed remnants of granitoid rocks and isotopic systems. Yet older evidence from the geochemistry of detrital zircons (Jack Hills) tracks back to 4.4 Ga and shows that oceans and plate boundary processes (possibly plate tectonics?) could also have been present in the Hadean (Hopkins et al. 2008). Hence, the old prevailing view of a largely molten surface blasted by sterilizing impactors and intrinsically incapable of hosting life until after 3.8 Ga has been superseded by new data. The new view of the Hadean eon (4.567–4 Ga; see ► [Cool Early Earth](#)) and subsequent Eoarchean (4.0–3.6 Ga) favors by far an earlier origin of life than had previously been thought (Fig. 1).

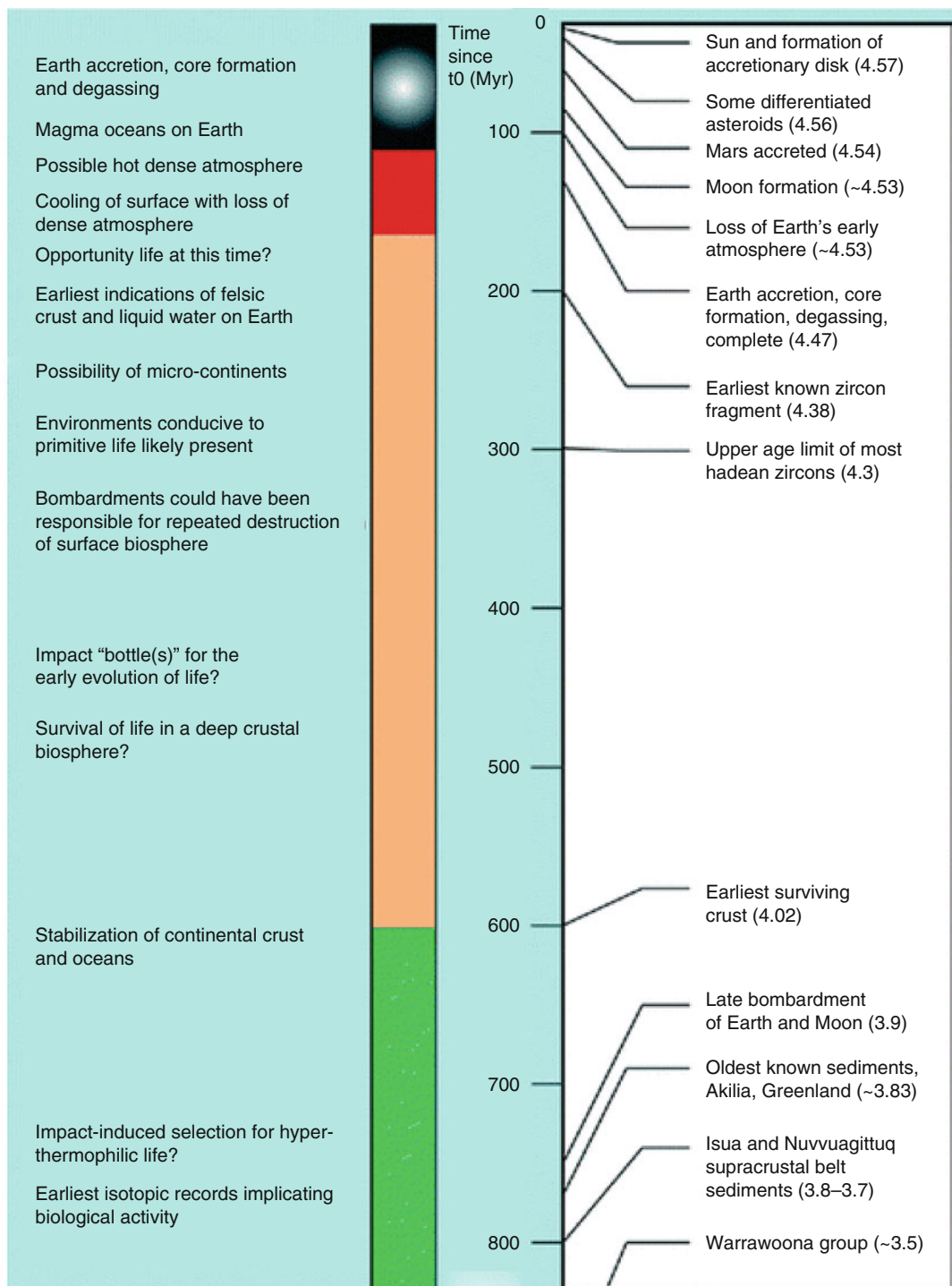
Early Solar System, Earth, and Moon

The age of the solar system is calculated to be about 4.568 Ga (Connelly et al. 2008; Bouvier and Wadhwa 2010) based on geochronological studies of (CAIs = Calcium-Aluminum-rich Inclusions). CAIs are the earliest solids that are native to the solar system, which crystallized in the solar nebula before their eventual incorporation into meteorites. The paradigm for solar system formation begins with the collapse of part of a giant molecular cloud that itself formed from gas and dust expelled in the explosion of one or more massive stars. While the exact mechanisms responsible for the initiation of nebular collapse are unclear, nearby supernova explosions played a role in the initial gravitational/mass instabilities of the cloud based on the presence of the daughter products of some extinct short-lived nuclides in the oldest solids. Direct astronomical observations of giant molecular clouds containing young stars show that disk collapse and probable incipient dust grain formation around such stars is commonplace. In the planet-forming process, these grains aggregated into larger objects and eventually to planetesimals that were the building blocks of the planets.

A detailed chronology of the earliest events in the solar system, which span the time from the first solids through the origin of the planets and ultimately to the formation of the ► [crust](#), ► [hydrosphere](#), and biosphere, will long be an area of intense study. The physics of Earth

accretion has been explored in detail with sophisticated dynamical computational tools that model the interactions of planetesimals that led to the growth (and in some cases the destruction) of ever-larger bodies. Numerical simulations of terrestrial planetary growth succeed in modeling the formation of planets of the size and distribution as Mercury, Venus, Earth, and Mars. Such models show that most of the mass of the Earth accreted in 10 Myr but that there is an accretionary tail, which extends for an additional 100 Myr. Most of these dynamical models seem to indicate that the colliding planetesimals that built the terrestrial planets came from beyond Mars' orbit, or well beyond 2 AU (astronomical unit), and delivered volatile elements and compounds to the intrinsically dry, hot, inner solar system well inboard from the solar system's "frost line" close to the asteroid belt. The climaxing event in the Earth's formation and earliest evolution is the origin of the Moon, which was the result of the last big impact to affect the Earth.

The current paradigm favors the origin of the Moon no earlier than about 30 Myr into the history of the Solar System (i.e., from what is termed "t-zero" at 4.568 Ga). Model studies indicate that the Moon originated from a massive collision of the proto-Earth when our planet was about 90% of its present mass ($\sim 5.4 \times 10^{24}$ kg) with another planet of about Mars' mass (6.5×10^{23} kg). Earth's current mass is 5.974×10^{24} kg and that of the Moon is 7.35×10^{22} kg, so that it appears, that mass loss from the impact process was negligible. The impact was so energetic and deeply destructive that it yielded a dense, hot, CO₂-rock vapor-steam atmosphere of hundreds of bars on top of a vigorously convective magma ocean that occupied most of the Earth's interior. An orbiting ring of super-hot devolatilized rock vapor coalesced into the Moon (Canup and Asphaug 2001). The Moon-forming impact raised the whole Earth's temperature to that of a small red star (>2300 K) for several 1000 years. For the neo-formed Earth, most cooling models indicate that the hydrosphere recondensed out of the atmosphere in less than 10 Myr (Sleep et al. 2001). It has been suggested that oceans were present on the proto-Earth prior to the Moon-forming event (Abe 1993). If there was a primary hydrosphere, it



Earth, Formation, and Early Evolution, Fig. 1 Timeline of significant events in Earth's early formation and evolution

was wholly vaporized by the ► [giant impact](#). Consequently, it did not restabilize into a "secondary hydrosphere" until later when the surface cooled

to the point where liquid water could begin to pool on a dense primordial "chilled crust" of likely ultramafic (Fe- and Mg-rich) composition at the

top of the magma ocean (Arndt and Chauvel 1991). It is possible that a primordial crust and watery veneer of the postimpact Earth existed as early as about 35 million years after t_0 or around 4.53 Ga. A record of this primordial crust may never be found since all traces of it are expected to have been destroyed (cf. Carlson and Boyet 2009).

Not until 150 Myr after the foundation of the solar system (t_0) do we have direct evidence of the first (granitoid) crust from ancient terrestrial zircons (at 4.38 Ga), and only 500 Myr after that do we have the first direct evidence of surface conditions from marine sediments and basaltic lavas (ca. 3.83 Ga). Hence, the geologic record from actual rocks (as opposed to detrital zircons) only extends back from the present through $\sim 88\%$ of Earth history. The Hadean zircons bring this record up to a remarkable 95%. It is not impossible that older actual rocks will be found, but at present, the most ancient units are about 4 Ga old and found in the ► **Acasta Gneiss** Complex of northern Canada (Bowring and Williams 1999; Reimink et al. 2018). A gallery of ages for the next oldest rocks begins at the 3.77–3.87 Ga Isua Supracrustal Belt and the ► **Akilia** association (Nutman et al. 1996) in southern West Greenland and in Canada at the ca. 3.75 Ga Nuvvuagittuq Supracrustal Belt in northern Quebec (Cates and Mojzsis 2009). All of these outcrops are dominated by highly deformed ► **tonalite-trondhjemite-granodiorite** (TTG) gneisses that often (but not always) host supracrustal enclaves of amphibolites and other lithologies. Amphibolites in these cases are the metamorphic equivalents of volcanic and intrusive igneous rocks such as basalt, gabbros, and komatiites, and they sometimes host rare metamorphosed sedimentary rocks such as ferruginous siliceous schists (banded iron formations, BIFs). Pillow lavas in the Isua belt unambiguously attest to the presence of subaqueously erupted basalts.

Early Atmosphere

The Sun has increased its luminosity with time as its core increased its density by hydrogen fusing to helium. Standard models for the behavior of stars

in the main sequence predict that the Sun was only about 70% as bright in the visible part of the electromagnetic spectrum as it is now when it entered the main sequence 100 Myr after t_0 , around 4.46 Ga (Ribas et al. 2005). The Sun had only brightened slightly more to $\sim 77\%$ present value by the time of the earliest morphological evidence of life in the form of bio-sedimentary structures (stromatolites) and purported microbial microfossils which appear much later in the rock record, about 3.5 Ga ago in the Dresser Formation in Western Australia (Van Kranendonk 2006). A dimmer early Sun remains a long-standing and mostly unresolved problem for atmospheric models that seek to keep the early Earth warm enough for liquid water to remain stable. So far, it is very difficult for these models to account for a warm early Earth, and no atmospheric models succeed in keeping ancient Mars above 0 °C. In the absence of abundant and efficient greenhouse gases, such as water vapor, CO₂, CH₄, and NH₃, the Earth before about two billion years ago ought to have been ice covered to equatorial latitudes (Snowball Earth, Hoffman and Schrag 2002). The only credible solution to account for oceans of liquid water is to have a denser atmosphere rich in powerful greenhouse gases compared to anything that has existed in the Phanerozoic time. Relatively speaking, there has been but a small variation in greenhouse gases – well within several tens of percent of present atmospheric concentrations – over the last 500 Myr.

Broad estimates for average surface temperature of the early Earth depend strongly on what plausible limits can be placed on CO₂, CH₄, and NH₃ abundances and the sources and lifetimes of these gases in the atmosphere. If all carbon currently present in Earth's crust as carbonate and organic matter was oxidized to CO₂ and stored in the atmosphere (Holland 1984), as happened on Venus, the resulting 60–100 bar CO₂ greenhouse could have produced surface temperatures to 180–230 °C even as far back as 4.4 Ga (Abe 1993). If pCO₂ values were reduced to around 0.5 bar (still a 1500-fold increase from modern values) by massive silicate weathering and carbonate sequestration in oceans as well as by

enhanced volcanism and plate recycling, estimates for Hadean-Eoarchean surface temperatures are reduced to near 0 °C. Was the early Earth warm or cold? Controversy prevails over the interpretation of proxy temperature data from isotopes of oxygen (Knauth 2005) and silicon (Robert and Chaussidon 2006; Marin Carbonne et al. 2014) in Precambrian oceans, temperature, and cherts. These data have been interpreted to indicate seawater temperatures above 50 °C back to about 3.5 Ga. Atmospheric models constructed to simulate conditions on the early Earth are inconsistent with the geochemistry of ancient sediments deposited in a hot ocean. Instead, model outputs for these atmosphere simulations usually call for temperatures at or below the freezing point of water. Hence, much more work remains to be done to resolve this fundamental discrepancy between model and experiment.

Late Heavy Bombardment and Its Effects

During the epoch of late accretion to the late Hadean and early Eoarchean Earth (4.5–3.9 Ga), meteoritic impacts modified geothermal, geochemical, and geomorphologic conditions at the surface. Large impactors, hundreds of kilometers in diameter, can transform a globally habitable Earth into a surface cauterized by a 100 m thick film of molten rock. However, only the largest of these impacts would have affected more than a hemisphere, leaving the rest relatively unaffected.

Almost all of our information about early bombardment of the inner solar system comes from studies of the surface of the Moon, but that has now changed with more information from the asteroid belt and dynamical simulations. Various objects in the Solar System preserve abundant evidence for an intense impact flux at some time between the formation of the crust of asteroid Vesta (4.53 Ga) and the outpourings of lava into the mare basins of the Moon (>3.1 Ga). Ages of recovered fragments of the ancient lunar highland crust returned during the Apollo program have been interpreted to represent either a short and intense ▶ “late heavy bombardment” (LHB) period at 3.9 Ga (Ryder 2002) or the tail end of an extended postaccretionary bombardment.

Some authors have argued that the absence of lunar impact melt ages older than about 3.9 Ga requires that the solar system was relatively quiet from the Moon-forming impact to the LHB (Ryder 2002). Independent verification of an LHB comes from studies of lunar meteorites that record impacts from the 3.9 Ga period (Cohen et al. 2000). If so, why was there a bombardment? The exact mechanism is unknown, but early gravitational resonance interaction between Jupiter and the other outer planets has been implicated (Gomes et al. 2005). The sources and tempo of bombardment, however, remain obscure. New work reveals a timeline that relates variably retentive radiometric ages documented from asteroidal meteorites to new dynamical models that invoke an early episode of planetesimal-driven giant planet migration after the dispersal of the protoplanetary disk (Mojzsis et al. 2019). We now know that a declining rate of impactors continue to strike the inner planets through a protracted monotonic decrease in impactor flux, in agreement with predictions from crater chronology.

Earth is a larger body than the Moon, with stronger gravity to attract bolides and more surface area to be struck. By inference from the well-preserved lunar and Martian records, Earth’s crust during the most intense bombardment phase of late accretion before about 4.3 Ga (Brasser et al. 2020) ought to have been pummeled to a molten state. Although basic features of such an impact environment have been investigated via numerical models, the specific consequences of these collisions for the crust and the overall effects they had (destructive or procreative) to the emergent biosphere are an area of intense current study (e.g., Genda et al. 2017). Numerical modeling studies of the consequences to the Earth of impacting after the Moon-forming event (ca. 4.53 Ga) show that temperatures planet-wide were never brought to levels necessary for global sterilization (Abramov and Mojzsis 2009).

Early Hydrosphere

Earth’s surface zone, from the top of the atmosphere to mid-crustal depths, has more than one ocean volume’s worth of liquid water (~0.03% of

Earth's mass). But uncertainty lingers over Earth's total inventory of water and the ultimate source of Earth's water also remains ill constrained: it could be from intrinsic outgassing during planetary growth of water supplied in accreting planetary material, or it could have come subsequently from accreting meteoritic or cometary matter ► [late veneer](#) (Albarède 2009). Probably all of these are correct. The availability and long-term stability of liquid water over geologic timescales is probably the determining factor that controls habitability of a planet's surface. Deciding whether Earth is relatively "dry" or "wet" as terrestrial planets go will depend on discoveries from future extrasolar systems by remote observations. Direct evidence for abundant surface water on Earth appears to extend as far back as the beginning of the geologic record.

Mildly deformed and metamorphosed volcanic and sedimentary rocks that formed subaqueously are found in 3.49 Ga rocks in the Pilbara craton of Western Australia and the Barberton greenstone belt of South Africa (Van Kranendonk 2006). However, all rocks older than about 3.6 Ga are highly deformed gneisses that have experienced pervasive metamorphism and recrystallization. The most ancient gneissic terranes consist of more than 90% of intrusive rocks and most of these are of granitoid (TTG) composition. These rock types, especially the tonalites and trondhjemites, are derived from Na-rich and K-poor melts of hydrated mafic (usually oceanic) crust following transformation into garnet amphibolite or eclogite. As with most (but not all) present occurrences of TTGs, these rocks probably formed in subduction zones (Martin et al. 2005, 2014). In older terranes such as the West Greenland Itsaq Gneiss Complex (Nutman et al. 1996), multiple generations of granitoids of different ages and compositions host enclaves and tectonized rafts ranging in size from meter to kilometer scale of yet older "supracrustal" rocks which constitute something less than 10% of the mapped outcrops. The oldest terrestrial rocks are found in the 4.03 Ga ► [Acasta Gneiss](#) Complex, but these deep-seated (7 km?) intrusive igneous protoliths do not convey direct information about the surface. Only when further discoveries are

made of pre-3.6 Ga gneisses and supracrustal enclaves will more direct information be revealed about the early Earth.

The oldest rocks with surviving volcanic and sedimentary structures indicative of a marine origin form a tiny amount of the dominantly amphibolite (metamorphosed basalt) rocks of the ca. 3.8 Ga Isua Supracrustal Belt which is part of the Itsaq Gneiss Complex. Within some low-strain zones of the amphibolites, clear pillow structures are preserved, and because such structures form when lavas erupt under water, they directly establish that liquid water was present when the Isua lavas erupted. At the Isua Supracrustal Belt, associated with these rocks are quartz-magnetite schists that in places are preserved as banded iron formations (BIF) with genuine sedimentary banding; such sedimentary rocks also formed in liquid water. The Isua Supracrustal Belt contains the oldest undisputed terrestrial record of a marine environment.

Of the other pre-3.8 Ga gneisses and amphibolites in Greenland, none has been more closely scrutinized than the ca. 3.85 Ga-old outcrops on the island of Akilia (Manning et al. 2006). Rocks on Akilia include the polyphase Itsaq Gneiss Complex with ages that span 3.87–3.62 Ga (Nutman et al. 1996). Unlike the Isua rocks, which encompass at least 200 km² of continuous exposure and preserve some primary structures, the gneisses on Akilia are very highly deformed. Although the Akilia association is widespread, with occurrences of enclaves throughout the southernmost part of the Itsaq Gneiss Complex, they are at much smaller scale and are less coherent than the Isua belt. At best, meter- to tens of meter-scale enclaves of amphibolites and ferruginous quartzites are present locally (Cates and Mojzsis 2006). Enclaves of Akilia quartz-magnetite-pyroxene schists have been interpreted as metasediments, and they share the trace element signatures of BIF from Isua and elsewhere (Manning et al. 2006). They preserve Fe isotope fractionations unlike igneous rocks and similar to Isua BIF (Dauphas et al. 2007). Several workers have proposed a minimum age of 3.83–3.85 Ga for the Akilia supracrustal rocks (Nutman et al.

1996; Manning et al. 2006), but this age, as well as the interpretation of these rocks as an originally volcano-sedimentary succession, has been stridently challenged.

Other localities with >3.7 Ga volcanic or sedimentary rocks are found in the northeasternmost margin of the Superior Province in the Nuvvuagittuq Supracrustal Belt (previously known as Porpoise Cove). The Superior Province in northern Quebec is dominantly composed of TTG and dioritic gneisses containing enclaves of older amphibolitized supracrustal rocks (Cates and Mojzsis 2009). As in West Greenland, these tend to comprise linear belts of metamorphosed sedimentary and extrusive igneous rocks that in rare cases preserve primary sedimentary and volcanic structures. Detailed mapping and geochronology of these units confirm a minimum age of 3.75 Ga for an 8 km² enclave of mafic and ultramafic amphibolites, quartz-magnetite BIFs, quartz-amphibole schists, and other possible detrital sediments at Nuvvuagittuq (Dauphas et al. 2007). On the other hand, Jack Hills zircon crystals, recorded the trace of interaction with liquid water, which is interpreted as an evidence in favor of oceans on Earth surface as early as 4.4 Ga (Mojzsis et al. 2001).

► **Plate tectonics**' mechanisms can be viewed as an adequate, but not exclusive, means of generating the ancient continental crust preserved in the West Greenland and northern Canada terranes cited above. Alternatively, ► **mantle** superplumes could have played at least a supporting role in the generation of this early crust. Future detailed studies of the oldest terranes will test the idea that plume's plate tectonics or some hybrid model can account for the structure and geochemistry of the oldest preserved crust.

Did Plate Tectonics Work Out in the Early Archean?

Within the most ancient terranes that have been mapped at the appropriate detail and which have been subjected to extensive geochronological studies, intrusive, volcanic, and sedimentary rocks of different ages are juxtaposed. Some authors have argued that this kind of geologic style preserved in West Greenland is a

consequence of a compressive regime and plate boundary processes that extended back to 3.8 Ga or even earlier in the Hadean (Korenaga 2008; Davies 2008). Like modern oceanic arc evolution, many ancient but much better-preserved terranes, such as the 3.5 Ga Pilbara craton, record permissive evidence of tectonic evolution from plate- or plume-related crust formation to episodic growth of continental crust through the emplacement of tonalites derived from partial melting of hydrated basalt (Martin et al. 2014). The granitoids intruded sequences of basalt with ferruginous-siliceous sedimentary layers, a scenario remarkably similar in both structure and chemistry to many contemporary island arcs above subducting oceanic slabs.

Did Plate Tectonics Exist in the Hadean?

Zircons older than 3.9 Ga are mostly found at Jack Hills and Mt. Narryer in the Narryer Gneiss Complex, Yilgarn craton, Western Australia (Froude et al. 1983; Compston and Pidgeon 1986). Others have been recovered from elsewhere in Western Australia (Wyche et al. 2004) and in scattered localities worldwide (e.g., Mueller et al. 1998; Paquette et al. 2015; Miller et al. 2018). Many of the most ancient Jack Hills' zircons contain inclusions of quartz, feldspar, muscovite, and other phases produced from silica-saturated igneous rocks, meaning that granites existed before 4.1 Ga (Hopkins et al. 2008). Low temperatures of formation, consistent with plate underthrusting, have been determined using titanium thermometry on >4.0 Ga Jack Hills' zircons (Watson and Harrison 2005). Many Hadean zircons also have isotopically heavy oxygen ($\delta^{18}\text{O}$ up to +7.3‰) which supports the view that melting of hydrated ► **crust** produced the pre-4.0 Ga granites and that some were possibly contaminated by subducted sediment (Mojzsis et al. 2001). Although the details of this hypothesis remain the focus of debate, the viewpoint of a hospitable, water-rich ► **Hadean** Earth leads to a number of predictions:

- Separation of crust into continental (granitic) and oceanic (mafic) styles prevailed since the earliest times.

- Conditions were conducive to the development of prebiotic chemistry and subsequently to the long-term sustainability of biological activity.
- Since the Hadean, actual preservation of Hadean zircons shows that Earth had crystallized its magma ocean and formed stable crust by 4.4 Ga and that no catastrophic impacts wholly destroyed that crust. Although the nature of the primordial crust and the composition of the source rocks of the 4.4–4.0 Ga zircons remain unresolved (Trail et al. 2007), there is now little doubt that the Hadean Earth could have supported life.

Finally, although no rocks and minerals are preserved from Earth's first 150 million years, there ought to be echoes of its prior existence. Recent work from both Nd and Hf isotope signatures from 4.4 to 3.5 Ga rocks and minerals provides evidence of planetary-scale events during the Earth's first 100 million years. These events that entailed major chemical fractionations in the mantle, perhaps as a consequence of an early magma ocean and the establishment of the proto-crust in the early Hadean, occurred prior to about 4.3 billion years ago or even earlier (Caro et al. 2006; Boyet and Carlson 2007; Blichert-Toft and Albarède 2008).

Cross-References

- [Acasta Gneiss](#)
- [Akilia](#)
- [Archean Environmental Conditions](#)
- [Archean Tectonics](#)
- [Chondrite](#)
- [Chronological History of Life on Earth](#)
- [Condensation Sequence](#)
- [Continental Crust](#)
- [Cool Early Earth](#)
- [Craton](#)
- [Earth, Age of](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Exoplanets, Discovery](#)
- [Geochronology](#)

- [Geological Time Scale, History of](#)
- [Giant Impact](#)
- [Greenstone Belt](#)
- [Hadean](#)
- [Isua Supracrustal Belt](#)
- [Jack Hills \(Yilgarn Craton, Western Australia\)](#)
- [Komatiite](#)
- [Late Heavy Bombardment](#)
- [Late Veneer](#)
- [Late-Stage Accretion](#)
- [Mantle Plume, Planetary](#)
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- [Oceans, Chemical Evolution of](#)
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- [Oxygen Isotopes](#)
- [Plate Tectonics](#)
- [Porpoise Cove Greenstone Belt](#)
- [Prebiotic Chemistry](#)
- [Radiogenic Isotopes](#)
- [System Solar Formation, Chronology of](#)
- [Tonalite-Trondhjemite-Granodiorite](#)

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Earth, Surface Evolution

Nicholas Arndt

Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Keywords

Chert · Greenstone belt · Komatiite ·
Sediment · South Africa · Traces of life

Definition

The surface of the Archean Earth was in many ways similar to that of today. Oceans covered most of the globe, but there were also regions of dry land. Oceanic crust could have been almost as thick as continental crust, mountain ranges were not very high, and parts of oceanic ridges and plateaus were emergent. Geological processes such as volcanism, erosion, and sediment deposition operated as now but were influenced by a lack of vegetation, higher ocean temperatures, and a hotter more aggressive, acidic atmosphere.

Overview

The total area covered by oceans was greater than today (Flament et al. 2008; Johnson and Wing 2019), and this, for two reasons. First, the volume of continental crust may have been less, if this crust had grown progressively through time (Benn et al. 2006). Second, the oceans were more voluminous because high temperatures in the mantle (Nisbet et al. 1993) destabilized hydrous minerals and drove water to the surface. Mountain ranges existed but were not as high as those of today were, because the continental crust was heated internally and rendered more ductile by more abundant radioactive elements. Continental crust was relatively thin, while oceanic crust, produced by high-degree melting of the hotter mantle, was thicker (Sleep and Windley 1982). The subdued topography, the limited contrast between the thicknesses of oceanic and continental crust, combined with bigger oceans, meant that much of the continental crust was probably flooded (Arndt 1998).

As during the more recent geological history, global temperatures waxed and waned. However, the Earth does not record periods of global glaciation before 2.5 Ga (Hoffman et al. 2017), the oldest, being also the most pronounced one, took place during the Proterozoic. Moreover, the O and Si isotopic compositions of Archean cherts suggest that ocean temperatures were commonly above 40 °C (Marin Carbonne et al. 2014). The atmosphere contained a little to no free oxygen but was rich in CO₂; rainwater was acid.

The normal cycle of erosion, transport, and deposition of sediment operated, but the rivers flowed through a landscape that was very different from that of today. The feature that most starkly distinguished the Archean and modern land surface was the lack of vegetation. Microbes no doubt colonized the subsurface and constructed biofilms (slime mats) that covered moist areas, but most of the landscape was a Martian vista of bare rocks and soil. The rate of erosion was enhanced by the lack of vegetation, high temperatures, and aggressive atmosphere but restrained by modest heights of mountain belts. Erosion was also more efficient due to greater tidal amplitude, as

consequence of a smaller Moon-Earth distance (Lathe 2004). Active volcanism covered much of the surface with lava flows or pyroclastic deposits.

The ► [oceanic crust](#) was composed of basaltic lavas like that of modern crust but more magnesian (picritic) in places (Sleep and Windley 1982). Parts of mid-ocean ridges and the summits of oceanic plateaus may have been emergent forming what might be called “melano (dark-colored)-continents.” The pelagic sediment that covered this crust was different from that of today. An absence of shell-forming organisms precluded the formation of biogenic calcareous or siliceous oozes; in their place were Si- or Fe-rich sediments that precipitated directly from the high-temperature seawater that contained high concentrations of these elements. Hydrothermal circulation of Si-charged seawater resulted in massive silicification of all near-surface rocks. Expulsion of fluids at hydrothermal vents led to the deposition of exhalative sediments variably composed of sulfides, sulfates, carbonates or silica minerals (Russell et al. 2005).

The earliest Archean coincided with the end of the ► [Late Heavy Bombardment](#), a time of massive meteorite impacts. The largest of these would have vaporized large expanses of the oceans and pulverized large parts of the continents, but their overall impact was local, not global.

Opinions differ concerning the surface environment in the Hadean. One school envisages a ► [cool early Earth](#) in which clement conditions reigned (Valley et al. 2002); another imagines a hellish environment in which periods of intense heating subsequent to meteorite impact alternated with global glaciation when the atmosphere budget of greenhouse gases was insufficient to counteract the weak luminescence of the young sun (Sleep and Zahnle 2001; Feulner 2012).

Cross-References

- [Archean Traces of Life](#)
- [Earth, Formation, and Early Evolution](#)
- [Impact Melt Rock](#)
- [Komatiite](#)
- [Oceans, Origin of](#)

- [Pilbara Craton](#)
- [Plate Tectonics](#)

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Earth's Oldest Microfossils

- [Apex Chert, Microfossils](#)

Earth's Oxygenation

- [Oxygenation of the Earth's Atmosphere](#)

Earth-Like Atmosphere

John Lee Grenfell
German Aerospace Center (DLR), Berlin,
Germany

Definition

An earth-like atmosphere is one whose dominant constituents are molecular nitrogen and molecular oxygen. This definition encompasses therefore (i) the early Earth since the start of the Proterozoic period where atmospheric oxygen started to rise, (ii) the modern Earth, and (iii) theoretical studies in exoplanet science investigating hypothetical planets assumed to possess significant earth-like atmospheres and which orbit, e.g., different classes of main sequence stars or/and which are at different positions in the habitable zone.

Earth-Like Planet

► [Terrestrial Planet](#)

Eccentricity

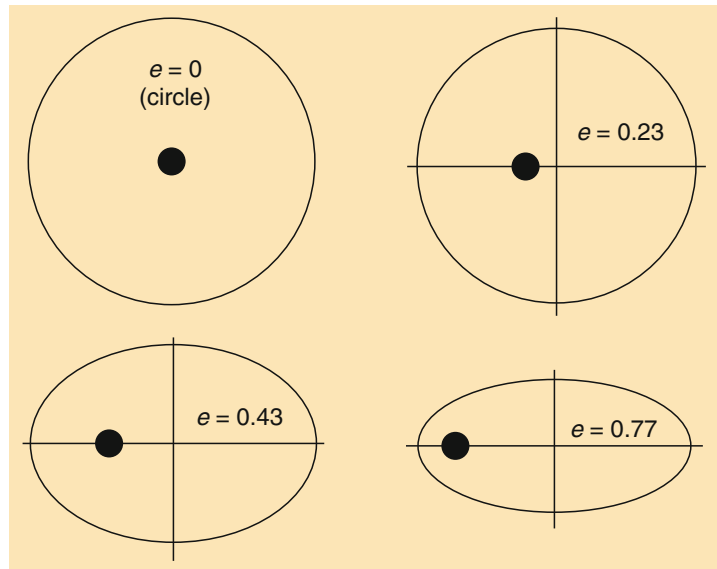
Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The eccentricity is a parameter (denoted by e) characterizing the orbit's shape for an object gravitationally bound to another one. It quantifies the amount by which the orbit deviates from a circle: $e = 0$ for a circle, $e = 1$ for a parabola, $e > 1$ for a hyperbola, and $0 < e < 1$ for an ellipse, where $e = c/a$, with c the distance from the center to a focus and a the semimajor axis. See Fig. 1 for an illustration of different values in the case of an ellipse. The eccentricities of planets belonging to the solar system are rather small, while a significant fraction of the discovered exoplanets exhibit large eccentricities, in excess of 0.3.

Eccentricity,

Fig. 1 Several examples of elliptical orbits with different eccentricities



Eclipse

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Synonyms

[Eclipsing binary](#); [Primary eclipse](#); [Secondary eclipse](#); [Transit](#)

Definition

In an astronomical system, when orbits of two or more objects are viewed edge-on, the components periodically pass in front of each other, thus reducing the amount of light that reaches the observer. This phenomenon is known as Eclipse. If both components are stars, the system is called an eclipsing binary. Normally the deeper eclipse occurs when the cooler object passes in front of the hotter one. This is traditionally denoted by the primary eclipse. The secondary eclipse refers to the shallower event when the cooler component passes behind the hotter one. However, there can be interesting exceptions to this general pattern. For example, with highly eccentric orbits and modest inclinations, one or the other of the eclipses may not occur.

By convention, the eclipse of a star by a much smaller and cooler object such as a planet is called a ► [transit](#), while the passage of the planet behind the star is termed either an occultation or a secondary eclipse. Another interesting case is a binary consisting of a normal star and a ► [white dwarf](#). White dwarfs are small enough to produce transit-like events when they pass in front of the star. But, if they are young enough, they can be hotter than the star, thus producing a deeper eclipse when they pass behind the star.

Eclipsing binaries for which the spectra of both stars can be detected are especially valuable. In

these systems, an analysis of the light curve (the graphs of the variation of the intensity of the light received from the system in term of time) together with the spectroscopic orbit derived from the radial velocities of the two stars can yield the absolute mass and radius of each stellar component. If the spectrum of only one of the stars is detected (presumably that of the brighter one), then only the ratios of the masses and radii can be derived directly. Interestingly, the density of the primary star and surface gravity of an unseen companion can also be derived from the light curve and orbital solution. If the mass of the primary can be estimated from other observations, such as spectroscopy and/or parallaxes combined with stellar models, then the actual mass and radius of the secondary can be derived. Transiting planets are simply an extreme example of the case where only the spectrum of the primary star yields an orbital solution.

Cross-References

- [Activity, Magnetic](#)
- [Transit](#)
- [Transiting Planets](#)
- [White Dwarf](#)

Eclipsing Binary

- [Eclipse](#)

Ecliptic

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The ecliptic is the geometric plane containing the Earth's ► [orbit](#). More precisely, it is the average plane of the orbit of the center of mass of the Earth-

Moon system. It is also the line delineating the projection of the Earth's orbital plane onto the celestial sphere. On the sky, the ecliptic is at the middle of the zodiacal belt that extends about 9° on either side and which contains the orbits of all the major planets orbiting the Sun. By extension, the ecliptic is often assimilated to the average plane of the solar system. The term ecliptic also designates the adjective that specifies quantities associated with the ecliptic, for example, *ecliptic coordinates*.

Cross-References

- [Coordinate Systems](#)
- [Orbit](#)
- [System Solar Formation, Chronology of](#)
- [Zodiacal Light](#)

Ecological Niche

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Niche in ecology is a term which refers to the relational position of a species or population in an ecosystem (environment). It refers to the behavior of the population to any external input or relationship including resources, competitors, physical conditions, etc.

Ecology, History of

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

The word ecology comes from the ancient Greek *oikos*, house, and *logos*, science. It was coined by

E. Haeckel in 1866 and means the relationship between living beings and their environment. Toward the end of the nineteenth century, this relation became a research topic for botanists. For instance, in 1895, Eugen Warming was a pioneer of the study of the distribution of plants.

In 1935, G. Tansley created the word ecosystem, which he defined as the functional ecological unit. During the 1950s, E.P. and H.T. Odum, inspired by thermodynamics, developed central concepts, such as a theory of open systems and the notion of a dynamical equilibrium regulated by energy flows. That was the development of systemic ecology.

Ecopoiesis

- [Planetary Ecosynthesis](#)

Ecosphere

- [Biosphere](#)

Ecosystem

J. Cynan Ellis-Evans
UK Arctic Office, Strategic Coordination Group, British Antarctic Survey, Cambridge, UK

Keywords

Abiotic · Biogeochemical cycles · Biological populations · Biotic · Environment · Physicochemical conditions

Definition

An ecosystem is part of the broad ► [environment](#), comprising of both physical (► [abiotic](#)) and interdependent biological (biotic) components, in which the community of living organisms continually interacts with all abiotic components (e.g., rock, water, air, soil, sunlight) through various interconnected relationships. The flow of energy within an ecosystem, manifested through cycling of materials between the biotic and abiotic components, defines its inherent trophic structure and biological diversity.

Overview

The ecosystem concept developed, as a more abstract replacement of the concept of community, out of theorizing in the 1930s on the organization and dynamics of natural systems. While a community is a group of populations of different organisms that interact with one another in a given ► [habitat](#) or area and are interdependent, an ecosystem is considered an area where living communities exchange materials "...with the whole complex of physical factors that form what we term an environment" (Tansley [1935](#)). Ecosystems are therefore essentially self-contained energy and nutrient cycles. An ecosystem can be long lived or temporary, and balance is a critical element of any viable ecosystem because disturbances and instability in its physical factors (e.g., rapid climate change) can threaten the existence of its component organisms. Ecosystems can be small or large, and the physical boundaries of an ecosystem can be defined as in a pond, or relatively blurred, as in the case of a marsh draining into a stream or river. Ecosystems are everywhere and the diversity is enormous on a planet such as Earth, and indeed we are still discovering environments (e.g., the deep subsurface, subglacial lakes) that harbor as yet barely researched ecosystems. Extreme environments on Earth provide analogues of possible extraterrestrial ecosystems. Potential locations include subsurface permafrost lithosols on Mars; the ice-covered ocean of the Jovian moon, Europa; the hydrocarbon lakes on Titan; or the subsurface water on Enceladus.

Cross-References

- [Abiotic](#)
- [Biogeochemical Cycles](#)
- [Environment](#)
- [Extreme Environment](#)
- [Habitat](#)

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ECSS

Catharine A. Conley

NASA Headquarters, Washington, DC, USA

Definition

The European Cooperation for Space Standardization (ECSS) is, since 1993, an organization that works to improve standardization within the European space sector. This organization is supported by the ► [European Space Agency](#) and the space agencies of some member states. Industry is also participating in the technical working groups which define the standards to be applied to the management, the organization, the quality assurance of the projects, as well as the engineering methods in various domains (electrical system, communication, mechanic, etc.).

Cross-References

- [European Space Agency](#)
- [ISO](#)

Effective Temperature

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Definition

The effective temperature of a star is the temperature of a ► [blackbody](#) of the same radius as the

star and that would radiate the same total amount of electromagnetic power as the star.

Overview

Noted T_{eff} , the effective temperature is one of the fundamental parameters that characterizes a star. If P_* is the power radiated by a star of radius R , then T_{eff} is derived by applying the Stefan-Boltzmann law: $P_* = 4\pi R^2 \sigma T_{\text{eff}}^4$. Indeed a star is not actually a blackbody, as its [▶ emissivity](#) varies with wavelength; however, the effective temperature generally provides a fair approximation of the actual temperature of the stellar photosphere. This is so because at any wavelength, the radiation comes from a layer which is always on the *skin* of the star (the [▶ photosphere](#)) and, thus, at approximately a constant temperature. The effective temperature is directly related to the color of the star: the higher the temperature, the bluer the light emitted by the star. The effective temperature is one of the two parameters, with the stellar luminosity, used to build the classical HR diagram that permits astronomers to classify stars. The effective temperature of the Sun is 5,780 K, while it is 40,000 K for an O star and 3,000 K for an M star. The term has been extended to planets, with a similar definition, but, there, the effective temperature can sometimes be fairly different from the surface temperature. This is, for instance, the case of Venus, where the [▶ greenhouse effect](#) in the atmosphere (due to CO_2) blocks the infrared outward radiation imposing a ground temperature of 735 K, much higher than the effective temperature of 225 K, in order to maintain the balance between the absorbed solar flux and the emitted thermal radiation. Note that the effective temperature depends on the reflectivity, or albedo, of the planet: the larger the [▶ albedo](#), the lower the effective temperature.

Cross-References

- ▶ [Blackbody](#)
- ▶ [Bolometric Magnitude](#)

- ▶ [Color Index](#)
- ▶ [Emissivity](#)
- ▶ [Grey Body](#)
- ▶ [Hertzsprung-Russell Diagram](#)

E_H

- ▶ [Redox Potential](#)

Ejecta

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montreal, QC, Canada

Synonyms

[Pyroclastics \(in volcanology\)](#)

Definition

Ejecta is solid or liquid material ejected from a source region. In geology, two types of ejecta exist: impact ejecta and volcanic ejecta. Impact ejecta is solid, liquid, or vaporized rock debris expelled from a crater during the excavation stage of a meteoritic impact. This ejecta can be dispersed around the crater (proximal) and form specific patterns or partially build the crater rim. Distal ejecta, such as tektites and microtektites, spreads to much greater distances and can eventually cover the entire planet, as in the case of the Chicxulub crater.

The volcanic ejecta is rock debris ejected by an explosive volcano and normally grouped in the more general term *pyroclastics*. In astrophysics, ejecta is the gaseous material expelled from a star, either quiescently (e.g., in coronal mass ejection or through the wind of an evolved star, like a red giant or an AGB star) or in a stellar explosion like in a supernova or nova.

Cross-References

- [Breccia](#)
- [Crater, Impact](#)
- [Impactite](#)
- [Red Giant](#)
- [Stars](#)
- [Supernova](#)
- [Tektite](#)

Ejection, Hyperbolic

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Hyperbolic ejection is the removal of an object from a gravitational system (e.g., a planetary system) on a hyperbolic ► [orbit](#), so that the object is permanently lost from the system. This is caused by an increase in a body's orbital energy that exceeds the gravitational binding energy of the system. In planetary systems, the increase in orbital energy usually comes from a close encounter with a massive planet. Objects that are ejected from planetary systems are thought to include a large number of ► [planetesimal](#)-sized bodies (asteroids and comets), a small number of ► [planetary embryo](#)-sized bodies, and, in some cases, fully grown terrestrial, ice giant, or gas giant planets.

Cross-References

- [Escape Velocity](#)
- [Exoplanets, Discovery](#)
- [Orbit](#)
- [Planet Formation](#)
- [Planetesimals](#)

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Electric Discharge

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Synonyms

[Spark discharge](#)

Definition

An electric discharge is the release and transmission of electricity in an applied electric field through a medium such as a gas. Several types of electric discharges occur naturally on Earth (American Geophysical Union, National Research Council (U.S.). Geophysics Study Committee 1986):

1. Atmospheric lightning, which is thought to be caused by the frictional generation, and separation, of positive and negative charges on ice and dust particles. As the charge on these particles builds up, the result is the often-spectacular discharge of electricity known as lightning. On average, there are 50–100 lightning strikes per second on Earth with most of the activity taking place in equatorial and northern latitudinal regions.
2. Corona discharges, which are caused by an electrical discharge produced by the ionization of the surrounding atmosphere, generating a luminous plasma (sometime referred to as St. Elmo's fire, a term used by sailors to describe the glow observed at the top of a

ship's mast during a thunderstorm). Unlike lightning, which is instantaneous and transient, coronal discharges are less brilliant, can last for a significant period of time (minutes or more), and occur over a large surface area. Continuous corona discharges have been observed on the nose cones of airplanes during thunderstorms.

3. Volcanic lightning, which is ubiquitous in most volcanic eruptions, especially water-rich eruptions. The cause of the lightning is not completely understood but is thought to be the charging of ash particles by frictional processes and the ionization of gases expelled in the eruption. Volcanic lightning has been observed to be nearly continuous during an eruption.

Overview

Electrical discharges have also been observed in the atmospheres of other bodies in the solar system (Aplin 2006). Lightning has been detected during observations of Jupiter and Saturn, and the NASA/ESA Cassini/Huygens mission has tentatively detected lightning in the atmosphere of Titan.

Electric discharges on Earth, and by implication elsewhere, play an important role in various aspects of atmospheric chemistry. On the present-day Earth, the major products of lightning acting on the gases in the atmosphere are NO, along with lesser amounts of ► [ozone](#). On the primitive Earth, a possible reducing atmosphere containing nitrogen and methane would have had HCN as the major product. In contrast, with a neutral nitrogen-carbon dioxide-rich primordial atmosphere, the major product would have been a mixture of NO and CO, as well as ammonia and HCN (Cleaves et al. 2008).

In the hydrogen-rich Jovian atmosphere, the products produced by lightning are much more diverse and include, besides HCN, low molecular weight hydrocarbons and formaldehyde. Lightning in the solar nebula may have also been important in the synthesis of reduced species of importance in prebiotic chemistry.

Electric discharges were first used in the context of astrobiology research in the 1952 Miller-Urey Experiment (Miller 1953) in which a spark was passed through a mixture of methane, ammonia, hydrogen, and water, simulating the action of lightning acting on what was then thought to be the composition of the primitive atmosphere. This experiment ultimately yielded amino acids, suggesting a facile route from simple environmental processes to the building blocks of modern organisms.

Cross-References

- [Ozone](#)
- [Spark Discharge](#)

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Electrochemical Potential

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Electrochemical potential is the free energy change (ΔG) associated with the movement of chemical species through a gradient of electric potential and/or a gradient of concentration established between the two sides of a

biomembrane. The electrochemical potentials of H^+ and/or Na^+ are a main fuel for the cell energy transductions.

Cross-References

- ▶ [ATP Synthase](#)
- ▶ [ATPase](#)
- ▶ [Bioenergetics](#)
- ▶ [Photosynthesis](#)
- ▶ [Proton Motive Force](#)
- ▶ [Respiration](#)
- ▶ [Transduction](#)

Electromagnetic Radiation

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The expression electromagnetic radiation designates the energy that is transported in the form of a propagating wave made of two perpendicular components, one an electric field and the other a magnetic field, which oscillate at the same frequency. This description applies to light in all its forms: radio waves, infrared, visible light, ultraviolet, x-rays, and gamma rays. It is by far the most important vector of information reaching us that comes from the universe and the objects it contains. Different physical processes give rise to electromagnetic radiation and are generally classified as thermal (resulting from the thermal motion in a medium), nonthermal radiation (synchrotron), or quantized (transitions between levels of energy in atoms, molecules, or nuclei).

Cross-References

- ▶ [Blackbody](#)
- ▶ [Bremsstrahlung Radiation](#)
- ▶ [Radiative Processes](#)
- ▶ [Synchrotron Radiation](#)

Electromagnetic Spectrum

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The electromagnetic spectrum is the domain of all possible frequencies or wavelengths over which electromagnetic waves can be observed. This is a huge domain spanning 23 decades in frequencies or wavelengths. It includes radio waves, millimetric waves, infrared, visible light, ultraviolet, x-rays, and gamma rays. The distribution versus frequency (or wavelength) of the radiation intensity emitted by a particular celestial object is called its electromagnetic spectrum or spectral energy distribution (SED); it contains in general extremely rich pieces of information on the nature and physical properties of the object, such as temperature, composition, velocity, etc. ▶ [Spectroscopy](#) is the art of measuring the spectrum of a source.

Cross-References

- ▶ [Electromagnetic Radiation](#)
- ▶ [Spectroscopy](#)

Electron Acceptor

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València, Spain

Synonyms

[Oxidant](#); [Oxidative agent](#)

Definition

Electron acceptor is any of the organic or inorganic oxidative agents participating in an

enzymatic reaction. In a restrictive sense, it is the terminal oxidant of an electron transport chain.

Cross-References

- ▶ [Anaerobic Respiration](#)
- ▶ [Photosynthesis](#)
- ▶ [Respiration](#)

Electron Attachment

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Electron attachment is the chemical process whereby an electron is attached to a neutral molecule. Examples include electron photo attachment to CN to produce CN[−] and a photon and dissociative electron attachment to HCN to produce CN[−] and a hydrogen atom.

Cross-References

- ▶ [Interstellar Chemical Processes](#)

Electron Carrier

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

An electron carrier is any of the soluble (e.g., NADH) or protein-bound (e.g., ▶ [cytochromes](#))

▶ [cofactors](#) participating as reversible ▶ [electron donor](#) and/or acceptor in an enzymatic reaction.

Cross-References

- ▶ [Coenzyme](#)
- ▶ [Cofactor](#)
- ▶ [Cytochromes](#)
- ▶ [Electron Acceptor](#)
- ▶ [Electron Donor](#)
- ▶ [NADH, NADPH](#)
- ▶ [Photosynthesis](#)
- ▶ [Respiration](#)

Electron Dissociative Recombination

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA
Goddard Space Flight Center, Greenbelt, MD,
USA

Definition

Electron dissociative recombination is the chemical process whereby an electron reacts with a positive molecular ion to produce two neutral species. Examples include electron recombination with H₃O⁺ to produce OH and 2H. This is a very important process in gas-phase interstellar chemistry.

Cross-References

- ▶ [Interstellar Chemical Processes](#)

Electron Donor

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Reducing agent](#); [Reductant](#)

Definition

Electron donor is any of the organic or inorganic substances acting as reducing agents in an enzymatic reaction. In a restrictive sense, the reducing agent at the beginning of an ► [electron transport chain](#) or the substrate is used to obtain energy by ► [respiration](#).

Cross-References

- [Electron Transport](#)
- [NADH, NADPH](#)
- [Photosynthesis](#)
- [Respiration](#)

Electron Radiative Recombination

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Radiative recombination](#)

Definition

Electron radiative recombination is a chemical process whereby an electron reacts with a positive atomic ion to produce a neutral atom with the emission of a photon (i.e., radiation). Examples include electron reaction with H^+ to produce a neutral H atom plus a photon; photons produced in this process are responsible for the red color of many low-density nebulae.

Cross-References

- [Electron Dissociative Recombination](#)
- [Interstellar Chemical Processes](#)

Electron Transport

Francisco Montero
Department of Biochemistry and Molecular
Biology I, Facultad de Ciencias Químicas,
Universidad Complutense de Madrid, Madrid,
Spain

Keywords

Electron carriers · Photosynthesis · Redox reactions · Respiration

Synonyms

[Electron transport chain](#)

Definition

Electron transport refers to the transfer of electrons from an initial donor (reducing substance) to a final acceptor (oxidizing substance) across different intermediaries, which takes place in biological membranes. Electron transport processes are usually associated with respiratory and photosynthetic processes.

Overview

The most common ways by which living organisms obtain energy from their surroundings is by the ► [oxidation](#) of external electron donors (chemotrophic organisms) or by the absorption of electromagnetic radiation (phototrophic organisms). In both cases, the energy translation mechanisms take place in membranes (the cytoplasmic membranes in the case of prokaryotes or subcellular particles such as mitochondria and chloroplasts in the case of eukaryotes). In the translation process, an electron transport takes place from a substance, which is an initial ► [electron donor](#) to a final acceptor, and since the ► [redox potential](#) of the donor is more negative than that of the acceptor, the global process is exergonic. This oxidation-reduction process takes place across a series of intermediaries (► [Electron Carrier](#)), which are not free in the intracellular medium as the majority of them form highly structured complexes inserted in the membranes. Therefore, the transfer of electrons that takes place between the different components does not occur using the conventional mechanism that takes place in the oxidation-reduction reactions of a homogenous system in dissolution. Instead, a directional electron transport takes place along the membrane and, in some cases, a transverse one as well. This explains how energy coupling between an oxidation-reduction reaction and a transport phenomenon is possible, as first, the free energy released by these processes is used to produce a proton transport against the gradient across the membrane, and then the proton ► [electrochemical potential](#) gradient is translated, by means of processes that also take place in the membrane, in ► [ATP](#).

For many years, the mechanism whereby electrons are transferred between the different electron carriers, which are frequently separated from each other when the structure of the complexes is greater than 10 Å, has been the subject of much debate. However, there is growing experimental and theoretical evidence that suggests that on some occasions the transport may be brought about by the “tunnel effect.”

The molecules that take part in the electron transport are quite ubiquitous. The most common molecules are cytochromes, quinones, iron-sulfur proteins, and flavoproteins. In addition, chlorophylls and pheophytins are involved in ► [photosynthesis](#).

Cross-References

- [ATP](#)
- [Electrochemical Potential](#)
- [Electron Acceptor](#)
- [Electron Carrier](#)
- [Electron Donor](#)
- [Oxidation](#)
- [Photosynthesis](#)
- [Redox Potential](#)
- [Reduction](#)
- [Respiration](#)

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Electron Transport Chain

- [Electron Transport](#)

Electrophoresis

Adrienne Kish
Institut de Génétique et Microbiologie, Université Paris-Sud 11, Orsay Cedex, France

Definition

Electrophoresis is the migration of charged molecules (for example ► [nucleic acids](#) or ► [proteins](#))

through a medium according to charge and molecular size as a consequence of an applied electric current and interactions with the medium. It is used as an analytical technique to separate molecules by charge, size, or binding affinity. Parameters including matrix composition and concentration, ionic strength, electrical current strength and field angle, and migration time can be varied. Electrophoretic methods commonly employed include capillary electrophoresis (CE), gel electrophoresis (GE), and pulsed-field gel electrophoresis (PFGE) for separation of chromosomal DNA; denaturing and/or temperature gradient gel electrophoresis (DGGE/TGGE) for separation according to sequence; polyacrylamide gel electrophoresis (PAGE) and SDS-PAGE for separation of proteins in their native and denatured conformations, respectively; and isoelectric focusing (IEF) and 2D electrophoresis for separation of proteins by isoelectric point with or without PAGE first.

Cross-References

- ▶ [DNA Sequencing](#)
- ▶ [Nucleic Acids](#)
- ▶ [Protein](#)

Elemental Carbon

- ▶ [Carbon](#)

Elemental Depletion

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Elemental depletion denotes the difference in elemental composition of an astronomical

source relative to some standard of reference, usually the Sun. Lines of sight through the local interstellar medium indicate much lower abundances of many chemical elements compared to the solar composition. This is largely due to the differential incorporation of these elements into interstellar dust grains. Different lines of sight through diffuse clouds show different depletions.

History

The definition of “cosmic abundances” also takes account of the relative abundances in carbonaceous chondrites, which generally correlate well with those in the solar photosphere (Anders and Grevesse 1989; Przybilla et al. 2008) apart from the most volatile elements such as hydrogen and helium.

Cross-References

- ▶ [Abundances of Elements](#)
- ▶ [Carbonaceous Chondrite](#)
- ▶ [Diffuse Cloud](#)
- ▶ [Interstellar Dust](#)

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Elephant Trunks

- ▶ [Pillars](#)

Eley-Rideal Mechanism

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

The Eley-Rideal mechanism is a theoretical model of how some bimolecular chemical reactions can take place on solid surfaces. In the theory, one atom or molecule is adsorbed on the surface, and another reacts directly from the gas phase. This may be contrasted with the ► [Langmuir-Hinshelwood mechanism](#). In the interstellar medium, the formation of molecular hydrogen is thought to occur primarily through reactions on the surfaces of dust grains.

Cross-References

- [Adsorption](#)
- [Interstellar Dust](#)
- [Langmuir-Hinshelwood Mechanism](#)

Embden-Meyerhof-Parnas Pathway

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

[Glycolysis](#)

Definition

The Embden-Meyerhof-Parnas (EMP) pathway allows the metabolic use of glucose to generate

ATP, NADH, and several biosynthetic precursors such as 3-phosphoglycerate or pyruvate. The EMP pathway can occur both anaerobically (leading to one or several ► [fermentation](#) pathways) and aerobically through the conversion of pyruvate to acetyl CoA and the connection with the tricarboxylic acids (TCA) cycle. The classical version of the EMP pathway is present in bacteria and eukaryotes whereas several modified versions are present in anaerobic archaea. The second half of the pathway is almost universal, and thus, it could represent the oldest part of the pathway, related to a primordial origin of ► [gluconeogenesis](#).

History

By 1940, the canonical glycolytic pathway (i.e., the one responsible for alcoholic fermentation in yeasts and anaerobic ► [glycolysis](#) in muscle) was elucidated. Actually, it was the result of a collective task with the contributions of, among others, Gustav Embden (1874–1933), Arthur Harden (1865–1940), Karl Lohmann (1898–1978), Otto Fritz Meyerhof (1841–1951), Jakub Karol Parnas (1884–1949), and Otto Heinrich Warburg (1883–1970).

Cross-References

- [Entner-Doudoroff Pathway](#)
- [Fermentation](#)
- [Gluconeogenesis](#)
- [Metabolism](#)

Embedded Bioburden

- [Encapsulated Bioburden](#)

Emergence of Life

- [Origin of Life](#)

Emission Nebula

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

That portion of an interstellar cloud that is heated and ionized by radiation from nearby stars shines as an emission nebula. The spectrum is characterized by emission lines from the constituent atoms and ions. Emission nebulae are typically H II regions, although planetary nebulae are sometimes also referred to as emission nebulae.

Cross-References

- ▶ [HII Region](#)
- ▶ [Planetary Nebula](#)

Emissivity

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Emissivity is a quantity in physics that depends on wavelength and that characterizes the efficiency with which a surface radiates, compared to a ▶ [black body](#) at the same temperature. A black surface has an emissivity close to 1 and a polished reflecting surface an emissivity close to 0. Because of Kirchhoff's law, the same quantity characterizes also the ability of a surface to absorb or to reflect impinging radiation (absorptivity = emissivity, ▶ [albedo](#) = 1 – emissivity). Emissivity is a positive, dimensionless quantity, lower than or equal to 1.

Cross-References

- ▶ [Albedo](#)
- ▶ [Blackbody](#)

Empire

- ▶ [Domain \(Taxonomy\)](#)

100% Enantiomeric Excess

- ▶ [Homochirality](#)

Enantiomeric Excess

Robert Hazen

Geophysical Laboratory, Carnegie Institution of
Washington, Washington, DC, USA

Synonyms

[Chiral excess](#); [Evolutionary Tree](#)

Definition

Enantiomeric excess (*ee*) is a measure of the deviation of a mixture of ▶ [chiral](#) (i.e., handed) molecules from the equimolar (or “racemic”) state. Enantiomeric excess is usually expressed as a percent; if D and L are the amounts of two chiral molecules, the enantiomeric excess is given as

$$ee = [(D - L) / (D + L)] \times 100$$

Thus, the *ee* of a 60:40 mixture of D:L is 20 – a value that can be thought of as a mixture with 20 % pure D plus 80 % racemic mixture; furthermore, *ee* equals 0 and 100 for racemic and chirally pure mixtures, respectively.

An enantiomeric excess can be measured in a number of ways, including specific optical rotation or chromatography with a chiral column. The enantiomeric excess is important in characterizing the purity of chiral pharmaceuticals and other chiral products. Many models of the origins of life postulate the local and/or global development of enantiomeric excesses in mixtures of amino acids or other biomolecules and their subsequent chiral amplification, as a prelude to life's ► [homochirality](#).

An enantiomeric excess has been reported in ► [carbonaceous chondrites](#) for some organic compounds, including amino acids (see ► [Chirality](#)).

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Enantiomers](#)
- [Homochirality](#)

50:50 Enantiomeric Mixture

- [Racemic Mixture](#)

Enantiomeric Ratio

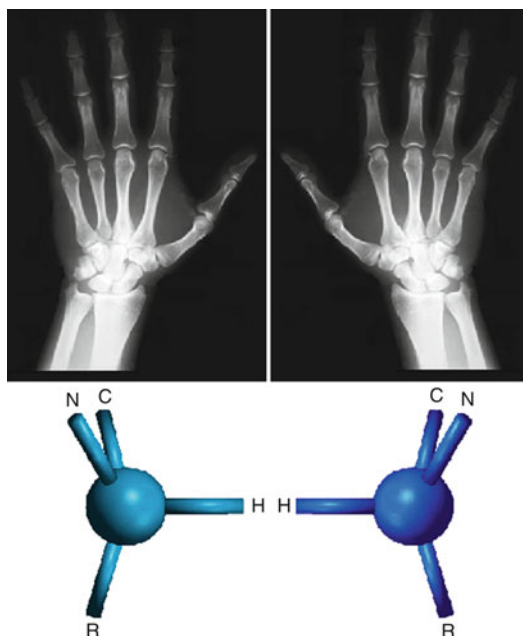
- [D/L-Ratio](#)

Enantiomers

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

An enantiomer is one of a pair of optical ► [iso-](#)
[mers](#), the structures of which are not



Enantiomers, Fig. 1 An amino acid (*bottom*) showing four different atoms (R is another carbon substituent, e.g., CH₃) attached to a central carbon atom. This configuration results in the property of asymmetry. The resulting enantiomers are mirror images of each other [much like the mirror images of your hands (*top*)], but they are otherwise chemical equivalent

superimposable on their mirror images. In organic compounds, enantiomers contain a carbon atom that has four different groups attached to it (asymmetric or chiral carbon) (see Fig. 1). The best-known examples are the L- and D-enantiomers of amino acids. Enantiomers have identical physical and chemical properties, with the exception that they rotate light in equal but opposite directions. Enantiomers based on other central atoms such as silicon, phosphorus, and germanium are also known.

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Stereoisomers](#)

Enantiopure

► [Homochirality](#)

Encapsulated Bioburden

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Synonyms

[Embedded bioburden](#)

Definition

In planetary protection, the term “encapsulated ► [bioburden](#)” is used to indicate the viable microorganisms that are trapped inside nonmetallic spacecraft materials. They can be, for example, in the adhesive for honeycomb structures, the conformal coating of electronic boards, or in the matrix of a material itself. The term embedded bioburden can be used as a synonym, although “embedded” does not carry the same emphasis that the microorganism is isolated from the point of view of restricting water vapor loss, compare to “encapsulated.”

A spaceflight project may choose to directly measure the number of microorganisms present in a specific material, or use specification values as a conservative estimate of the number of microorganisms present. NASA and ESA have established consensus specifications describing the number of microorganisms that are assumed to be present in a variety of materials manufactured or prepared under defined environmental cleanliness conditions.

Encapsulation of a microorganism in a material matrix is thought to reduce the rate of water loss during heat sterilization processes (relative to surface bioburden) that is one of the causative factors for cell death during DHMR. The lethality of DHMR processes on encapsulated bioburden is

taken as one-tenth the lethality for exposed bioburden.

Cross-References

- [Bioburden](#)
- [DHMR](#)
- [Planetary Protection](#)
- [Sterilization](#)

Enceladus

Thérèse Encrenaz
LESIA, Observatoire de Paris, PSL, CNRS,
Sorbonne University, Université Paris-Diderot,
UPMC, Meudon, France

Keywords

Saturn’s satellites

Definition

Enceladus is one of the mid-sized icy satellites of Saturn (500 km in diameter). It was discovered by William Herschel in 1789. Its distance to Saturn is 238,100 km or about 4 Saturnian radii. Its density is 1.0 g/cm³, corresponding to a bulk composition of water ice. With an albedo of 0.9, Enceladus is the brightest object known in the solar system; such a high albedo results in very low surface temperature (~70 K). Enceladus is best known for its plumes emanating from the south pole probably as an expression of the global salty ocean underneath the surface, which makes this satellite one of the most promising habitable environment in the solar system.

Overview

The exploration of Enceladus started with the Voyager missions. The first images of Voyager 1, taken in December 1980, already indicated a bright and young surface with relatively few

craters. Voyager 2, in August 1981, not only confirmed this result but also provided evidence for tectonic activity, which was totally unexpected on such a small object. These results raised the interest of scientists who considered Enceladus as a prime objective for the Cassini mission.

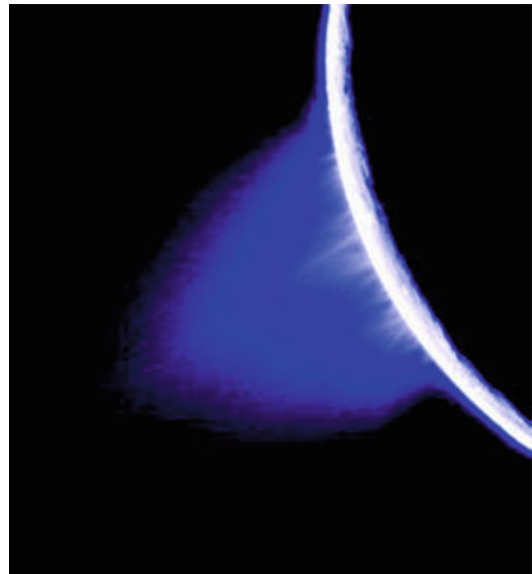
The exploration of Enceladus by Cassini started in 2005 with a series of flybys; the closest ones took place in March 2005 and July 2005, with respective distances of 501 and 172 km. Most of Enceladus' surface is covered with impact craters distorted by viscous relaxation and also by a more recent tectonic activity. Cassini images showed several different tectonic features: linear faults, curved stripes, and rifts (called "*fossae*") of over 200 km in length, 10–15 km in width, and 1 km in depth.

In addition, the Cassini instruments discovered at the South Pole a new region, previously unobserved, different from the northern hemisphere, which was rather smooth. This region, which extends southward up to a latitude of about 55S, is crater-free with many tectonic fractures and faults. The Cassini camera discovered therein four large faults distant from each other by about 35 km; they are up to 130 km in length, 2 km in width and 0.5 km in depth. They are known as the "tiger stripes" and are the youngest structures observed on the satellite. The Visible and Infrared Mapping Spectrometer of Cassini (VIMS) detected crystalline ice in this region, which indicates a very young origin (less than 1000 years): if older, the water ice would have been transformed into amorphous ice by the solar UV radiation. The frontier between the South Pole region and its surrounding is marked by parallel cliffs and valleys.

After the Voyager encounters, it was already proposed that cryovolcanism could be active on Enceladus thus accounting for its recent resurfacing. In addition, such a cryovolcanism would provide a source for the E-ring of Saturn which is located exactly at the same orbital distance as Enceladus. These hypotheses were fully confirmed by the Cassini observations in July 2005 and later on. First, observations by the magnetometer of Cassini showed, in the vicinity of Enceladus, a deviation of Saturn's magnetic field lines which

could be attributed to the interaction between this magnetic field and ionized particles surrounding the satellite. In addition, ultraviolet spectra recorded during a stellar occultation by the UVIS instrument showed a localized atmosphere, mostly made of water vapor around the South Pole. Simultaneously, the Cassini Ion and Neutral Mass Spectrometer (INMS) detected H₂O, but also N₂ and CO₂ in the cloud surrounding the South Pole. Finally, the Cosmic Dust Analyzer (CDA) detected near the tiger stripes microcrystals of water, similar to those of the E-ring, thus confirming Enceladus as the main provider of material in the E ring (Fig. 1).

Because of the low gravity field of Enceladus, the atmosphere (in the form of a torus) surrounding the South Pole cannot be stable and must be continuously replenished. The most likely mechanism for feeding this atmosphere is cryovolcanism through the tiger stripes. This also accounts for the temperature excess of about 15 K measured by the Composite Infrared Spectrometer (CIRS) around the tiger stripes. In November 2005, a visual confirmation was brought by the camera of the Cassini orbiter which observed jets of icy particles above the South Pole region.



Enceladus, Fig. 1 Enceladus as observed by the Voyager spacecraft. (©NASA)

Since 2005, repeated flybys have allowed scientists to accumulate data about the surface structure of the South Pole, the geysers, and the composition of the plumes. In addition to H_2O , N_2 , CO_2 , and CO , other simple and complex hydrocarbon chains have been identified. The presence of nitrogen has been interpreted as a dissociation product of NH_3 , which suggests the possible presence of liquid NH_4OH associated to H_2O under the surface of Enceladus. Enceladus' cryovolcanism is believed to be the feeding mechanism for the E-ring of Saturn, located at the same orbital distance.

In June 2009, the Cosmic Dust Analyzer has identified sodium salt (NaCl), in the icy grains which compose the E-ring. This constitutes a strong argument in favor of the presence of a salty water ocean below the satellite's surface. The presence of salts and carbonates in the geyser products suggests that such a liquid ocean of water could be in direct contact with a silicate core, which could have important implications for astrobiology. In 2017, the Ion and Neutral Mass Spectrometer of Cassini has detected molecular hydrogen in the plumes of Enceladus. Its origin could be due to the reaction of water with minerals and organics at the transition region between the water ocean and the solid surface; such a reaction (called serpentinization) is actually observed in terrestrial hydrothermal vents. The presence of dihydrogen in the plumes of Enceladus might be an indication for the presence of hydrothermal vents in Enceladus also.

What could be the origin of the internal energy that drives cryovolcanism on Enceladus? Solar energy which works for our planet is not effective at almost 10 AU. Tidal effects linked to the orbital resonance of Enceladus with Dione (another icy satellite of Saturn) could generate some internal energy, however, by far not enough to account for tectonic activity. According to some scientists, Enceladus, as other icy satellites of Saturn, might have formed very quickly. As a result, the satellite would have acquired a differentiated structure with a silicate core and an ice mantle. Subsequent radioactive and tidal heating would have raised the inner temperature enough to melt the icy mantle and part of the core, possibly

creating magma chambers which would feed cryovolcanism.

The water torus of Enceladus has been detected using the HIFI heterodyne spectrometer of the Herschel space observatory, which measured the water content along the line of sight and a very low temperature (16 K). From estimates of the water influx rate on Saturn and Titan, it was found that the water torus of Enceladus was probably the main source of stratospheric water for Saturn, and possibly for Titan as well. Future in situ investigations for both of Saturn satellites are necessary to precisely describe the habitability potential of these two worlds.

Cross-References

- [Cryovolcanism](#)
- [Dione](#)
- [Saturn](#)
- [Titan](#)

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Endergonic

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

An endergonic reaction is one that requires ► [free energy](#) to proceed. An example of an endergonic reaction of biological interest is ► [photosynthesis](#). Photosynthetic organisms conduct this reaction by using solar photons to drive the reduction of carbon dioxide to glucose and the oxidation of water to oxygen. The free energy change during a chemical reaction or a physical transformation which takes place at constant pressure is described by the familiar ΔG symbol where G is the Gibbs free energy. By definition, ΔG is positive for an endergonic process (and negative for an ► [exergonic](#) process). When the reaction takes place at constant volume, the free energy change is described by the symbol ΔF , where F is the Helmholtz free energy.

Cross-References

- [Exergonic](#)
- [Free Energy](#)
- [Photosynthesis](#)

Endogenetic

- [Endogenous](#)

Endogenicity

Nicola McLoughlin

Department for Geology, Rhodes University,
Makhanda (Grahamstown), South Africa

Keywords

Biosignatures · Contamination

Synonyms

[Indigenous](#)

Definition

A component that may be textural, chemical, mineral, or biological and that formed within the host material. For example, a mineral phase or organic structure found in a rock that is indigenous to that rock and not derived from external sources. Endogenicity concerns the source of a component with respect to space and this differs from syngenetic that concerns the source of a component with respect to time.

History

Traditionally, the term endogenetic has been used in geology to refer to processes originating below the Earth's surface as opposed to exogenetic that describes geological processes acting at or near the Earth's surface. This definition is here modified for the investigation of astrobiological samples obtained from a range of planetary surfaces and to operate at all observational scales from the field outcrop, hand sample to microscope.

Overview

A component formed within the host material that is indigenous to that sample and formed in a closed system. Endogenetic components are not sourced from interactions with external environments – such components are termed exogenous. Most often, endogenetic components are also syngenetic and formed at the same time as the host material but not always. For example, diagenetic and metamorphic phases produced by changes in pressure and temperature after formation of the host rock are endogenetic to that system (provided it was closed to fluid flow) but are not syngenetic, because they formed later in time. Often, exogenous components can be readily recognized because they occur in younger cross-cutting veins or the alteration rims of, for example,

meteorites and are derived from interactions with the terrestrial atmosphere or surface.

To demonstrate the endogenicity of a component requires its composition, structure, and context to indicate an origin from within that system. For instance, organic material found in a rock should occur in primary mineral phases or sedimentary fabrics; have an isotopic fingerprint that is distinct from externally sourced, migrating organic material; and exhibit a crystallinity and/or reflectance that is compatible with the thermal maturity of the host rock. One way to demonstrate this for carbonaceous material is to show that the Raman spectra of the candidate biosignature and host rock match, indicating that they have experienced the same degree of thermal alteration (Javaux et al. 2010). In addition, carbon isotopic measurements made both in-situ and on extractable phases can be used to characterize and distinguish endogenous from exogenous pools of organic material (Rasmussen et al. 2008). Fabric investigations are also crucial to eliminate exogenous components that are hosted by younger, possibly meta-stable phases produced by, for example, hydrothermal alteration, or weathering near the planetary surface and occur near cross-cutting features or external surfaces (Pinti et al. 2009). In meteorites, for example, it has been shown by biological staining and epifluorescence microscopy that terrestrial microbial hyphae can rapidly colonize the interior (Toporski and Steele 2007). Thus storage and handling protocols are essential to protect endogenous remains collected by sample return missions or delivered by impactors. Lastly, emerging nanoscale techniques for observing the interface between a candidate biosignature and host material can help to understand their preservational history and provide a further tool for assessing endogenicity (Wacey et al. 2008; Thomas-Keptra et al. 2009; Bernard et al. 2007).

Cross-References

- [Archaeal Traces of Life](#)
- [Biogenicity](#)
- [Biomarkers, Morphological](#)
- [Biosignatures, Effect of Metamorphism](#)

- [Diagenesis](#)
- [Raman Spectroscopy](#)
- [Syngenicity](#)

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Endogenous

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Endogenetic](#)

Definition

In geology, endogenous (from Greek *endon*, within) is an adjective which refers to all processes produced in the interior of a telluric planet – such as tectonics, volcanism, and metamorphism –

but that can have subsequent effects on the surface of the planet itself. An example is the mantle convection which drives the movement of tectonic plates at the surface of the Earth. The main source of energy of endogenous geological processes is the heat produced by the radioactive decay of elements U, Th, and K and the residual heat from planetary accretion.

Cross-References

- [Exogenous](#)
- [Plate Tectonics](#)

Endogenous Synthesis

André Brack
Centre de Biophysique Moléculaire CNRS,
Orléans Cedex 2, France

Keywords

Amino acids · Formaldehyde · Hydrogen cyanide · Hydrothermal systems · Lipids · Organic molecules · Prebiotic chemistry · Primitive atmosphere

Synonyms

[Building blocks of primitive life](#)

Definition

Life, defined as an open chemical system capable of self-reproduction and evolution, is thought to have originated from reduced organic matter in water. Carbon was available as gaseous compounds in the primitive atmosphere, either oxidized as carbon monoxide and carbon dioxide or reduced as methane. When subjected to energy sources (UV, heat, electric discharges, cosmic rays, shock waves) and mixed with water and ammonia or nitrogen, these gases generate hydrogen cyanide and formaldehyde that lead to many of the building blocks of life, such as amino acids.

Deep-sea hydrothermal systems may also represent an environment for the synthesis of prebiotic organic molecules.

Overview

It is generally believed that life on Earth arose in liquid water about 4 billion years ago. It is likely that the ingredients of primitive life were organic molecules based on carbon and hydrogen atoms associated with oxygen, nitrogen, and sulfur. The simplest sources of carbon susceptible to lead to prebiotic organic molecules are gaseous, that is, carbon dioxide, carbon monoxide, and methane. A prebiotic environment must produce reduced organic molecules in which carbon is dominantly associated with hydrogen rather than oxygen.

Production of Organics in the Atmosphere

Oparin (1924) suggested that the small reduced organic molecules needed for primitive life were formed in a primitive atmosphere dominated by methane. The idea was tested in the laboratory by Miller (1953) who exposed a mixture of methane, ammonia, hydrogen, and water to spark discharge and silent electric discharge. In his initial experiment, he obtained three amino acids (glycine, alanine, and β -alanine) via the intermediary formation of hydrogen cyanide and aldehydes. More generally, simple gaseous molecules, like CH_4 , H_2 , NH_3 , and H_2O , require a supply of energy (UV, heat, electric discharges, cosmic rays, shock waves) to react with each other. They generate compounds like formaldehyde and hydrogen cyanide that store chemical energy in their double and triple chemical bonds, respectively. The possible sources of atmospheric synthesis, including electric effects, solar UV, and impact shocks, have been reviewed by Chang (1993).

Miller's laboratory synthesis of amino acids occurs efficiently when a reducing gas mixture containing significant amounts of hydrogen is used. However, the actual composition of primitive Earth's atmosphere is not known. The dominant view in recent years is that the primitive atmosphere consisted mainly of CO_2 , N_2 , and H_2O along with small amounts of CO and H_2 (Kasting and Brown 1998; Catling and Kasting

2007). Only small yields of amino acids are formed in such a mixture (Schlesinger and Miller 1983; Miller 1998). Recent studies show that the low yields previously reported appear to be the outcome of oxidation of the organic compounds during hydrolytic workup by nitrite and nitrate produced in the reactions. The yield of amino acids is greatly increased when oxidation inhibitors, such as ferrous iron, are added prior to hydrolysis, suggesting that endogenous synthesis from neutral atmospheres may be more important than previously thought (Cleaves et al. 2008). Additionally, 22 amino acids and 5 amines were obtained when reanalyzing archived samples of experiment run by Miller and simulating production of organic molecules in volcanic gases by lightning. The volcanic apparatus experiment suggests that, even if the overall atmosphere was not reducing, localized prebiotic synthesis could have been effective in volcanic plumes (Johnson et al. 2008). Unreported H₂S-containing experimental samples were also found and analyzed and were composed of numerous organosulfur compounds (Parker et al. 2011a, b, c). The H₂S samples were analyzed by high-performance liquid chromatography with fluorescence detection (HPLC-FD) and ultraperformance liquid chromatography-fluorescence detection with time-of-flight mass spectrometry. Miller's H₂S experiment synthesized 23 amino acids and 4 amines. Many non-protein amino acids, including several rare or absent, in biology were detected.

The atmospheric formation of glycolaldehyde, a key RNA precursor, has been investigated using a one-dimensional photochemical model. Maximum atmospheric production of glycolaldehyde occurs when the CH₄:CO₂ ratio is close to 0.02. The total atmospheric production rate remains small, only 1×10^7 mol yr⁻¹. Additional production or concentration mechanisms for glycolaldehyde or alternative formation mechanisms are needed (Harman et al. 2013).

The escape of hydrogen from the early Earth's atmosphere has recently been reevaluated (Tian et al. 2005). It may have occurred at rates slower by two orders of magnitude than previously thought. The balance between slow hydrogen escape and volcanic outgassing could have maintained a hydrogen mixing ratio of more than

30%, thus making endogenous organic synthesis more robust than previously thought.

Intense bombardment probably caused some chemical reprocessing of the Earth's primitive atmosphere by impact shock chemistry. An indication of the number and timing of the impacts onto the early Earth can be obtained by comparison with the crater record of the Moon, which records impacts from the earliest history of the solar system (Ryder 2003). Because of the larger size of the Earth and its greater gravitational pull, about 20 times as many impacts would have occurred on the early Earth as on the Moon. Computer modeling of impact shock chemistry shows that the nature of the atmosphere strongly influences the shock products (Fegley et al. 1986). A neutral CO₂-rich atmosphere produces CO, O₂, H₂, and NO, while a reducing CO-rich atmosphere yields primarily CO₂, H₂, CH₄, HCN, NH₃, and H₂CO. The last three compounds are particularly interesting for prebiotic chemistry since they can lead to amino acids via the Strecker synthesis. However, a CO-rich primitive atmosphere may be unlikely due to the instability of CO to photolysis. In laboratory experiments, a gas mixture of methane, ammonia, and water subjected to shock heating followed by a rapid thermal quenching yielded the amino acids glycine, alanine, valine, and leucine (Bar-Nun et al. 1970). Here again, the gas mixture used does not represent a realistic primitive atmosphere, which was probably dominated by CO₂. Laboratory simulations of shocks were also run with a high-energy laser. CH₄-containing mixtures generated hydrogen cyanide and acetylene, but no organics could be obtained with CO₂-rich mixtures (McKay and Borucki 1997).

Submarine Hydrothermal Systems

The reducing conditions in hydrothermal systems may have been an important source of biomolecules on the primitive Earth (Baross and Hoffman 1985; Holm and Andersson 1998, 2005). The reducing environment results from the flow of substances dissolved in seawater passing inorganic compounds present in very hot crustal material that reduce compounds in the seawater. These reduced compounds flow out of the hydrothermal system, and the inorganic sulfides formed

precipitate when they mix with the cold (4 °C) ocean water. For example, hydrocarbons containing 16–29 carbon atoms have been detected in the Rainbow ultramafic hydrothermal system, Mid-Atlantic Ridge (Holm and Charlou 2001). Hydrothermal vents are often disqualified as efficient reactors for the synthesis of bioorganic molecules, because of the high temperature. However, the products that are synthesized in hot vents are rapidly quenched in the surrounding cold water, which may preserve those organics formed.

In laboratory experiments, one amino acid synthesis started with a mixture of hydrogen cyanide, formaldehyde, and ammonia, so it is not really a hydrothermal process (Hennet et al. 1992). The same holds for a reported hydrothermal synthesis of amino acids that used calcium metal, formaldehyde, ammonia hydrogen, and oxygen in different combinations to generate amino acids (Marshall 1994). Amino acids and polymers of amino acids are formed by the reaction of methane and nitrogen at 325 °C in “modified seawater” in a glass-lined vessel (Yanagawa and Kobayashi 1992). “Modified seawater” contains the principal metal ions present in seawater but at much higher concentrations so as to amplify the chemical processes catalyzed by the ions so they can be more easily detected. The role of the silicate and metal ions in this complex reaction mixture is not clear, and this system may not be a good model of a hydrothermal system.

The role of submarine hydrothermal systems in the synthesis of amino acids has been carefully examined (Aubrey et al. 2009). The results of experiments exploring the potential for amino acid synthesis at high temperature from synthetic seawater solutions of varying composition have been reported. The synthesis of amino acids was examined as a function of temperature, heating time, starting material composition, and concentration. Using very favorable reactant conditions (high concentrations of reactive, reduced species), small amounts of a limited set of amino acids are generated at moderate temperature conditions (~125–175 °C) over short heating times of a few days, but even these products are significantly decomposed after exposure times of

approximately 1 week. Although amino acids can be generated from simple likely environmentally available precursors under submarine hydrothermal system conditions, the equilibrium at high temperatures favors net amino acid degradation rather than synthesis, and that synthesis at lower temperatures may be more favorable.

The Role of Minerals

Clay minerals are formed by water weathering of silicate minerals. As soon as liquid water was permanently present in the surface of the Earth, clay minerals accumulated. The importance of clay mineral in the origins of life was first suggested by Bernal (1949). The advantageous features of clays for Bernal were their ordered arrangement, their large adsorption capacity, their shielding against sunlight, their ability to concentrate organic chemicals, and their ability to serve as polymerization templates. Since the seminal hypothesis of Bernal, many prebiotic experiments have been run with clays (Ponnamperuma et al. 1982; Brack 2006; Negron-Mendoza et al. 2010).

Since during the Hadean to early Archean period (4.5–3.5 Ga) the surface of the Earth’s crust was predominantly composed of basalt and komatiite lavas, Meunier et al. (2010) considered that the composition of these rocks favored the crystallization of Fe-Mg clays rather than that of Al-rich ones (montmorillonite). It is assumed that every square meter of basalt or komatiite rocks was punctuated by myriads of clay-rich patches, each of them potentially behaving as a single chemical reactor which could concentrate the organics diluted in the ocean water. Considering the high catalytic potentiality of clays and particularly those of the Fe-rich ones (electron exchangers), it is probable that large parts of the surface of the young Earth participated in the synthesis of prebiotic molecules during the Hadean to early Archean period through innumerable clay-rich micro-settings in the massive parts and the altered surfaces of komatiite and basaltic lavas. This leads the authors to suggest that Fe-Mg clays should be preferred to Al-rich ones (montmorillonite) to conduct experiments for the synthesis of prebiotic molecules.

If the carbon source for life was carbon dioxide, the energy source required to reduce the carbon dioxide might have been provided by the oxidative formation of pyrite from iron sulfide and hydrogen sulfide. Pyrite has positive surface charges and bonds the products of carbon dioxide reduction, giving rise to a two-dimensional reaction system, a “surface metabolism” (Wächtershäuser 1994, 1998, 2007). Laboratory work has provided some support for this promising hypothesis. An early laboratory simulation of hydrothermal synthetic reactions is the reduction of carbon dioxide to organic sulfides at 75 °C in the presence of FeS and H₂S. Methyl- and ethyl-thiol were the principal thiols formed along with smaller amounts of others containing up to five carbon atoms. The CO₂ was also converted to CS₂ and COS (Heinen and Lauwers 1996). The direct reduction of CO₂ to acetic acid, acetaldehyde, ethanol, and smaller amounts of carbon compounds containing up to six carbon atoms was observed to take place at 350 °C and high pressure in the presence of magnetite (FeO:Fe₂O₃) and small amounts (2%) of water. The yields of organics decreased 10–100% when the proportion of water was increased to 90% (Chen and Bahnmann 2000). A similar inhibitory effect of large amounts of water was observed in the reduction of nitrogen to ammonia in the presence of magnetite and ten bars of CO₂ at 350 °C. The yield of ammonia decreased 10- to 100-fold when the water/iron ratio was increased from 0.5 to 6 (Brandes et al. 1998).

There are also reports of the reaction of CO in simulated hydrothermal systems. When a mixture of CO and CH₃SH was reacted with a combination of a NiS-FeS at 100 °C, acetic acid and its corresponding thioester were formed (Huber and Wächtershäuser 1997). This system was extended to the formation of keto esters at higher temperatures and pressures where CO is inserted into the thioester to form a keto thioester that in turn hydrolyzed to pyruvic acid (Cody et al. 2000). More recently, α -hydroxy and α -amino acids have been obtained under possible volcanic origin-of-life conditions by heating CO in the presence of nickel or nickel/iron precipitates with carbonyl, cyano, and methylthio ligands as carbon sources (Huber and Wächtershäuser

2006). However, the plausibility of the conditions used has been debated (Bada et al. 2007).

Cross-References

- [Chemical Evolution](#)
- [Extraterrestrial Delivery of Organic Compounds](#)

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Endolithic

Angeles Aguilera
Laboratorio de Extremófilos, Centro de
Astrobiología (INTA-CSIC), Madrid, Spain

Definition

Endolithic refers to any ► [microorganisms](#) which are able to colonize and survive inside a rock.

Endoliths are classified into three different classes depending on the part of the interior of the rock that the organisms colonize: chasmoendoliths (chasm means cleft) are the organisms that colonize open spaces in the rock such as fissures and cracks; cryptoendoliths (crypto means hidden) are the organisms that colonize the interior of porous rocks; and euendoliths (eu which means true endolith) are the organisms that actively colonize the interior of the rock by forming tunnels with the shape of their bodies. These organisms are of extreme astrobiological interest because the interior of a ► [meteorite](#) can give shelter to endolithic organisms under the extreme conditions of an interplanetary voyage (► [lithopanspermia](#)).

Cross-References

- [Cryptoendolithic](#)
- [Lithopanspermia](#)
- [Microorganism](#)
- [Panspermia](#)

Endospore

Wayne L. Nicholson^{1,2} and Ralf Moeller³

¹Space Life Sciences Laboratory, University of Florida, Merritt Island, FL, USA

²Space Life Sciences Laboratory, Kennedy Space Center, University of Florida, Gainesville, FL, USA

³German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Synonyms

[Bacterial spore](#); [Spore](#)

Definition

An endospore is a tough, dormant structure produced by certain species of Gram positive bacteria, most notably of the genera *Bacillus* and *Clostridium*.

Cross-References

- [Sporulation](#)

Endosymbiosis

Amparo Latorre

Institute Cavanilles for Biodiversity and Evolutionary Biology, Universitat de Valencia, Valencia, Spain

Keywords

Bacteriocyte · Chloroplast · Endosymbiont · Mitochondria · Obligate mutualism · Symbiogenesis

Definition

Endosymbiosis is a symbiotic association in which one partner, generally a prokaryote symbiont, lives sequestered inside specialized eukaryotic host cells called bacteriocytes. The association is obligate for both partners.

Overview

Symbiogenesis, the evolutionary process of establishing a symbiotic association, has been one of the dominant forces in the early evolution of life on Earth. In 1967 Lynn Margulis postulated the serial endosymbiotic theory of eukaryotic ► [cell](#) evolution, currently accepted with respect to the origin of mitochondria and ► [chloroplasts](#) (Margulis 1993). These two eukaryotic ► [organelles](#) are beyond doubt the product of symbiogenic events between prokaryotes and primitive eukaryotes, as supported by many different types of genetic, biochemical, and phylogenetic evidence. The origin of mitochondria dates back to 2×10^9 years ago, whereas chloroplasts originated more than 1.2×10^9 years ago, because fossil red algae of that age have been found. DNA sequence comparisons and phylogenetic analyses have identified alpha-

proteobacteria and cyanobacteria as the bacterial groups to which the ancestors of mitochondria and plastids, respectively, belonged.

Nowadays, symbiotic associations have been documented in practically every major branch of the ► [tree of life](#), and this observation reinforces the role played by ► [symbiosis](#) in the emergence of evolutionary innovations in eukaryotes. Recently, the genomic era has opened the access to the characterization of the organisms involved in symbiosis, mainly those non-cultivable microbial endosymbionts, allowing the comparison among the different evolutionary innovations carried out by these bacteria on their way from a free-living lifestyle to varied stages of integration with their respective hosts (Dale and Moran 2006; Moya et al. 2008; McCutcheon and Moran 2012). Thus, endosymbiosis is an ongoing phenomenon in the evolution of life and played a key role in the origin and evolution of the eukaryotic cell.

In general, it is well established that endosymbiotic integration is a process that commonly changes profoundly the gene repertoire of the free-living ancestor. Depending on the type of symbiotic relationship (i.e., mutualistic or parasitic, facultative or obligate, etc.), age of the association, and host necessities (i.e., nutritional, defensive, waste recycling, etc.), the genetic and metabolic changes will be more or less dramatic (Wernegreen 2005; Moran et al. 2008).

We should not disregard the discovery of new instances of endosymbionts currently en route to become organelles or fully fledged eukaryotic compartments of bacterial origin (Nakabachi et al. 2006; Pérez-Brocal et al. 2006; Nowack et al. 2008; McCutcheon and von Dohlen 2011). Current “omics” (such as genomics, proteomics, or metabolomics) methodologies allow us not only to further unravel the steps toward the origin of the eukaryotic cell but also to assess the question of how much of the eukaryotic complexity originated through evolutionary innovations by symbiogenesis.

Cross-References

- [Cell](#)
- [Chloroplast](#)

- [Eukarya](#)
- [Evolution, Biological](#)
- [Mitochondrion](#)
- [Organelle](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Symbiosis](#)
- [Taxonomy](#)

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Endothermic

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

An endothermic reaction is a physical transformation which requires an energy supply if it takes place at constant volume or which requires an

enthalpy supply if it takes place at constant pressure. A familiar endothermic physical transformation is the evaporation of water. The enthalpy change (ΔH) or the energy change (ΔU) during an endothermic reaction or transformation is positive by definition.

Cross-References

► [Exothermic](#)

Energy

Francisco Montero

Department of Biochemistry and Molecular Biology I, Facultad de Ciencias Químicas, Universidad Complutense de Madrid, Madrid, Spain

Keywords

ATP · Bioenergetics · Chemical work · Electrochemical potential gradient · Electromagnetic energy · Energy transduction · Osmotic work

Definition

In physics, energy is defined as the capacity of a system to produce work. There are many forms of energy (e.g., mechanical, electrical, electromagnetic, chemical, etc.), and it is possible to convert some energy forms into others, with the condition that the energy is conserved.

History

A coherent theory on energy and its transformations was first advanced in the nineteenth century, chiefly as a consequence of the Industrial Revolution. The propounding of the fundamental principles (or laws) of thermodynamics established the basic rules for energy conversions.

Although important observations had already been made on the effect of energy on biological systems by the nineteenth century, it was not until the development of biochemistry in the twentieth century that energy conversion mechanisms in biological systems were explained. In 1941, Lipmann established that ATP is an energy currency in the biological system, while in 1961, Mitchell proposed the chemiosmotic hypothesis, which constitutes the base of all modern ► [bioenergetics](#). Nowadays, the majority of energy transduction processes at molecular level are well understood.

Overview

Ever since the Industrial Revolution, one of mankind's greatest challenges has been to find interconversion mechanisms for different energy forms (i.e. conversion of thermal, wind, electromagnetic, or atomic energy into mechanical or electrical energy). Although all energy forms are interconvertible, there are limitations with regard to the amount and quality of the energy released in a process that can be used in another one. For this reason, the total energy in a system is usually classified into different categories, such as internal energy, free energy, enthalpy, entropic contribution, etc. Of these, free energy is the only one that can be transferred from one process to another. Therefore, processes are classified as ► [endergonic](#) or ► [exergonic](#) depending, respectively, on whether they need or release ► [free energy](#) during their development.

Biological systems, when viewed as thermodynamic systems, are considered to be open systems, which means they can exchange matter and energy with their surroundings in order to maintain the dissipative structures, which characterize them. Basically, energy can be exchanged with the surroundings in two ways: through matter, by taking molecules from the environment whose catabolic processes (of degradation) release free energy, or by absorbing electromagnetic radiation. Furthermore, biological systems have mechanisms which can convert some forms of energy into

others, e.g., electromagnetic energy into osmotic energy, osmotic energy into chemical and mechanical energy, etc. These general mechanisms for the translation of energy within a biological system, which are the result of evolution and natural selection, constitute the field of study of bioenergetics and are truly astonishing. A general law governing energy coupling in biological systems states that they are not usually direct. Instead, they are produced through universal intermediaries or “energy currencies.” An exergonic process produces an energy currency which can then be used in an endergonic process. All of the energy currencies can be used to produce chemical work (production of molecules whose formation requires energy, in general anabolic processes), osmotic work (the transport of substances across membranes against their ► [electrochemical](#) potential gradients), or mechanical work (movement of flagella and cilia, contractile movements, etc.).

Cross-References

- [ATP](#)
- [ATP Synthase](#)
- [Bioenergetics](#)
- [Electrochemical Potential](#)
- [Endergonic](#)
- [Endothermic](#)
- [Energy Conservation](#)
- [Energy Sources](#)
- [Enthalpy](#)
- [Entropy](#)
- [Exergonic](#)
- [Exothermic](#)
- [Free Energy](#)

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Energy Conservation

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

► [Energy](#) conservation refers to the mechanisms by which organisms can transform different ► [energy sources](#) (radiation, reduced organic or inorganic compounds) into cellular useful energy: proton motive force, ► [ATP](#), and reducing power. It is common for energy to be converted from one form to another; however, the law of conservation of energy, a fundamental law of physics, states that although energy can be changed in form, it can be neither created nor destroyed. The main energy conservation mechanisms used by biological systems are ► [respiration](#) (aerobic and anaerobic), fermentation, and ► [photosynthesis](#) (oxygenic and anoxygenic).

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Anoxygenic Photosynthesis](#)
- [ATP](#)
- [ATP Synthase](#)
- [ATPase](#)
- [Bioenergetics](#)
- [Electron Acceptor](#)
- [Electron Carrier](#)
- [Electron Transport](#)
- [Energy](#)
- [Energy Sources](#)
- [Fermentation](#)
- [NADH, NADPH](#)
- [Oxidation](#)
- [Oxygenic Photosynthesis](#)
- [Photosynthesis](#)
- [Proton Motive Force](#)
- [Proton Pump](#)
- [Respiration](#)

Energy Sources

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Keywords

Electron donors · Energy conservation · Fermentation · Photosynthesis · Radiation · Redox reactions · Reduced inorganic compounds · Reduced organic compounds · Respiration

Definition

Life implies work, in other words, it requires ► [energy](#). Metabolite transport across membranes, cellular ► [motility](#), or the biosynthesis of macromolecules are examples of cellular processes that require energy. Any living system relies on an external source of energy. The external sources of energy useful for living systems are only two: radiation and reduced chemical compounds. Living systems transform external energy sources into energy useful for cellular processes according to the thermodynamic law of energy conservation.

History

Peter Mitchell was awarded the 1978 Nobel Prize in Chemistry for his work in the description of the Chemiosmosis. Paul D. Boyer and John E. Walker were awarded part of the 1997 Nobel Prize in Chemistry for their clarification of the mechanism of ATP synthesis.

Overview

Energetic processes are basically related to oxidation-reduction reactions associated with the transformation of the energy sources. Energy sources are key elements for the classification of organisms. According to this, organisms can be classified as

chemotrophs if the external source of energy is chemical or phototrophs if it is radiation. Chemotrophs can be subdivided as chemoorganotrophs if the source of energy is a reduced organic compound (e.g., glucose, acetate), or chemolithotrophs if the source of energy is a reduced inorganic compound (e.g., ferrous iron, ammonia). The mechanisms by which organisms transform the external source of energy into cellular energy are three: ► [respiration](#), ► [fermentation](#), which is used by chemotrophs, and ► [photosynthesis](#), which is used by phototrophs. Cells can store the transformed energy as ► [proton motive force](#) (proton gradient) or in the form of energetic compounds like ► [ATP](#) or NADH. Some reactions or functions are driven by the proton motive force (transport of metabolites through the membrane, the rotation of the bacterial flagella); others require the use of ATP, such as the synthesis of macromolecules. An important achievement was the establishment of the chemiosmotic hypothesis coupling the ► [electron transport](#) in the respiratory chain with the generation of a proton motive force and the synthesis of ATP proposed by Peter Mitchell in 1961, and for which he was awarded the Nobel Prize.

Cross-References

- [ATP Synthase](#)
- [Chemotroph](#)
- [Electrochemical Potential](#)
- [Electron Donor](#)
- [Electron Transport](#)
- [Energy](#)
- [Fermentation](#)
- [Metabolism](#)
- [Motility](#)
- [Photosynthesis](#)
- [Proton Motive Force](#)
- [Radiation](#)
- [Respiration](#)

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Enthalpy

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

The enthalpy change is the heat produced or absorbed during a chemical or physical transformation taking place at constant pressure. The thermodynamic definition of enthalpy is $H = U + PV$, where H stands for enthalpy, U for internal energy, P for pressure, and V for volume.

Cross-References

- [Free Energy](#)

Entner-Doudoroff Pathway

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

[Glycolysis](#)

Definition

The Entner-Doudoroff (ED) pathway is the glycolytic pathway that allows to catabolize sugar acids, such as gluconate. Several enzymatic steps allow the conversion of six carbon sugar acids in two trioses that can be further metabolized through the universal lower part of the ► [Embden-Meyerhof-Parnas \(EMP\) pathway](#). This pathway is present in bacteria, but modifications have been described in all three domains of life. For example, the semi-phosphorylative ED pathway has been demonstrated in several anaerobic bacteria and in the halophilic archaea, whereas the non-phosphorylative ED pathway is found in some fungi and thermophilic and hyperthermophilic archaea. It has been suggested that the ED pathway is older than the EMP pathway.

History

The ED pathway was first discovered in 1952 in *Pseudomonas saccharophila* and in 1967 was shown to be also present in *Escherichia coli*.

Cross-References

- [Embden-Meyerhof-Parnas Pathway](#)
- [Metabolism](#)

Entropy

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

Entropy is a thermodynamic concept introduced in 1865 by Clausius. Entropy, represented by S , increases in any spontaneous processes (where ΔS is positive) taking place in an isolated system, i.e., a system which does not exchange matter or energy with its surroundings. If two gases are in

a constant-temperature box, initially separated by a partition and that partition is removed, the gases will mix without a change in enthalpy. Entropy, however, increases as the gases mix in this spontaneous process and acts as the driving force.

Cross-References

- [Enthalpy](#)
- [Free Energy](#)

Environment

José Luis Sanz

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Acidity · Atmosphere · Ionic strength · Life ·
Molecular ecology · Oceans · Pressure ·
Radiation · Redox conditions · Temperature

Synonyms

[Ecosystem](#); [Habitat](#)

Definition

Natural environment refers to the collection of objects both living and inanimate as well as the fluid, gaseous, or solid media that together make up a ► [habitat](#). The term includes soil, the subsurface, the atmosphere, the oceans and smaller bodies of water, and the interiors of plants and animals. The description of an environment requires definitions of its physical and chemical characteristics – temperature and pressure, acidity, redox conditions, radiation, etc.

Overview

The ensemble of biological communities and their surroundings constitutes an

► [“ecosystem,”](#) and the science that studies these ecosystems is known as Ecology. From a microbiological point of view, “environmental microbiology” studies the microbial processes that take place in the soil, water, food, depuration systems, etc., and “microbial ecology” describes qualitatively and quantitatively the ► [microorganisms](#) that occupy a specific ecological niche and the activities that take place within it. Culture-independent molecular biology techniques, such as in situ hybridization with fluorescent probes (FISH) or those based on PCR- denaturing gradient gel electrophoresis or the creation of genetic libraries, have given rise to “molecular microbial ecology” allowing great steps to be made in the understanding of microbial communities that live in specific habitats that would have been impossible with traditional microbiological research techniques.

Microorganisms occupy extraordinarily diverse habitats needing only liquid water to develop. They not only thrive in soils and water (fresh or marine) with “normal” physical/chemical conditions but have also adapted to ► [extreme environments](#): low and high temperatures and pHs, high salt concentrations, high pressure, etc. Furthermore, given the diminutive size of microorganisms, microniches or microenvironments can exist in conditions, which may differ greatly from those of the general environment, where they are contained. This is especially important in sediments and subsurfaces where the semisolid structure of the substrate allows microniches, whose properties may vary dramatically to coexist in proximity. Environmental conditions are very important in astrobiology because they can determine the habitability of a given planet or planetary body.

Cross-References

- [Biogeochemical Cycles](#)
- [Biosphere](#)
- [Biotope](#)
- [Ecosystem](#)
- [Extreme Environment](#)
- [pH](#)

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Environmental Chamber

- [Simulation Chambers](#)

Environmental Genome

- [Metagenome](#)

Environmental Sequence

- [Phylotype](#)

Environmental Transcriptome

- [Metatranscriptome](#)

EnVision

Dmitrij Titov¹, Richard Ghail² and Walter Kiefer³
¹European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

²Department of Earth Sciences, Royal Holloway, University of London, London, UK

³Lunar and Planetary Institute/USRA, Houston, TX, USA

Keywords

Venus · History · Activity · Climate

Acronyms

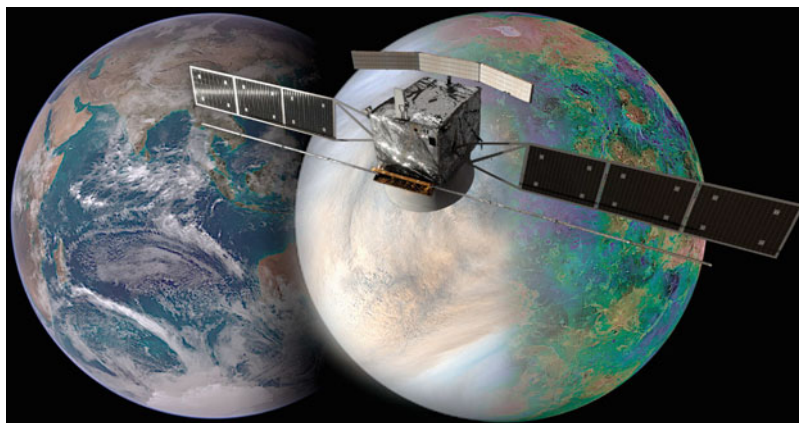
ESA; NASA; JAXA; SAR; VeGa; JPL; VenSAR; SRS; VenSpec-M; VenSpec-H; VenSpec-U; RSE

Definition

EnVision is the fifth medium-class mission in the ESA's Cosmic Vision program (Space science for Europe 2005) in collaboration with NASA. The Venus orbiter, scheduled for launch in the early 2030s, aims to provide a holistic view of the planet from its core to upper atmosphere and determine how and why Venus and Earth evolved so differently (Ghail et al. 2017; EnVision ESA Assessment Study Report, ESA/SCI 2021). EnVision investigations conducted over six cycles (a sidereal Venus day of 243 Earth days) will provide a leap in our understanding of the history, activity, and climate of our planetary neighbor. (Credit: NASA /ESA /JAXA/ISAS /DARTS /VR2Planets).

History

Venus has been a planet of fascination for centuries, and the object of many space “firsts.” The highly successful early series of Soviet Venera, VeGa, and US Pioneer Venus missions in 1970–1980s revealed an inhospitable world with crushing pressure and furnace-like temperatures on the surface and a corrosive atmosphere with rich exotic chemistry (Hunten et al. 1983). Surface imaging by synthetic aperture radars (SARs) on Venera-15, Venera-16, and NASA's Magellan in 1980–1990s unveiled an alien geology and evolution of the planet (Bougher et al. 1997). In 2000s, ESA's Venus Express and JAXA's Akatsuki missions focused mainly on the atmospheric and plasma investigations (Bezard et al. 2020). Nonetheless, some enigmatic results from Venus Express provided hints of current volcanic activity including a tenfold change in mesospheric sulfur dioxide abundance (Marcq et al. 2013), anomalously dark lavas around volcanoes (Smrekar et al. 2010), and transient hot spots on



EnVision, Fig. a

the surface (Shalygin et al. 2015). To pursue these intriguing discoveries, the EnVision concept was developed to bring Venus geology investigations up to date with twenty-first century SAR capabilities complemented by atmospheric, subsurface, and interior investigations heavily informed by Earth observation heritage.

Overview

Venus exploration offers unique opportunities to answer fundamental questions about the evolution of terrestrial planets and their habitability from within our own solar system. Many significant questions remain about the current state of Venus, suggesting major gaps in our understanding of how Venus's evolutionary pathway diverged from Earth's (Way and Del Genio 2020; Weller and Kiefer 2020). Comparing the interior, surface, and atmospheric evolution of Earth and Venus is essential to understanding what processes have shaped our planet, and is particularly relevant in an era where we expect thousands of terrestrial exoplanets to be discovered (Schiels 2018; Kane et al. 2019).

EnVision Science Questions and Objectives

Venus is Earth's closest sibling geologically and has likely remained active into the present era but does not exhibit Earth-like plate tectonics.

Lacking liquid water to sequester atmospheric CO₂ into carbonate rocks and with few other sinks for volcanically emitted volatiles, Venus is left with its present massive atmosphere. Perched at the inner edge of the habitable zone and having drastically different conditions, Venus provides a natural laboratory for understanding the evolution of terrestrial planets and conditions for life. EnVision will address the following objectives within three major science topics (EnVision ESA Assessment Study Report, ESA/SCI 2021).

1. **History:** *How have the surface and interior of Venus evolved?*
 - Determine the styles of volcanic processes which have occurred on Venus, studying the sources, emplacement styles, magma properties, and relative ages of different volcanic flows.
 - Determine the styles of tectonic deformation that have operated on Venus by studying their surface expression and gravity signatures, and determining their role in planetary heat loss.
 - Characterize surface modification processes such as impact crater modification, low emissivity/radar bright highlands, to improve our understanding of Venus geochronology.
 - Constrain Venus' internal structure, through measurements of gravity field and tidal response, to constrain the properties and

thicknesses of Venus' crust, mantle, and core.

2. **Activity:** *How geologically active is Venus?*

- Constrain the nature and occurrence of recent volcanism on Venus, how processes compare with Earth and other terrestrial planets, characterizing its morphological, thermal, and volatile signatures.
- Study landscape evolution on Venus, such as gravity-driven mass-movements erosion and deposition, and active chemical weathering on time scales of months to years.

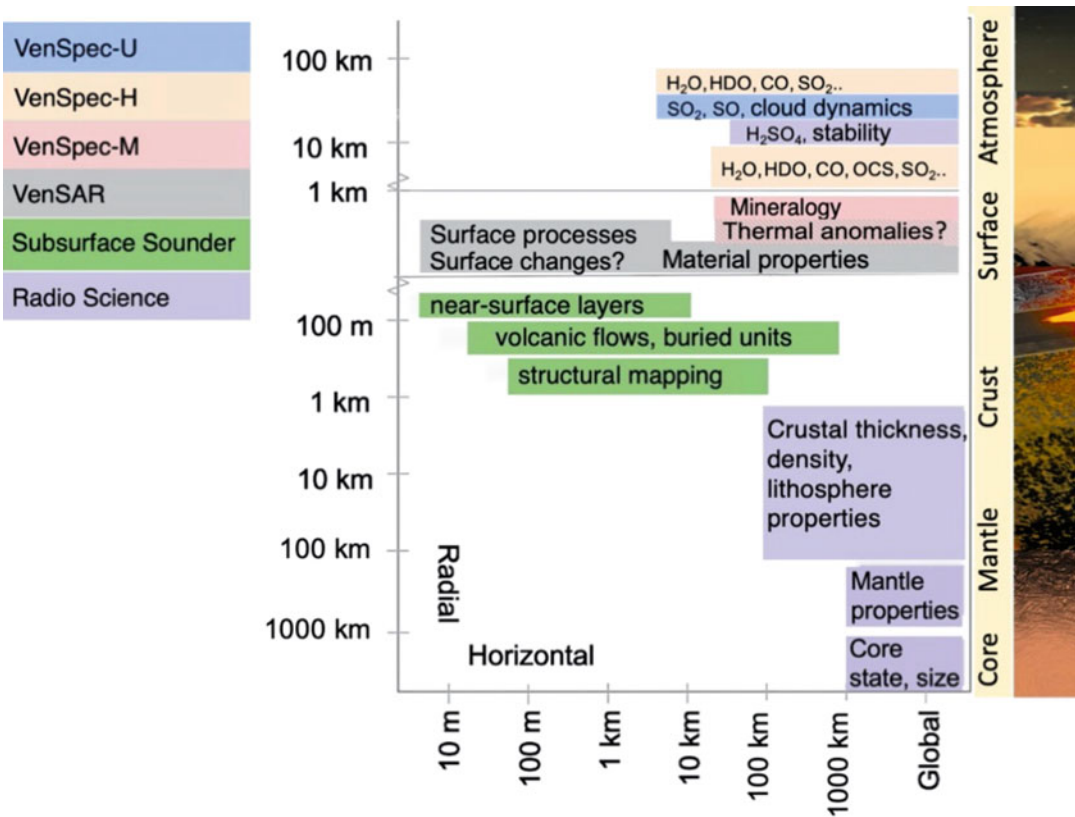
3. **Climate:** *How are Venus' atmosphere & climate shaped by geological processes?*

- Explore the role of geological activity, through volcanism and surface-atmosphere chemical reactions, in sustaining the volatile and cloud content of the atmosphere, and climate evolution.
- Study transport of geophysically meaningful volatile species through the atmosphere and clouds of Venus, through measurements below, within, and above the cloud layer.

Scientific strategy and payload. EnVision will synergistically exploit imagery, polarimetry, radiometry, and spectroscopy of the surface coupled with subsurface sounding and gravity mapping, and complemented by tracing key volatile species by spectroscopy and radio-occultation techniques (EnVision ESA Assessment Study Report, ESA/SCI 2021).

EnVision will investigate Venus from its interior to the atmosphere by a suite of five science instruments. A dual polarization S-band **Synthetic Aperture Radar (VenSAR)** designed and built by NASA's JPL will work at 9.5 cm to image pre-selected regions of interest at 30 and 10 meters/pixel resolution, which is key to understanding geological processes from the local to global scale. Topographic information at 300 m spatial and 20 m vertical resolution derived from stereo imaging will be complemented by a global network of altimetry measurements with a vertical resolution of 2.5 m enabling the quantitative analysis of geological processes. Surface properties such as roughness will be derived from active

imaging and passive radiometry in both HH and HV polarizations, which also permits the detection of surface temperature anomalies. Repeated observations and comparisons with Magellan imagery allow for the detection of changes over periods of months, years, and decades. A **Subsurface Sounder (SRS)** procured by University of Trento, Italy, will work at frequency of 9 MHz and will for the first time characterize the vertical structure and stratigraphy of geological units down to ~1 km depth with ~20 m vertical resolution. It will provide information on the surface roughness, composition, and dielectric permittivity at wavelengths longer than those of VenSAR. SRS will also deliver low-resolution surface altimetry. **VenSpec-M spectrometer** (IPF-DLR, Germany) will perform almost global mapping of the surface emissivity in six wavelength bands using six narrow bands in the range from 0.86 to 1.18 μm to constrain surface mineralogy, informing evolutionary scenarios, and undertake a comprehensive search for surface changes and volcanic activity. **VenSpec-H** (BIRA-IASB, Belgium) will use extremely high-resolution infrared spectroscopy to quantify volcanogenic species SO_2 , H_2O , and HDO below and above the clouds, characterizing gas exchanges from the surface and within the atmosphere and searching for sources such as volcanic plumes. It will measure variations of mesospheric species and link them to tropospheric composition and volcanism. **VenSpec-U ultraviolet spectrometer** (LATMOS, France) will monitor minor sulfur-bearing species (mainly SO and SO_2) and investigate the complex and highly variable upper atmosphere and its relationship with the troposphere. A **Radio Science Experiment (RSE)** (LPG, France) will use the spacecraft communications system to map the gravity field with a spatial resolution of ~250 km to better constrain the crustal and lithospheric structure variations and calculate the tidal Love number k_2 with an accuracy of 0.01, sufficient to constrain the distribution of internal mass as well as size and state of the core. The experiment will also probe the structure and composition of the middle atmosphere and the cloud layer and structure of the ionosphere in radio occultations. The synergistic and holistic



EnVision, Fig. 1 EnVision's multi-messenger observation strategy

way in which the payload instruments collaborate to investigate processes at different altitudes, depths, and spatial scales is graphically illustrated in Fig. 1.

Spacecraft and mission design. EnVision will be a three-axis stabilized orbiter approximately 2 m*2 m*3 m in size in stowed configuration with a launch dry mass of about 1350 kg and power consumption of 2.8 kW. EnVision will operate at Venus in a low quasi-polar orbit at 220–540 km altitude and orbital period of ~92 min. EnVision will downlink 210 Tbits of science data using a Ka-/X-band communication system with a 2.5 m diameter fixed high-gain antenna. The spacecraft will be launched by Ariane 6.2 from ESA's spaceport Kourou in 2032 arriving at Venus after a 15-month cruise. Science orbit will be achieved by about 500 days of aerobraking in the Venus upper atmosphere.

The nominal science mission will last for 6 Venus sidereal days (4 Earth years).

EnVision is the ESA-led mission with significant NASA contribution through the provision of VenSAR instrument building on JPL's years of experience with planetary radar. EnVision therefore benefits from decades of scientific and technical heritage from both ESA Venus Express and NASA Magellan missions, as well as from many other missions including Mars Express, Cassini, and Sentinel-1. EnVision will adopt an open data policy, with data publicly released immediately after validation and verification.

Cross-References

- [Atmosphere, Structure](#)
- [Atmospheric Processes, Escape](#)

- Basalt
- Carbon Dioxide
- Chasma, Chasmata
- Climates, Terrestrial Planets
- Clouds
- CNES, France
- Crust
- DLR, Germany
- Emissivity
- ESTEC
- European Space Agency
- Greenhouse Effect
- Habitable Zone
- Imaging
- Interior Structure, Planetary
- Mafic and Felsic
- Mesosphere
- Mineral
- Nadir
- Occultation
- Opacity
- Optical Depth
- Orbit
- Orbital Period
- Plate Tectonics
- Spectrometer
- Stagnant Lid Convection
- Sulfur Chemistry
- Superrotation
- Tessera, Tesserae
- UV Radiation
- Venus
- Venus Clouds
- Venus Express
- Wavelength
- Weathering

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Enzyme

Athel Cornish-Bowden and María Luz Cárdenas
 Unité de Bioénergétique et Ingénierie des
 Protéines, Centre National de la Recherche
 Scientifique, Aix-Marseille Université, Marseille,
 France

Keywords

Active site · Allosteric site · Catalysis ·
 Isoenzyme · Kinetics · Metabolism ·
 Ribozyme

Synonyms

Ferment (obsolete)

Definition

An enzyme is a biological ► **catalyst** necessary for metabolic reactions to occur at an adequate rate under mild conditions of pH and temperature, typically consisting largely or entirely of protein, though catalytic RNA molecules are also known.

History

Enzyme catalysis was discovered by Lazzaro Spallanzani in the eighteenth century as an observation that the digestion of food in the animal stomach was chemical rather than a purely mechanical process of grinding. Subsequent advances in the nineteenth century came primarily from studies of digestion and of the action of yeast in fermentation. Until the early twentieth century, the usual word for enzyme was *ferment*, now entirely superseded by *enzyme*, a name that also referred originally to yeast, as it was coined by Wilhelm Kühne from Greek words meaning “in yeast.” When the last printed version of *Enzyme Nomenclature* was published in 1992, about 3200 distinct enzyme activities were recognized, but the current number is about 6500, and the number of distinct proteins known to be enzymes is very much larger.

Overview

All metabolic reactions are catalyzed by specific molecules called *enzymes*. Even reactions that proceed spontaneously and rapidly, such as the hydration of CO₂, are normally catalyzed in physiological systems. Before the discovery of catalytic RNA molecules (sometimes called ribozymes), all enzymes were believed to consist mainly or entirely of protein molecules, typically with more than 100 ► **amino acid** residues in each

subunit. It is now widely accepted that catalytic RNA satisfies the definition of an enzyme, and the ► **ribosome** is a fundamental example of catalytic RNA (Steitz and Moore 2003). Biological catalysts include metabolites that participate in cycles of reactions, such as citrate, regenerated in each turn of the tricarboxylate (Krebs) cycle, but also many other metabolites. These are certainly catalysts, but they are not conventionally regarded as enzymes; however, from the point of view of astrobiology, they probably should be regarded as enzymes because at the origin of life, there must have been catalysts produced by the first organisms that were neither protein nor RNA, but much simpler molecules.

Although the effectiveness of enzymes as efficient catalysts is normally emphasized, their fundamental property is *specificity* because without specificity, there could be no organization or regulation of metabolic processes. Most enzymes catalyze just one or a small number of reactions and are largely or completely inactive in others that appear quite similar. Bacterial glucokinase, for example, catalyzes the phosphorylation of glucose by ATP, but does not catalyze the phosphorylation of a hexose as similar as mannose. Even relatively unspecific enzymes, mostly involved in catabolic processes such as digestion, are highly specific by the standards of inorganic catalysts. Another property exhibited by all enzymes is *saturation*: although the rate of reaction may be proportional to the concentration of each reactant at low concentrations, it never increases indefinitely with increases in concentration, the rate v typically depending on the substrate concentration a according to the *Michaelis-Menten equation*, $v = Va/(K_m + a)$, in which V , the *limiting rate*, and K_m , the *Michaelis constant*, are constants. In vivo, however, enzymes typically operate in or close to the proportional zone, in other words at substrate concentrations similar to or smaller than K_m . Certain enzymes, known as *regulatory enzymes*, are inhibited or activated by molecules structurally different from their substrates or products, which are called *effectors*, or display special kinetic laws that enable them to respond with high sensitivity to changes in conditions. The part of an enzyme

where catalysis occurs is called the *active site*, and if a different site exists for binding effectors, it is called an *allosteric site*.

Enzymes are grouped in *Enzyme Nomenclature* into six classes, of which three (oxidoreductases, transferases, and hydrolases) catalyze group-transfer reactions and three (lyases, isomerases, and ligases) catalyze other types of reaction. This is a classification of reactions catalyzed, not a classification of proteins catalyzing them. The number of known proteins acting as enzymes is very much larger than the number of known activities (because the proteins catalyzing any given reaction in different organisms are nearly always different), and the amount of variation in structure among the known cases suggests that the total number is huge. In most of the known cases, the proteins are similar enough to be clearly homologous, but some exceptions, exemplified by superoxide dismutase, are known. Even within a single species, it is common to find multiple proteins, known as *isoenzymes*, catalyzing the same reaction, often with distinct regulatory properties.

Cross-References

- [Amino Acid](#)
- [Metabolism](#)
- [Prebiotic Chemistry](#)
- [Ribosome](#)
- [Ribozyme](#)

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Enzymology, History of

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Definition

In 1833, the French biologists A. Payen (1795–1871) and J. F. Persoz (1805–1868) isolated a malt-soluble ferment able to digest the amide and called it diastase. In 1878, the German physiologist Wilhelm Kühne (1837–1900) named the contents of this digestive juice as enzyme. During the second part of the nineteenth century, there was an active debate between Louis Pasteur (1822–1895) and Justus Freiherr von Liebig (1803–1873) about the cause of fermentation. Pasteur argued that fermentation is a process of microscopic living entities, like yeast, and Liebig argued that fermentation is a spontaneous decomposition of matter.

In 1897, the German chemistry Edüard Buchner (1860–1917) made an *in vitro* fermentation of sugars in an acellular fraction of yeast. Some authors said that this result probably constituted the beginning of biochemistry science. A few years later, in 1903, the French-Russian physical chemist Victor Henry (1872–1940) stated that all enzymes are proteins.

The 1920s have witnessed important developments of enzymology with the purification and the crystallization of numerous enzymes (urease, pepsin, trypsin, etc.) and the study of the enzymatic kinetic.

Cross-References

- [Catalyst](#)
- [Enzyme](#)

Ephemeris

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

- [Endolithic](#)
- [Extreme Environment](#)
- [Extreme Ultraviolet Light](#)
- [Hypolithic](#)
- [Lichens](#)
- [Microbial Mats](#)

Definition

An ephemeris is the set of tabulated coordinates of an astronomical object in the sky at successive dates. Plural: ephemerides.

Cross-References

- [Coordinate Systems](#)
- [Declination](#)
- [Right Ascension](#)

Epilithic

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Definition

Epiliths are organisms or microbial communities that live on the surface of rocks. Examples are ► [lichens](#), mosses, biofilms, and desert varnish. Epiliths are generally well adapted to resist environmental extreme conditions, such as large variations in temperature, extreme dryness, and intense solar irradiation. They are sometimes the only colonizers in desert and high-mountain regions.

Cross-References

- [Biofilm](#)
- [Desiccation](#)

Episome

- [Plasmid](#)

EPOXI Mission

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

EPOXI was an extension of the NASA Deep Impact mission (► [Deep Impact](#)) with two goals: to observe extrasolar planets using the transit method and to study comet 103P/Hartley 2 using the same instruments used for the Deep Impact observations of comet 9P/Tempel 1. Several transiting planets were observed, and Earth was also observed, in an effort to see what characteristics of Earth-like planets might be most easily measured remotely. The closest approach to comet 103P/Hartley 2 occurred on November 4, 2010. The name EPOXI is a hybrid of EPOCH (Extrasolar Planet Observation and CHaracterization Investigation) and DIXI (Deep Impact eXtended Investigation). The EPOXI Mission web page maintained by NASA includes status reports on the various activities undertaken (<http://epoxi.umd.edu/1mission/status.shtml>).

The team working with EPOXI lost communication to the spacecraft sometime between August 11 and 14, 2013. On Monday, September 16, 2013, after considerable effort transmitting low-level hardware commands, EPOXI team determined that there were no other plausible scenarios under which they could recover command

and control of the spacecraft. They recommended that NASA declares the mission lost. That declaration was announced by NASA on Thursday, September 19, 2013.

Cross-References

- [Deep Impact](#)
- [Transiting Planets](#)

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EPS

- [Exopolymers](#)

Equation of State

Tristan Guillot
Observatoire de la Côte d'Azur, Université de
Nice-Sophia Antipolis, Nice, France

Keywords

Density · Pressure · Temperature ·
Thermodynamics

Definition

An equation of state is a relation (or by extension a series of relations) between thermodynamic state variables characterizing matter in a given state, for instance, in a celestial body. It describes how a macroscopic entity is affected by external changes (e.g., changes in temperature, pressure, volume, etc.). When modeling stars and planets, equations of state are used in particular to calculate density as a function of pressure and temperature, the phases (e.g., gaseous, liquid, solid, etc.) of the materials considered, and how temperature

changes with pressure during macroscopic motions.

Overview

The first and most widely known equation of state is the so-called ideal gas law. It links the pressure P , volume V , absolute temperature T , and number of particles N in a gas composed of nonrelativistic, noninteracting mass particles through the relation $PV = NkT$, where $k = 1.38065034 \times 10^{23} \text{ J K}^{-1}$ is Boltzmann's constant. Equations of state of arbitrary complexity can be calculated for elements that undergo a phase transition (i.e., become gaseous, liquid, or solid), for mixtures, for photons, for charged particles, in the presence of magnetic fields, etc. Among other things, equations of state are crucial to model atmospheric structures: when a parcel of air (or fluid) is transformed (e.g., by its motion) without losing heat (i.e., *adiabatically*), it conserves its ► [entropy](#). Entropy is a thermodynamic state variable and, as such, it also obeys an equation of state relation that links it to the other thermodynamic state variables of the problem (e.g., temperature, pressure). Using its conservation, one can therefore calculate the rate of change of temperature with pressure in such a transformation. In atmospheres that are thick enough for convection to occur nearly adiabatically, the temperature profile is mostly set by the temperature of the photosphere (the level at which most of the photons can escape freely to space) and by the equation of state of the atmospheric mixture.

Equations of state are also at the heart of our knowledge of planetary and stellar interiors. They describe how matter is affected by the extreme conditions that occur there. With a pressure of about 360 GPa (about 3.6 million times the atmospheric pressure at sea level on Earth) and a temperature of about 7000 K, the iron which forms most of the core at the center of the Earth is believed to be in solid form. However, the equation of state of iron tells us that at conditions relevant slightly higher up in the Earth, it should be liquid, therefore forming the so-called liquid

outer core. In giant planets such as Jupiter and Saturn, the equation of state of hydrogen indicates that this element ionizes from a molecular state, H_2 , to a conducting state called metallic hydrogen at pressures of about 150 GPa and temperatures of 10,000 K or less.

Cross-References

- [Atmosphere, Structure](#)
- [Interior Structure, Planetary](#)
- [Low Mass Star](#)
- [Stellar Evolution](#)

Equinox

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Autumnal point](#); [Vernal point](#)

Definition

The equinox is one or the other of the two points on the celestial sphere where the equatorial plane intersects the ► [ecliptic](#) plane. When the Sun is at one of these points, daytime and nighttime have the same duration everywhere on Earth. The term equinox is also used for the date and time corresponding to those two positions of the Sun, which mark the beginning of spring (vernal equinox) and the beginning of fall (autumnal equinox).

Cross-References

- [Coordinate Systems](#)
- [Ecliptic](#)
- [Right Ascension](#)

ERA

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Definition

The Exobiology Radiation Assembly (ERA) is a facility to expose various chemical and biological objects to the conditions of outer space, such as space vacuum, solar extraterrestrial radiation, and cosmic rays.

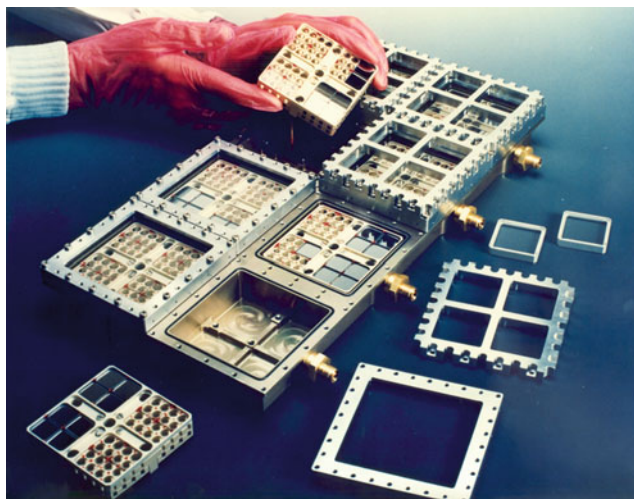
Overview

ERA was mounted on the sun-pointing cold plate of ESA's European Retrievable Carrier (► [EURECA](#)), which was launched to Low Earth Orbit (LEO) on July 31, 1992, and remained there until August 7, 1993 (Innocenti and Mesland 1995). ERA consisted of an exposure tray (Fig. 1) and a lid accommodating the following experiments:

- Exobiological unit that studied the action of solar UV radiation and/or space vacuum on the survival and genetic changes of invertebrates, ► [microorganisms](#), viruses, and DNA and the role of chemical and physical protection mechanisms (Horneck et al. 1995).
- Space biochemistry that elucidated dehydration and photochemical reactions in cellular, subcellular, and molecular systems under outer space conditions (Dose et al. 1995).
- Effects of solar UV on yeast cells
- Photoprocessing of grain mantle analogues that studied photolytical processes during chemical evolution of interstellar grains (Greenberg 2000)

Beneath the tray was another compartment accommodating the following experiment:

ERA, Fig. 1 Tray of the exposure facility ERA with sample carriers and optical filters during assembly. (Credit ESA, from Horneck et al. 2010)



- Free Flyer ► [Biostack](#) that studied the biological responses of different systems to the structured components of cosmic radiation, i.e., ► [HZE particles](#) (cosmic rays consisting of energetic nuclei with atomic number 3 or greater) and nuclear disintegration events (Reitz et al. 1995; Horneck 2007; Horneck et al. 2010).

Cross-References

- [Biostack](#)
- [EURECA](#)
- [Expose](#)
- [Exposure Facilities](#)
- [HZE Particle](#)
- [Interstellar Chemical Processes](#)
- [Microorganism](#)
- [Radiation Biology](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [Space Vacuum Effects](#)
- [Yeast](#)

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ERE

- [Extended Red Emission](#)

Eros Asteroid

Gerhard Hahn
Asteroids and Comets, DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Asteroid \(433\) Eros](#)

Definition

(433) Eros is the second largest Amor asteroid, of irregular shape measuring $34 \times 11 \times 11$ km and of spectral type S. Its rotation period is 5.27 h, exhibiting large brightness variations caused by the elongated shape. In 2000, NASA's NEAR-Shoemaker mission visited the asteroid, orbiting it for about 1 year, before descending to the surface.

History

(433) Eros was discovered on August 13, 1898, by Gustav Witt in Berlin and almost simultaneously by Auguste Charlois in Nice (see Scholl and Schmadel (2002) for details). It was the first near-Earth asteroid found.

Cross-References

- [NASA](#)
- [Near-Earth Objects](#)

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Error Rate

Ester Lázaro
Molecular Evolution Laboratory, Centro de Astrobiología (CSIC-INTA), Madrid, Spain

Definition

In biology, the error rate is the average number of ► [mutations](#) per nucleotide and round of

copy produced during genomic ► [replication](#). For example, an error rate of 10^{-10} in a certain species means that, in average, one in every 10^{10} nucleotides will be misincorporated each time its genome is replicated. The error rate varies by orders of magnitude among species (from 10^{-3} – 10^{-5} in RNA viruses to 10^{-9} – 10^{-12} in cellular organisms). It also can present intraspecific variations, depending on the nature and frequency of change of the selective pressures. The optimal value of the error rate results from the necessity to optimize different conflicting features, such as the generation of genetic diversity, the preservation of genetic information, the minimization of the number of deleterious mutations, and the metabolic costs of systems that increase replication fidelity.

Cross-References

- [Mutation](#)
- [Natural Selection](#)
- [Replication \(Genetics\)](#)

ESA

- [Venus Express](#)

ESA – European Space Agency

- [ESA Solar Orbiter Mission](#)

ESA Solar Orbiter Mission

Olivier Witasse
European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Keywords

Sun · Solar wind · Heliophysics · ESA mission

Synonyms

ESA – European Space Agency; NASA

Definition

Solar Orbiter is an ESA-led mission with strong NASA participation which was launched on 10 February 2020 from Cape Canaveral. It carries the most comprehensive payload flown in the inner heliosphere to date, with six remote sensing instruments that image the Sun and its surroundings as well as four in situ instruments for monitoring the solar wind. The mission will address key questions of solar and heliospheric physics pertaining to how the Sun creates and controls the heliosphere, and why solar activity changes with time.

History

The Solar Orbiter mission has its origins in a proposal called “Messenger” that was submitted in 1982 in response to an ESA call for mission ideas. At the meeting “Crossroads for European Solar and Heliospheric Physics” held on Tenerife in March 1998, the heliophysics community recommended to launch an ESA Solar Orbiter as ESA’s next flexible mission, with possible international participation, for launch around 2007. Solar Orbiter was eventually selected and adopted as the first M-class mission of ESA’s Cosmic Vision program in October 2011. The spacecraft was launched on 10 February 2020 on board an Atlas V launcher from Cape Canaveral, completed the in-orbit commissioning in June 2020, and its cruise phase in December 2021, when it started nominal science operations.

Overview

Solar Orbiter is an ESA mission with strong NASA participation dedicated to solar and heliospheric physics.

Solar Orbiter’s elliptic orbit put the spacecraft between 1.2 and 0.28 AU from the Sun. The operational orbit is reached in 2022 by using gravity assist maneuvers at Earth and Venus. Subsequent Venus flybys will increase its inclination with respect to the solar equator, reaching up to 24° at the end of the nominal mission (approximately 7 years after launch) and up to 33.4° in the extended mission phase.

Solar Orbiter aims to make significant breakthroughs in our understanding both of how the inner heliosphere works, and of the effects of solar activity on it. The spacecraft will take a unique combination of measurements: in situ measurements will be used alongside remote sensing close to the Sun to relate these measurements back to their source regions and structures on the Sun’s surface. It will operate both in and out of the ecliptic plane.

Solar Orbiter will study solar energetic particles that may be hazardous to human explorers as well as spacecrafts that operate in the highly variable environment outside of Earth’s magnetosphere. Beyond our own solar system, studying the Sun and the solar wind is also relevant for our understanding of other stellar systems.

The payload includes a combination of four in situ and six remote sensing instruments, with a total mass of 209 kg:

- 1) EPD (energetic particle detector) is an instrument suite comprising different sensors that measures the properties of suprathermal ions and energetic particles in the energy range of a few keV/n to relativistic electrons and high-energy ions.
- 2) MAG (magnetometer) measures the in situ magnetic field.
- 3) The RPW (radio and plasma waves) instrument measures magnetic and electric fields, plasma wave spectra and polarization properties, as well as the spacecraft floating potential and radio emissions of solar origin generated in the interplanetary medium.

- 4) SWA (solar wind analyzer) instrument suite measures the ion and electron bulk properties (including density, velocity, and temperature) of the solar wind and its ion composition for key elements.
- 5) EUI (extreme ultraviolet imager) provides images of the solar atmospheric layers above the photosphere, providing an indispensable link between the solar surface and outer corona that ultimately shapes the characteristics of the interplanetary medium. EUI will also provide the first-ever UV images of the Sun from an out-of-ecliptic viewpoint.
- 6) Metis is a coronagraph that simultaneously images the visible and ultraviolet emission of the solar corona and diagnose, with unprecedented temporal coverage and spatial resolution, the structure and dynamics of the full corona.
- 7) PHI (polarimetric and helioseismic imager) provides high-resolution and full-disc measurements of the photospheric vector magnetic field and line-of-sight velocity as well as the continuum intensity in the visible wavelength range. The line-of-sight velocity maps will have the accuracy and stability to allow detailed helioseismic investigations of the solar interior, in particular of the solar convection zone.
- 8) SoloHI (heliospheric imager) images the inner heliosphere over a wide field of view by observing visible photospheric light scattered by electrons in the solar wind emitted by the Sun and interplanetary dust in orbit about the Sun. It will provide unique measurements to pinpoint coronal mass ejections.
- 9) SPICE (spectral imaging of the coronal environment) performs extreme ultraviolet imaging spectroscopy to remotely characterize plasma properties of the Sun's on-disc corona. This will enable matching in situ composition signatures of solar wind streams to their source regions on the Sun's surface.
- 10) STIX (X-ray spectrometer/telescope) provides imaging spectroscopy of solar

thermal and nonthermal X-ray emission. STIX will provide quantitative information on the timing, location, intensity, and spectra of accelerated electrons as well as of high temperature thermal plasmas, mostly associated with flares and/or microflares.

Cross-References

- [European Space Agency](#)
- [Parker Solar Probe](#)
- [Solar Particle Events](#)
- [Sun \(and Young Sun\)](#)

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Escape Velocity

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Escape velocity is the critical velocity above which a body is no longer gravitationally bound to a larger mass. This is important for numerous processes: atmospheric molecules escaping from a planet, a planet escaping from its host star, and stars escaping from either mutual orbits or stellar clusters. For a simple

Keplerian potential (where the gravitational force is proportional to the central mass and inversely proportional to the distance squared), the escape speed is given by

$$v_{\text{esc}} = \sqrt{2G \frac{M}{R}}$$

where G is the gravitational constant, M is the central mass, and R is the distance from the central mass.

Cross-References

► [Ejection, Hyperbolic](#)

ESPRESSO

Francesco A. Pepe
Department of Astronomy, University of Geneva,
Versoix, Switzerland

Acronyms

Echelle Spectrograph for Rocky Exoplanets and
Stable Spectroscopy Observations

Definition

ESPRESSO is a high-resolution spectrograph on the Very-Large Telescope (VLT) at ESO's Paranal Observatory, Chile. It operates in the optical wavelength range from 380 to 780 nm and delivers spectral resolution up to $R = \lambda / \Delta\lambda = 200\,000$. ESPRESSO is the first instrument of the VLT able to combine incoherently the light from the four 8-m telescopes and turn the VLT into a 16-m equivalent telescope. The speciality of ESPRESSO is, on the example of its predecessor HARPS, the extreme precision that is required for the search and characterization of low-mass exoplanets, the study of fundamental physical constants and cosmology.

Cross-References

► [HARPS](#)
► [VLT](#)

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ESTEC

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[European Space Research and Technology Centre](#)

Definition

ESTEC is the main technology center for ESA, the European Space Agency. It is located in Noordwijk in the Netherlands. ESTEC is responsible for developing and managing ESA missions, including those involving science, exploration, telecommunications, satellite navigation, and Earth observation. ESTEC operates an environmental test center for spacecraft and engineering laboratories for components, materials, and systems engineering. It works closely with other institutions and industry in Europe and with space agencies from around the world.

Cross-References

► [ESA](#)

Ester

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

In chemistry, esters are compounds derived by condensation of an oxoacid (one containing an oxo group, $X = O$, e.g., phosphoric acid ($O=P(OH)_3$) or a carboxylic acid ($RCOOH$)) with an alcohol. Many biological lipids are fatty acid esters of glycerol derivatives. Phosphoesters form the backbone of DNA molecules. Polyesters such as poly-hydroxy butyrate are important energy storage molecules in some microbes. Cyclic esters formed from carboxylic acid and alcohol functional groups are called lactones.

Esters contain a carbonyl functionality, but unlike amides, esters are structurally flexible because there is a low energetic barrier to rotation about the $X(=O)-O-C$ bond. Esters thus tend to be more volatile (i.e., have a lower boiling point, particularly with low molecular weight esters) than the corresponding amides. Their carbonyl group can serve as a hydrogen bond acceptor, and this ability to engage in hydrogen bonding renders them somewhat water soluble. The inability of the linking ester oxygen atom to engage in hydrogen bonding with another ester group, unlike the protonated nitrogen atom in an amide or a protonated carboxylic acid, also results in their greater structural flexibility and volatility, but renders them unable to form the hydrogen-bonded structural motifs such as α -helices and β -sheets that polyamides can.

Esters can react at one of two locations of their molecular structure. The carbonyl group is weakly electrophilic and is attacked by strong nucleophiles (amines, alkoxides, etc.). The C–H bonds of the carbon atoms adjacent to the carbonyl group are weakly acidic but can be deprotonated by

strong bases and can thus serve as nucleophiles. Esters undergo both acid- and base-catalyzed hydrolysis. Under basic conditions, hydroxide acts as a nucleophile, while an alkoxide is the leaving group. This reaction is known as saponification. Esters may also be cleaved by amines such as ammonia and primary or secondary amines to give amides, in a process known as aminolysis or amidation.

Eta-Earth

Nader Haghighipour
Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Definition

The term eta-Earth (also written as η_E) is defined as the mean number per star of rocky planets with between 1 and 1.5–2 Earth-radii that reside in the optimistic habitable zone (HZ) of their host star. Eta-Earth enters one formulation of the ► [Drake equation](#), which endeavors to estimate the occurrence of intelligent life in the Galaxy; at the present time, it is usually calculated separately for each stellar spectral type. Thus, eta-Earth represents the occurrence rate of rocky planets in the optimistic HZ of different stars.

The references present some values for eta Earth based on different statistical analyses of the data from the Kepler space telescope.

Cross References

- [Exoplanets, Discovery](#)
- [Habitable Zone](#)

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Ethanal

► [Acetaldehyde](#)

Ethanamide

► [Acetamide](#)

Ethane

Kensei Kobayashi
Department of Chemistry, Yokohama National University, Yokohama, Japan

Chemical Formula

C_2H_6

Definition

Ethane, C_2H_6 , is a saturated hydrocarbon having two carbon atoms, whose molecular weight is 30.07. It is a colorless, odorless gas at ambient temperature and pressure. It is a component of natural gas and can be obtained during petroleum refining. Its melting point is $-182.9\text{ }^{\circ}\text{C}$, and its boiling point is $-88.5\text{ }^{\circ}\text{C}$. When a hydrogen atom is substituted with the other atom or group, the ethane moiety (i.e., a part or functional group of a molecule) is called an ethyl group. Acetylene (ethyne, C_2H_2) and ethylene (ethene, C_2H_4) are two other aliphatic hydrocarbons with two carbon atoms. Ethane has been detected in the atmosphere of the outer planets (Jupiter, Saturn, Uranus, and Neptune) as well as in a number of comets (Dello Russo et al. 2001), but it has not been identified as

an interstellar molecule until now (September 2019). Ethane is also found in the atmosphere of Titan. Cassini spacecraft found hydrocarbon lakes on the surface of Titan, and ethane was detected in it with its Visible and Infrared Mapping Spectrometer (VIMS) in 2008 (Brown et al. 2008). The surface temperature of Titan is about $-179\text{ }^{\circ}\text{C}$, so ethane can exist as liquid.

Cross-References

► [Acetylene \(\$C_2H_2\$ \)](#)
► [Comet](#)
► [Methane](#)
► [Titan](#)

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1,2-Ethanediol

► [Ethylene Glycol \(\$HOCH_2CH_2OH\$ \)](#)

Ethanimine

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

CH_3CHNH

Definition

Ethanimine is an 8-atom, nitrogen-containing organic molecule that is the next heavier

homologue of methanimine (CH_2NH). In laboratory experiments involving the irradiation of interstellar ice analogs, it has been suggested that ethanimine is a precursor to the formation of the amino acid alanine.

History

Methanimine was detected in the interstellar medium in 1973 (Godfrey et al. 1973), and ethanimine has more recently been found in the Milky Way's galactic center molecular cloud Sagittarius B2 North (Loomis et al. 2013).

Cross-References

► [Molecules in Space](#)

References and Further Reading

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Ethanoic Acid

► [Acetic Acid](#)

Ethanol, Fig. 1 Rotational isomers of ethanol

Ethanol

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Synonyms

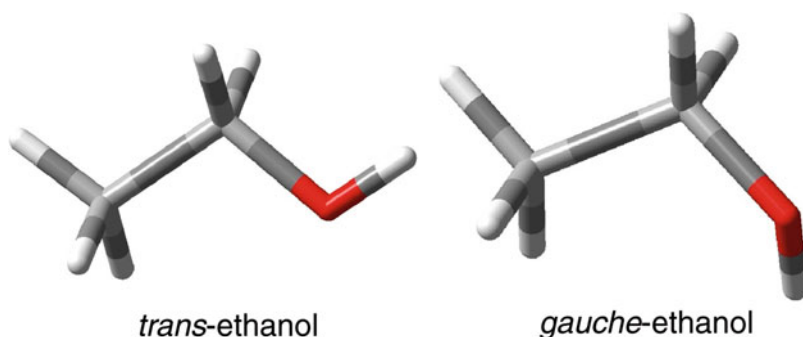
[Ethyl alcohol](#)

Definition

Ethanol is an organic compound belonging to the group of ► [alcohols](#) whose structural formula is $\text{C}_2\text{H}_5\text{OH}$. It is a constituent of alcoholic beverages. Ethanol is a colorless, volatile, and flammable liquid. Its melting and boiling points are -114.3°C and 78.4°C , respectively. It is made from sugar by fermentation, and it is metabolized in vivo to carbon dioxide via acetaldehyde and acetic acid. Ethanol has rotational isomers, and they are referred to as trans-ethanol and gauche-ethanol (Fig. 1). In 1975, trans-ethanol was identified as an interstellar molecule, while gauche-ethanol was detected in 1996. Ethanol condenses with carboxylic acids to form esters, and it condenses with itself to form diethyl ether.

Cross-References

- [Alcohol](#)
- [Methanol](#)
- [Molecular Cloud](#)



Ether

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Ethers are a class of organic compounds containing an ether group (R-O-R) – an oxygen atom connecting two alkyl or aryl groups. A typical example is diethyl ether, commonly referred to simply as “ether” (CH₃-CH₂-O-CH₂-CH₃). Polyethers are compounds with more than one ether group. Low- to medium-range molecular weight polyethers with a hydroxyl end group are termed glycols. The crown ethers are examples of low-molecular weight cyclic polyethers. Other common cyclic ethers include the furans (five-membered rings) and epoxides (three-membered rings).

Ethers cannot form intermolecular hydrogen bonds between each other, resulting in relatively low boiling points compared to their parent alcohols. The difference in the boiling points of ethers and their parent alcohols becomes less significant as the carbon chains become longer, as van der Waals interactions between the extended carbon chains come to dominate intermolecular interaction.

Ethers in general are of low chemical reactivity, and indeed in many extremophilic organisms, the cell membranes contain glycerol ethers rather than glycerol esters.

Ethics of Astrobiology

► [Astrobioethics](#)

Ethyl Alcohol

► [Ethanol](#)

Ethyl Cyanide (CH₃CH₂CN)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

CH₃CH₂CN; [Cyanoethane](#); [Propanenitrile](#) (IUPAC name); [Propionitrile](#)

Definition

Under standard laboratory conditions, ethyl cyanide is a clear liquid with a sweet odor. It is commonly found in the gas phase in interstellar molecular clouds, specifically in “hot cores” (the regions where massive stars are forming), and has more recently been located in regions of low-mass star formation (hot corinos). Ethyl cyanide has a rich rotational spectrum that is observed by radio astronomers in the millimeter wavelength region. In addition to transitions in the ground vibrational state, rotational lines in low-lying vibrational states have been detected. All three 13-carbon isotopic species have been detected in hot cores.

History

The first astronomical detection was made by Johnson et al. (1977); subsequently it has been found in most spectral surveys of hot cores (e.g., Nummelin et al. 2000; Daly et al. 2013).

Cross-References

► [Hot Core](#)
► [Hot Corino](#)

- [Isotope](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

References and Further Reading

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Ethyl Formate

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[C₂H₅OCHO](#); [Ethyl methanoate](#)

Definition

Ethyl formate is among the largest organic molecules unambiguously detected by radio astronomers in the interstellar medium. It is also called ethyl methanoate. Ethyl formate is partly responsible for the flavor of raspberries, and it has the characteristic odor of rum.

History

The *trans* conformer of ethyl formate was detected in the Galactic Center molecular cloud Sagittarius B2(N) by Belloche et al. (2009), who suggest that it may be produced by surface reactions on interstellar dust grains, perhaps involving precursors such

as methyl formate and ethanol (for the definition of conformers, see ► [isomer](#)). More recently, the *gauche* conformer has also been detected, in a line survey of the Orion molecular cloud (Tercero et al. 2013). Ethyl formate is the second formate, after ► [methyl formate](#), to be detected in the ► [interstellar medium](#). Its isomer methyl acetate (CH₃COOCH₃) has also been recently detected in a molecular cloud in the Milky Way.

Cross-References

- [Interstellar Medium](#)
- [Methyl Acetate \(CH₃COOCH₃\)](#)
- [Methyl Formate \(HCOOCH₃\)](#)
- [Molecules in Space](#)

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Ethyl Methanoate

- [Ethyl Formate](#)

Ethyl Methyl Ether (C₂H₅OCH₃)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Methoxyethane](#); [Methyl ethyl ether](#)

Chemical Formula

C₂H₅OCH₃

Definition

The organic molecule ethyl methyl ether (IUPAC name methoxyethane) in the laboratory is a colorless gas with a medicinal odor. It has very probably been detected in the interstellar medium in hot core regions such as Orion KL (see ► [Molecules in Space](#)). Its reported abundance relative to related organic species helps to constrain models of interstellar chemistry.

Cross-References

- [Hot Core](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

References and Further Reading

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Ethylene Glycol (HOCH₂CH₂OH)

Didier Despois¹ and Audrey Coutens²

¹Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

²Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Toulouse, France

Synonyms

(CH₂OH)₂; 1,2-Ethanediol; Glycol;
HOCH₂CH₂OH

Chemical Formula

HOCH₂CH₂OH; (CH₂OH)₂

Definition

Ethylene glycol [IUPAC name 1,2-ethanediol] is the simplest dialcohol (or diol). A (toxic) liquid under the standard pressure from 197 °C down to −12 °C, its mixture (70–30%) with water remains liquid down to −51 °C, which explains its use as antifreeze. It is currently produced by reaction of ► [ethylene oxide](#) (oxirane, C₂H₄O) with water. Ethylene glycol has been found in the interstellar medium and in ► [comets](#).

History

Detection of ethylene glycol in the interstellar medium was rather difficult; it was performed for the first time by Hollis et al. (2002) toward the galactic center (► [SgrB2](#)). This contrasts with the relative strength of the lines in comet C/1995 O1 (► [Hale-Bopp](#)), where this molecule was identified in archive spectra as soon as the line frequencies were available (Crovisier et al. 2004). Since then, ethylene glycol has been found in several ► [comets](#) (e.g., Biver et al. 2014, 2021, Goesmann et al. 2015) and star-forming regions of different masses (e.g., Fuente et al. 2014, Maury et al. 2014, and Brouillet et al. 2015). Several conformers of ethylene glycol exist (Hollis et al. 2002), and the astronomical detections prior to 2012 referred to the lowest energy conformer (aGg'). A second conformer (gGg') was first tentatively identified towards ► [IRAS 16293–2422](#) by Jørgensen et al. (2012) and later confirmed by Jørgensen et al. (2016).

Cross-References

- [Comet](#)
- [Comet Hale–Bopp](#)

- Ethylene Oxide (C₂H₄O)
- IRAS16293-2422
- Molecules in Space
- SgrB2

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Ethylene Oxide (C₂H₄O)

William M. Irvine

Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

C₂H₄O; Oxirane

Definition

Under laboratory conditions, ethylene oxide is a colorless, flammable gas.

History

Ethylene oxide was isolated in 1859 by the French chemist C.A. Wurtz. It subsequently became commercially important as a precursor to ethylene glycol, and it was used during World War I in the production of mustard gas. The astronomical detection was carried out after a failed search for its derivative, oxiranecarbonitrile (C₃H₃NO), which had been suggested as a possible precursor to glycolaldehyde phosphate and hence to sugar phosphates (Dickens et al. 1996). Ethylene oxide (IUPAC name oxirane) is one of only a handful of cyclic molecules that have been found in the interstellar medium, all of which except benzene and benzene derivatives involve three-membered rings. It was detected by radio astronomers by observing pure rotational transitions at millimeter wavelengths in the Galactic Center ► [hot core SgrB2\(N\)](#) (Dickens et al. 1997). Ethylene oxide is isomeric with ► [acetaldehyde](#) (CH₃CHO) and vinyl alcohol (CH₂CHOH), both of which are also observed in the interstellar medium. NASA has used ethylene oxide for sterilization of spacecraft as part of its ► [planetary protection](#) program.

Cross-References

- [Acetaldehyde](#)
- [Hot Core](#)
- [Isomer](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Planetary Protection](#)

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Ethyl-glycine

- [Aminobutyric Acid](#)

Ethyne, HCCH

- [Acetylene \(\$C_2H_2\$ \)](#)

Ethynyl Radical (C_2H)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

C_2H

Definition

This triatomic ► [radical](#) plays an important role in the gas phase chemistry of interstellar

► [molecular clouds](#), since it provides a link in the chemistry of acetylene and higher-order polyacetylenes, the presence of the latter being deduced from observations of the corresponding nitriles (► [cyanopolylyne](#)). Both carbon-13 and deuterated isotopic variants of C_2H are observed in ► [molecular clouds](#).

History

The fundamental pure rotational transition ($N = 1 - 0$) of C_2H at a frequency of 87 GHz was observed astronomically before corresponding laboratory measurements were available, with the identification resting on the pattern of the four detected hyperfine components (Tucker et al. 1974).

Cross-References

- [Cyanopolylyne](#)
- [Deuterium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radical](#)

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Ethynyloxy

- [Ketenyl Radical \(\$HCCO\$ \)](#)

Eucarya

- [Eukarya](#)

Eukarya

Linda Amaral-Zettler

Marine Biological Laboratory, Josephine Bay
Paul Center for Comparative Molecular Biology
and Evolution, Woods Hole, MA, USA

Keywords

Classification · Domain · Tree of life

Synonyms

[Eucarya](#); [Eukaryote](#)

Definition

Eukarya is one of the three domains of life distinguished from ► [Bacteria](#) and ► [Archaea](#) at the morphological and molecular levels. All members of the Eukarya have a nucleus and are further distinguished from *Bacteria* and *Archaea* by a complex cellular organization with ultrastructural features including but not limited to nuclear pores, endoplasmic reticulum, 9 + 2 flagellar apparatus, mitotic spindle formation, acidified vacuoles, Golgi apparatus, multiple linear chromosomes, eukaryotic telomeres, and cellular processes that typically include mitosis, meiotic sex, endocytosis, and mitochondrial respiration. They are also differentiated from the other two domains by the presence of specific genes and proteins (e.g., tubulins, actin, dyneins, centrin, myosin, calmodulin, and ubiquitin).

Overview

Members of the domain Eukarya include both unicellular and multicellular representatives from the ~1-μm ocean-dwelling “picoplanktonic” alga *Ostreococcus* to the blue whale (~34 m) – a difference in size of over 7 orders of magnitude. Animals, plants, and

► [fungi](#) all have microbial eukaryotic (protistan) sister groups. Traditional taxonomic classifications of the Eukarya are morphology based and have described ~1.25 million animal species (mostly insects), 297,326 plant species and ~75,000 fungal species, and ~200,000 protistan species (<http://www.eol.org/>). Single-cell and some multicellular protists contribute to the greatest diversity of life on Earth in the domain Eukarya. Beginning in the 1960s, a large portion of this diversity was unveiled with the assistance of technologies including high-powered electron microscopy. Unlike bacteria and archaea, many microbial eukaryotes have ultrastructural features that can help to differentiate the major groups. These ultrastructural features are summarized in below (Patterson 1999).

Ultrastructural features that differentiate major groups of eukaryotes are:

- Shape of mitochondrial cristae (i.e., tubular, elongated, branching, flat, or discoidal)
- Presence or absence of hairs, scales, or other extensions on the flagella
- Organization of the axoneme into the nine-triplet structure of the basal bodies
- Basal body length and orientation association with other organelles
- Microtubule and rootlet structures arising from the basal bodies
- Source and deployment of microtubular or other cytoskeletal arrays within the cell
- Presence and nature of microtubule-organizing centers
- Number, nature, and heterogeneity of nuclei, structures within the nuclear envelope, intranuclear and paranuclear inclusions
- Behavior of the nuclear envelope during mitosis
- Behavior of the mitotic spindle
- For chloroplast-containing cells: number of bounding membranes, thylakoids per lamella, and the presence and nature of contained (e.g., stigma) or associated (e.g., nucleomorph) organelles
- Identity and nature of other membrane-bound organelles in the cell

Based on these ultrastructural features, Patterson (1999) defined 71 groups of protists but identified an additional 200 with no clear ultrastructural identity. While ultrastructure has its virtues in the eukaryotic domain, molecular approaches quickly superseded morphological ones in accelerating our ability to delineate species and higher-order taxa of eukaryotes. After Woese and Fox's (1977) seminal work on applying ribosomal RNA-based strategy for inferring the relationships between the major branches of the tree of life, this approach quickly became the gold standard in molecular systematics studies in the 1980s and 1990s across all domains of life. In 1990, Woese et al. (1990) formally erected the three domains including the *Bacteria*, *Archaea*, and *Eukarya*. Many studies employing rRNA-based approaches ensued and made important contributions to the placement of eukaryotes into major groups (Sogin 1991).

Despite insights gained in applying molecular metrics to redefining the organization of life, modern taxonomic revisions have been slow to reach textbooks. The animal-plant dichotomy was replaced with the Whittaker five kingdoms recognizing *Monera*, *Animalia*, *Plantae*, *Fungi*, and *Protista*, but the transition to the three-domain classification has been a gradual one at best. Another holdfast has been the prokaryote-eukaryote dichotomy. Pace (2006) pointed out the need to recognize the value of the three-domain system in doing away with the artificial lumping of bacteria and archaea via the term "prokaryote." While ribosomal RNA approaches failed to unveil higher-order relationships between the three domains, amino acid-based analyses using vacuolar H⁺-ATPases showed that *Archaea* are more closely related to *Eukarya* than they are to *Bacteria* (Gogarten et al. 1989), further obfuscating the prokaryote-eukaryote division.

While important in establishing lower-level taxonomic relationships, single-gene approaches such as rRNA, tubulin, and others often returned ambiguous relationships between major groups of eukaryotes. The adoption of multigene phylogenetic approaches to inferring relationships between eukaryotes, followed by the use of

genomic and expressed sequence tag (EST) data, ushered in the "phylogenomic" era in eukaryotic phylogeny research. These approaches allowed for the testing of relationships between major lineages of eukaryotes and lead to the adoption of the "supergroup" concept of eukaryotic phylogeny that encompasses a varying number of higher taxonomic groupings than phyla depending on the extent of the supergroup. These include the Opisthokonta, Amoebozoa, Archaeplastida (*Plantae*), Rhizaria, Chromalveolata (chromalveolates, chromists plus alveolates), and the Excavata (Baldauf 2003; Keeling et al. 2005; Simpson and Roger 2004).

More detailed information on these supergroups can be found in the references listed above, but a brief description follows. The Opisthokonta encompass the animal and fungal kingdoms, as well as several groups of protists related to both of these lineages, choanoflagellates and Mesomycetozoea (a group of parasitic protists, many in fishes), branch with the animals, and nucleariids and microsporidia (a group of obligate endoparasites) branch with the *Fungi*. Their name reveals the nature of the synapomorphy or shared derived trait that its members share – a single posterior flagellum. This higher-order relationship between two kingdom-level eukaryotic groups has been known for some time and was first proposed on the basis of morphological characters (Cavalier-Smith 1987), confirmed via single-gene rRNA-based molecular analyses (Wainright et al. 1993) and more recently supported by various phylogenomic investigations (Burki et al. 2007; Hampl et al. 2009; Parfrey et al. 2006).

The Amoebozoa form a second supergroup comprising lobose amoebae, slime molds, as well as some amitochondriate amoebae including pelobionts and entamoebae (sometimes referred to as Archamoebae). Like the terms "alga" and "worm," "amoeba" joins the ranks of ecological concepts as opposed to phylogenetic ones because the term does not refer to a coherent group of organisms that share common ancestry. Amoeboid organisms, organisms that possess pseudopodia or "false feet" that enable the cell to engulf food via phagocytosis, are sprinkled over the tree of life and occur in the Opisthokonta

(i.e., nucleariids), Amoebozoa, Rhizaria (i.e., Foraminifera, Polycystines, Phaeodaria, Acantharea), and Excavata (i.e., Heterolobosea). Amoebozoa include free-living, facultative, and obligate parasites including the genus *Amoeba*, *Acanthamoeba*, and *Entamoeba*. As with the Opisthokonta, Amoebozoa have multicellular representatives including members of the slime molds such as *Dictyostelium*.

The Plantae supergroup, also called the Archaeplastida, includes unicellular and multicellular members such as the land plants, charophytes, chlorophytes, red [algae](#), and glaucophytes. All the members of this group are photosynthetic or contain relict plastids resulting from a primary endosymbiosis with a cyanobacterium. Surprisingly, a recent phylogenomic assessment of this supergroup along with other supergroups including 143 proteins and 48 taxa failed to support the monophyly of the Archaeplastida (Hampel et al. 2009). Beyond systematic errors associated with the analysis, one possible explanation is related to the symptomatic problem of the host nuclear genome being a potential mosaic of genes derived from multiple nuclei (Lane and Archibald 2008).

The Chromalveolata supergroup itself contains higher-order groupings of eukaryotes including the alveolates (i.e., ciliates, apicomplexans, dinoflagellates) and chromists (Stramenopiles – brown algae, diatoms, pelagophytes, labyrinthulids, oomycetes, bicosoecids, opalindids), haptophytes, and cryptomonads. Members of this supergroup are ecologically diverse ranging from free-living to obligately parasitic and heterotrophic, autotrophic, and mixotrophic. The Chromalveolates remains among the most controversial of supergroups and may require more taxon sampling to justify (Hampel et al. 2009).

The Rhizaria consists of unicellular and colony-forming (therefore multicellular) protists that include the geologically significant Radiolaria and Foraminifera that are well preserved in the fossil record, as well as a hodgepodge of other amoeboid and flagellated forms collectively referred to as the Cercozoa. Members of the Radiolaria have been detected in molecular studies targeting picoplankton-sized (<2 μm) cells, as

well as colonies that reach several meters in length. In addition to exhibiting extreme morphological variability, like the Chromalveolates, the supergroup also exhibits varied ecological roles including heterotrophic, autotrophic, and parasitic lifestyles, and many members of the Radiolaria and Foraminifera in particular possess symbiotic algae. Rhizaria is defined solely on the basis of molecular phylogenies and lacks any synapomorphic characters.

The final supergroup is the Excavata (Patterson 1999) that include the Heterolobosea, euglenids, diplomonids, kinetoplastids, jacobids, *Carpodemonas*, diplomonads, retortamonads, trichomonads, hypermastigotes, *Trimastix*, and the oxymonads. Phylogenomic analyses have only recently supported the monophyly of this supergroup (Hampel et al. 2009), which, unlike other supergroups, was primarily conceived on the basis of an ultrastructural feature of a distinctive ventral feeding groove occurring in the flagellated members of the group and further expanded via molecular studies. The Excavata contains many human disease-causing representatives including *Giardia* (diplomonad), *Naegleria* (heterolobosean), and *Trypanosoma* (kinetoplastid), as well as many free-living nonpathogenic members. Among them is *Euglena* that includes both heterotrophic and autotrophic representatives. As with other supergroups, the Excavata also contains members that are multicellular, namely, heterolobosean acrasids that form a sporangia much like the slime molds of the Amoebozoa – but phylogenetically distinct. Also like slime molds, they serve as major decomposers in the environment.

Future Directions

With increasing numbers of rRNA-based environmental clone surveys unveiling potentially novel eukaryotic groups, there is still the chance that there remain unexplored supergroups of the domain Eukarya (Massana and Pedros-Alio 2008). Among the possibilities are sequences related to Apusomonads and Picobiliphyta, two protist groups that do not have clear affinities to existing supergroups. New technologies afforded

by next-generation pyrosequencing (Amaral-Zettler et al. 2009) and single-cell ► [genomics](#) approaches hold promise for completing our search for novelty among the Eukarya.

Cross-References

- [Algae](#)
- [Fungi](#)
- [Genomics](#)
- [Multicellular Organisms](#)
- [Ribosome](#)
- [Sequence Analysis](#)
- [Yeast](#)

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Eukaryote

- [Eukarya](#)

Eukaryotes, Appearance and Early Evolution of

Emmanuelle J. Javaux

Early Life Traces & Evolution-Astrobiology,
University of Liège, Liège, Belgium

Keywords

Acritarchs · Eucarya · Evolution ·
Precambrian · Protists

Definition

Eukaryotes are the organisms belonging to the phylogenetic domain Eucarya. Eukaryotic cells are less diverse than ► [prokaryotes](#) (phylogenetic domains ► [Archaea](#) and ► [Bacteria](#)), but have a complex cellular architecture comprising a ► [nucleus](#), a cytoskeleton (a proteinaceous network structuring the cytoplasm to facilitate intracellular traffic, endo- and exocytosis, phagocytosis, cellular division, cell membrane and wall deformation and amoeboid locomotion), an

endomembrane system (a system of internal membranes subdivided into several organelles and used for synthesis, processing, packaging, and transport of macromolecules such as lipids and ► [proteins](#)), and organelles such as mitochondria (or derived organelles) and ► [chloroplasts](#) in photosynthetic eukaryotes.

Overview

Unicellular eukaryotes are called protists. They are very diverse and occur in all the supergroups of the eukaryotic tree (Burki et al. 2020). Multicellular eukaryotes include fungi, animals, algae, and plants. Models for the origin of eukaryotes are numerous, including a phagotrophic origin (e.g., Cavalier-Smith and Chao 2020) or a syntrophic origin with the association of prokaryotes – one archaeon and one or more bacteria – to form FECA, the first eukaryotic common ancestor (e.g., Moreira and López-García 1998; Martin and Müller 1998; López-García and Moreira 2015, 2019; Bulzu et al. 2019; Imachi et al. 2019; Spang et al. 2019). Recently, new clades of archaea called Asgard were discovered, and their genes indicate that they include the closest relatives to eukaryotes (Spang et al. 2019). However, other studies propose a closer relationship between eukarya and planctobacteria, and that archaea are sister, not ancestor of eukarya (e.g., Cavalier-Smith and Chao 2020; Devos 2021). One Asgard archaeon was isolated from deep sea sediment and successfully cultivated (Imachi et al. 2019). This tiny (550 nm) anaerobic slow-growing archaeon degrades amino acids through syntrophy, and shows no internal organelles (nor nucleus), but has long, often branching protrusions and genes of a cytoskeleton (Imachi et al. 2019).

Eukaryogenesis is “the whole sequence of evolutionary events occurring between FECA and LECA the last eukaryotic common ancestor (or the most recent ancestor of all modern eukaryotes), explaining the process by which eukaryotic cells emerged from prokaryotic ancestors” (Eme et al. 2017).

To date, the timing and relative order of evolution of eukaryotic cellular features characterizing

LECA, such as the nucleus, endomembranes, cytoskeleton, meiosis, and mitochondria, is unknown (Koumandou et al. 2013; Ettema 2016; Dacks et al. 2016; Eme et al. 2017; Martin et al. 2017; Roger et al. 2017). Based on comparison with Asgard Archaea genomes, FECA probably had key elements of the cytoskeleton and vesicle budding and trafficking, suggesting that some cellular complexity may have emerged before the mitochondria (Eme et al. 2017). The mitochondrion derives from an alpha-proteobacterium ancestor but several scenarios exist for the timing of its acquisition: at an “early” stage coinciding to the birth of FECA, an “intermediate” stage between FECA and LECA, or a “late” stage with the birth of LECA (Ettema 2016; Roger et al. 2017). The age of LECA is also debated, based on the interpretation of the fossil record and on estimations by molecular clocks, ranging from an early LECA in the late Paleoproterozoic (1.9–1.7 Ga) (Javaux 2011; Parfrey et al. 2011; Eme et al. 2014; Butterfield 2015; Javaux and Knoll 2017; Betts et al. 2018; Javaux et al. 2021) to a late LECA in the Meso- to Neoproterozoic (0.7–1.5 Ga; Chernikova et al. 2011) or late Mesoproterozoic (1.2–1.0 Ga) (Chernikova et al. 2011; Porter 2020) or early Neoproterozoic (1.18–0.74 Ga; Cavalier-Smith and Chao 2020).

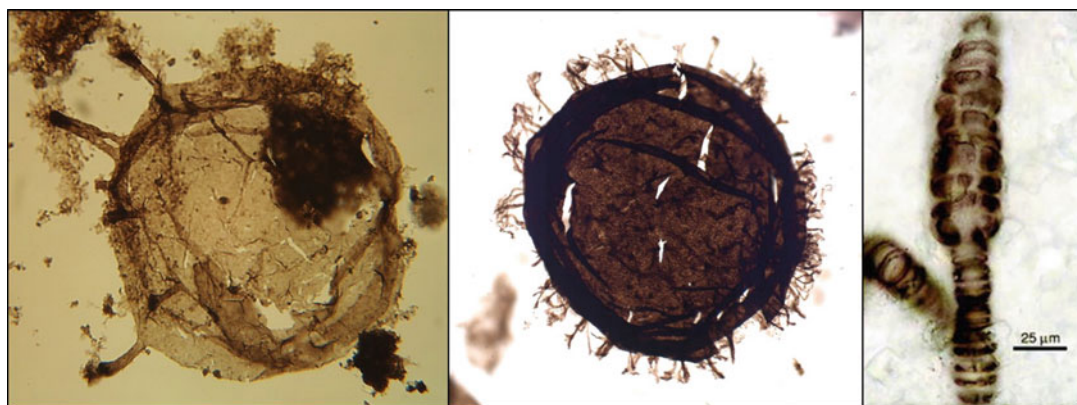
Regardless of fossil interpretation or taxonomic identification, the evolution of biological innovations can be preserved in part – or inferred from the morphology, ultrastructure, and chemistry of early eukaryotes. It can be traced back through time and inform on the timing and pattern of eukaryogenesis and diversification of stem and crown clades (Javaux et al. 2003, 2004; Javaux and Marshal 2006; Javaux 2007, 2011; Knoll 2014; Knoll et al. 2006; Javaux and Knoll 2017; Butterfield 2009, 2015; Porter 2020). In addition, artificial fossilization (taphonomic) experiments may also permit to test the possible preservation of soft tissues and cellular organelles in the geological record (e.g., Carlisle et al. 2021).

The early eukaryotic fossil record includes carbonaceous compressions where the organic-walled microscopic or macroscopic organisms are preserved flattened parallel to fine-grained

clay-rich rocks (shales and siltstones), parallel to rock bedding; permineralized fossils where the organic and/or mineral parts of organisms are preserved three-dimensionally in silica (chert); molds and casts of microscopic and macroscopic remain where their original organic or mineral components have been replaced by other minerals (carbonate, phosphate, pyrite, silica); mineralized skeletons, walls, or scales preserving their original mineralogy; and phylogenetically informative molecules (molecular biomarkers) (Javaux 2011). Among microfossils, ► *acritarchs* include the oldest eukaryotic fossils. They are organic-walled hollow vesicles with unknown biological affinities, rare in the Archean and in the late Phanerozoic, common in the Proterozoic and early Phanerozoic. The origin of the domain Eucarya (the age of FECA) is not constrained and might be an Archean event. However, the Archean eukaryotic record is debated. Previous reports of biomarkers (fossil molecules), possibly indicating the presence of cells able to synthesize eukaryotic sterols in their flexible membranes, were reassessed as contaminants. Molecular phylogenies indicate the capacity to synthesize sterols in bacteria, probably in stem eukaryotes and in aerobic LECA (Goldman and Summons 2009; Desmond and Gribaldo 2009; Hoshino and Gaucher 2021), but crown-group eukaryotic

biomarkers are confirmed only in the Neoproterozoic (0.8 Ga) (Brocks et al. 2017) and in the Mesoproterozoic (1.4 Ga) (Zhang et al. 2021). Large unornamented organic-walled microfossils reported in the 3.2 Ga Moodies Group, South Africa, are enigmatic and could be prokaryotic or eukaryotic (Javaux et al. 2010). Older possible microfossils, some with flanged lenticular shapes, are reported in 3.4 Ga Strelley Pool Formation from the Pilbara in Australia, but the biogenicity of the morphologies is discussed (review in Javaux 2019).

The earliest unambiguous eukaryotic fossils are about 1.75–1.65 Ga acritarchs with organic walls ornamented by concentric striations, plates, or spines (ca. 1.78–1.73 Ga McDermott Formation, Australia, Javaux, 2021; ca. 1.67–1.63 Ga Changcheng Group, China, Miao et al. 2019; >1.65 Ga Mallapunyah Formation, Javaux et al. 2004; Javaux 2019; ca. 1630 Deonar Formation, Vindhyan Supergroup, India, Prasad et al. 2005). In the Mesoproterozoic, the eukaryotic microfossil record shows higher diversity and more obvious ecological heterogeneity (Beghin et al. 2017; Javaux and Knoll 2017). The first process-bearing acritarch (*Tappania plana*, Fig. 1) appears and is interpreted as eukaryotic based on the combined characters of its complex ornamentation, large size, and decay-resistant wall (Javaux et al.



Eukaryotes, Appearance and Early Evolution of, Fig. 1 Examples of fossil eukaryotes. Left: *Tappania plana*, a spiny acritarch (about 150 μm in diameter) interpreted as an early eukaryote from the 1.5 Ga Roper Group, Australia. (Photo: E. Javaux). Center: *Shuiyousphaeridium macroreticulatum*, a spiny acritarch

(about 200 μm in diameter) with an organic wall made of imbricated plates, interpreted as an early eukaryote from the 1.65 Ga Ruyang group, China, Australia. (Photo: E. Javaux). Right: *Bangiomorpha*, a multicellular red alga, from the 1.047 Ga Hunting Formation, arctic Canada. (Photo: N. Butterfield)

2001). It occurs in several late Paleoproterozoic to Mesoproterozoic strata worldwide with other protists with ornamented walls. Another early protist has a complex morphology with wall bearing processes (spines) and made of organic scales (*Shuiyousphaeridium macroreticulatum*, Fig. 1) found in the <1.74 to >1.41 Ga Ruyang Group, China (Javaux et al. 2004; Agić et al. 2017). These and other associated early microfossils display characters of a eukaryotic degree of organization and are interpreted as eukaryotes with a sophisticated cytoskeleton and endomembrane system (review in Knoll et al. 2006; Javaux and Knoll 2017). They probably lived in slightly oxygenated niches close to cyanobacterial mats (Javaux et al. 2021). The earliest eukaryote that can be related to an extant clade is a multicellular red alga (*Bangiomorpha*) dated to 1.047 Ga (Butterfield 2000; Gibson et al. 2017), although fossils interpreted as red algae have been reported at 1.6 Ga (Bengtson et al. 2017), their age and identity are debated (Gibson et al. 2017; Betts et al. 2018). From the late Mesoproterozoic through the middle Neoproterozoic (1.2–0.63 Ga), possible members of several extant supergroups are recorded in the fossil record: fungi, green algae, red algae, xanthophyte algae, testate amoebae, foraminifers, ciliates, and stem metazoans (see summary in Loron et al. 2019, 2021). Major biological innovations such as multicellularity, biomineralization, heterotrophy, predation, two stages life cycle with vegetative cells and cyst and excystment structures, and eukaryotic photosynthesis appear, leading to ecological tiering and complex food webs and interactions (review in Javaux 2011; Cohen and Riedman 2018). The biases and incompleteness of the fossil and sampling records need also to be considered for diversity estimates (Cohen and Macdonald 2015; Riedman and Sadler 2017).

Complex multicellularity (tissue-grade then organ-grade organization) and animal biomineralization and predation evolved during the Ediacaran (635–542 Ma). In parallel to eukaryotic and prokaryotic evolution, simultaneously to these important biological innovations and changing ecology, the physicochemical environments in which these microbial communities

thrived also changed, with heterogeneous oxygenation of ocean and atmosphere, availability of nutrients, and large tectonic, volcanic, climatic and meteoritic impact events. However, it is still not clear how and when these physicochemical, biological, and ecological factors impacted the origin and diversification of the domain Eucarya.

Cross-References

- [Acritarch](#)
- [Archaea](#)
- [Bacteria](#)
- [Chloroplast](#)
- [Cytoplasm](#)
- [Mitochondrion](#)
- [Nucleus](#)
- [Phylogeny](#)
- [Precambrian](#)
- [Prokaryote](#)
- [Proterozoic Eon](#)
- [Tree of Life](#)

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EURECA

Hervé Cottin
Laboratoire Interuniversitaire des Systèmes
Atmosphériques, Université Paris Est-Créteil,
Créteil, France

Definition

EURECA (EUropean REtrievable CARRIER) was a 4.5-t satellite designed to carry spaceborne experiments for a duration of a few months. EURECA was released and retrieved by ► [NASA's](#) space shuttle. It was the first satellite designed

specifically for microgravity experiments, providing 10^{-5} g conditions for long periods.

An important feature was reusability: EURECA was built to survive during five flights over a 10-year period. However, it was used only once, due to lack of funding.

EURECA-1 and its 15 experiments were launched with shuttle mission STS-46 in July 1992 and were recovered during shuttle mission STS-57 in June 1993. Among those experiments was ERA (Exobiology and Radiation Assembly) in which bacteria and organic materials were exposed to study their survival and evolution in space.

It was a precursor to the ► [BIOPAN](#) and ► [EXPOSE](#) facilities.

Cross-References

- [BIOPAN](#)
- [EXPOSE](#)
- [Exposure Facilities](#)

Europa

Thérèse Encrenaz
LESIA, Observatoire de Paris, PSL, CNRS,
Sorbonne Universités, Université Paris Diderot,
Meudon, France

Keywords

Galilean satellites

Definition

Europa, discovered by Galileo Galilei in 1610, is the smallest of the four Galilean satellites orbiting Jupiter. Its distance to Jupiter is 670,900 km, or about 9 Jovian radii. With a diameter of 3140 km, Europa is slightly smaller than the Moon. Its density is 3.013 g/cm^3 , typical of a mixture of rock and some ice. Its high albedo (0.67) suggests that its surface is mostly water ice. The surface temperature of Europa ranges between $\sim 125 \text{ K}$ at the equator and $\sim 50 \text{ K}$ at the poles. Galileo spacecraft

data found an induced magnetic field at Europa, suggesting the existence of a liquid water ocean underneath the near-surface ice layer. Surface morphological features as well as recent evidence for geysers are consistent with an ocean at a few kilometers to tens of kilometer depth. Underneath the ocean at about 100 km depth likely is a silicate layer mantling an iron-rich core.

Overview

Europa's exploration started with the Voyager 2 encounter in 1979. The Voyager camera revealed a strange surface topography of low-relief ridges and chaotic terrains with few impact craters. The pattern of the ridges seemed to indicate that the icy crust is detached from the interior and slightly moves with respect to it. Because Europa is subject to tidal heating due to the proximity of Jupiter (at a level of about one-tenth of that of Io), it was proposed that the icy crust of the surface might cover a liquid or viscous water reservoir. Europa then became a prime target of the Galileo mission which approached Jupiter in 1995 and explored the Jovian system until 2003. Information was retrieved about Europa's surface features, its internal structure, and its interaction with the Jovian magnetosphere.

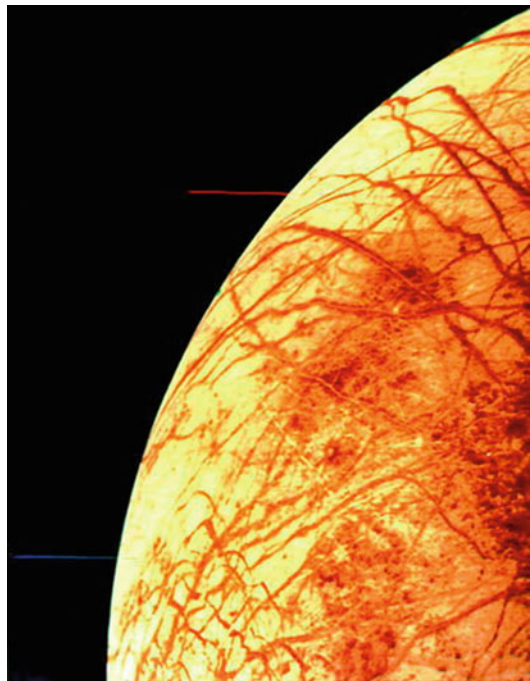
Surface Geology

The most striking features of Europa's surface are the series of dark streaks, called *linae* which criss-cross the whole globe. They are innumerable, overlapping, up to 1000 km long and 20 km wide. In many cases, the ridges are double, often with dark outer edges and a central band. Images show that on each side of the lines, the edges have moved relative to each other. These *linae*, possibly of cryovolcanic origin, are interpreted as resulting from eruptions of warm water, in a scenario similar to the present day mid-oceanic ridges on Earth. In addition, the fracture patterns on Europa's surface are different from those expected for the case of an entirely solid planet. The old and young fractures show different orientations, with more diverse orientations the older they are. This pattern suggests that Europa's surface rotates

slightly faster than the subsurface material, which implies a liquid or viscous subsurface (Fig. 1).

Europa's surface also shows fractured and chaotic features called *lenticulae*, with diameters ranging from 10 to 100 km. Many are domes, broad bulges, which may have formed by cryovolcanic activity. Warm water may have been rising in the icy crust, in a scenario reminiscent of rising magma chambers on Earth.

Impact craters are relatively few, indicating that the surface of Europa is young. Its age can be estimated on the basis of the estimated number of comets and asteroids in Jupiter's environment and suggests an age of about 100–300 Ma. This is very young when compared to the age of the satellite. It is widely agreed that the Galilean satellites formed about 4.5 Ga ago. Most likely, Europa is still geologically active today.



Europa, Fig. 1 This color image of Europa was taken by Voyager 2 during its close encounter on July 9, 1979. The array of streaks shows that the surface has been fractured and filled in some places with material coming from the interior. The relative absence of features and craters indicates that the surface is young. (Source: © NASA)

Internal Structure and Subsurface Ocean

It is now generally accepted that a water ocean lies below the icy crust of Europa. This ocean provides the best explanation for the features observed on the surface: *linae*, *lenticulae* domes, fracture patterns. In 2000, another discovery provided the most direct evidence for the Europa ocean hypothesis: the magnetometer of Galileo detected a weak magnetic moment, induced by the varying part of the Jovian magnetic field. The existence of this induced magnetic field requires the presence of a highly electrically conductive material inside the satellite. The most plausible candidate is a large subsurface layer of liquid water. The presence of salts in this ocean is suspected from the spectral analysis of the dark surface features. Magnesium sulfate and sulfuric acids are possible candidates; sulfur components could account for the reddish color of the streaks.

What is the internal energy which keeps the water warm? Radioactive heating can support a few tens of kilometers thick ocean as thermal models suggest, but tidal heating is likely an even more effective energy source. Europa is likely to be differentiated with a central core of iron and some lighter element such as possibly sulfur, surrounded by a silicate mantle and then by water-rich ocean with an ice crust. Europa's orbit around Jupiter is slightly eccentric and is in orbital resonance with Io and Ganymede. Consequently, although it is in synchronous rotation with Jupiter (showing always the same face to Jupiter), the tidal bulge raised by Jupiter oscillates slightly in height and orientation as Europa moves along its orbit. As a result, energy is dissipated inside Europa and models indicate that the maximum dissipation may take place in the lower part of the ice layer. But dissipation in the silicate mantle is a possible alternative that would provide a mechanism for the delivery of nutrients to the ocean through silicate volcanism. In 2008, scientists proposed that another efficient energy source might come from large planetary tides, generated by Rossby waves, due to the nonzero obliquity of the satellite.

What could be the thickness of the ice crust? According to the models, it could range between a few kilometers and a few tens of kilometers. The

study of Europa's largest craters, surrounded by concentric rings and filled with flat and fresh ice, suggests a 10–30 km thick ice crust, including a ductile warm ice layer, over a liquid ocean which might be about 100 km deep. This thickness would also be consistent with ice shell tidal heating. According to most models of internal structure, the liquid ocean is expected to be in direct contact with the silicate mantle.

An important result has come recently from the reanalysis of Galileo images of chaos. This work suggests that these areas are formed above liquid water lenses located within an ice shell as shallow as 3 km. Although drilling the surface of Europa at 3 km depth is beyond our present capabilities, this result, if confirmed, would have significant implications for astrobiology.

Transient Atmosphere

In 1995, HST observations revealed that Europa has a very thin atmosphere mostly composed of molecular oxygen O_2 , with a surface pressure of about 10^{-12} bar. Two years later, the Galileo spacecraft identified also a tenuous ionosphere resulting from the interaction of Europa's surface with high-energy particles of the Jovian magnetosphere. This magnetosphere carries a dense plasma of energetic sulfur and oxygen ions which have escaped from Io. The trailing hemisphere of Europa is especially exposed to this effect, as shown by the darkening of its UV spectrum. The colliding ions eject water molecules from Europa's surface (this is the "sputtering effect"); as some of them leave to space, the surface is slowly eroded: erosion rate is estimated at about 5–20 cm per million years. This provides additional evidence that the surface of Europa is relatively young. The surface sputtering is also responsible for the molecular oxygen tenuous atmosphere. O_2 is the major atmospheric component because it does not freeze at the equator. Hydrogen peroxide (H_2O_2) ice has been also detected on Europa by the Near Infrared Mapping Spectrometer of Galileo, and hydrogen peroxide acid mixtures might account for some of the features of the surface spectrum. Molecular hydrogen cannot remain on Europa's surface because the satellite's gravity field is too low. It escapes in a

torus, along with atomic and molecular oxygen, to form a neutral torus along the orbit of Europa. This torus has been identified by the Galileo and Cassini spacecraft.

In 2016, water plumes were episodically detected on Europa by the HST, possibly indicative of cryovolcanic activity, as on Saturn's satellite Enceladus. In 2018, this result was confirmed by a reanalysis of Galileo data of 1997, providing new evidence for the presence of a water ocean below the icy crust.

Potential for Extraterrestrial Life

Europa's interior is considered as a possible candidate for extraterrestrial life in the solar system. Indeed, there are three conditions which seem to be required for the development of life on Earth: the presence of carbon, an energy source, and liquid water. Many carbon-rich compounds have been found in comets and meteorites, and such elements may have been brought to Europa by meteoritic impacts. Even if impact craters have been filled in by resurfacing, Europa probably underwent an intense meteoritic bombardment similar to Ganymede and Callisto. The energy source, as discussed above, is provided by tidal heating together with radioactive heating. Life could exist in an ocean underneath the ice crust in an environment comparable to the Earth's hydrothermal vents or the Antarctic lake Vostok. On Europa, free radicals delivered by subduction of surface ice may provide a sufficient source of free oxygen, even in the absence of photosynthesis. Life on Europa, if it exists, could be clustered around hydrothermal vents on the ocean floor. Similarly to what we find on Earth, a process called serpentinization could occur in Europa's ocean as seawater reacts with rock to form new minerals, releasing hydrogen. Alternatively, life could exist clinging to the lower surface of Europa's ice layer, much like algae and bacteria in Earth's polar regions, or float freely in Europa's ocean. If Europa's ocean is too cold or too salty, only extremophiles could survive in its environment.

It should be recalled that there is no any evidence that life exists on Europa today. However, there is a large consensus in the scientific

community about the existence of an ocean of salty liquid water, probably in contact with a silicate mantle to account for the salty content, under an icy crust which is probably several kilometers or several tens of kilometers thick. It remains however to be determined if some of life's other major constituents like carbon, nitrogen, phosphorus, and sulfur also exist in the ocean and at what quantities. The fact that Europa is a potential candidate for extraterrestrial life or at least for habitable conditions has motivated the scientific community for designing two ambitious missions. Jupiter Icy moons Explorer (JUICE) has been selected by ESA for launch in 2022 and arrival in the Jupiter system in 2030. The spacecraft will achieve several flybys of Jupiter and the Galilean satellites, including two flybys of Europa, and will be put in orbit around Ganymede in 2033 for an in-depth exploration of the habitability conditions of the icy moons. Europa Clipper, developed by NASA, is planned for launch in the early 2020s for an arrival in the Jovian system between 3 and 6 years later, to perform a series of 45 close flybys of the satellite. The main challenge for both spacecraft is how to survive in the high radiation field generated by the magnetic field of Jupiter and hence a lander concept is still only in study phase.

Cross-References

- [Callisto](#)
- [Cryovolcanism](#)
- [Ganymede](#)
- [Io](#)
- [Jupiter](#)

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Europa Analogues

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Keywords

Antarctica · Jupiter · Europa

Definition

Extreme field sites on Earth that mimic some of the conditions on Jupiter's moon Europa are considered Europa analogues. Some Earth natural field sites are extreme, due to very low temperature, high salinity, or high pressure conditions. These extreme conditions partially characterize the environment of Europa. Lake Vostok in Antarctica is one of the best recognized Europa analogues. Due to the thick ice crust, a liquid water reservoir underneath is stable due to salinity and high pressure conditions. Lake Tirez in La Mancha (Spain) is considered a geochemical analogue of Europa due to the ionic content of its waters.

Cross-References

- [Europa](#)
- [Vostok, Subglacial Lake](#)

European Astrobiology Institute

Wolf D. Geppert

Department of Physics, Stockholm University, Stockholm, Sweden

Acronyms

EAI

Definition

The European Astrobiology Institute (EAI) is a virtual institute consisting of more than Around 20 research and higher education institutions in the European Research Area as well as European research bodies and infrastructures. It aims to create a European environment of research, training, and public engagement in astrobiology. To achieve its goals, the EAI cooperates with entities engaged in education on all levels and public authorities promoting science (e.g., museums, space agencies, adult training centers, etc.) as well as industries and other stakeholders. The EAI was founded in 2019. Further information is available at the website: <http://www.europeanastrobiology.eu>.

European Cooperation in Science and Technology

► [COST](#)

European Space Agency

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Definition

The European Space Agency (ESA) was established in 1975 and is responsible for

coordinating the exploration of space by its member countries, which numbered 22 in 2021: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, and the United Kingdom, with Canada as an associate member. In addition, Bulgaria, Cyprus, Malta, Lithuania, and Slovakia have cooperation agreements with ESA. ESA's program includes human space flight, primarily through participation in the ► [International Space Station](#), and a variety of scientific missions. Of particular interest to astrobiology is Gaia, an all-sky astrometric survey mission that will detect hundreds, if not thousands, of extrasolar planets. Other exoplanet missions include Cheops (launched in 2019), Plato, and Ariel. ESA is also committed to the exploration of ► [Titan](#) with the successful landing at the surface of the satellite of the ► [Huygens probe](#) in 2005, the exploration of Jupiter's icy moons with JUICE, and in the exploration of comets with the Giotto mission in 1986 and the Rosetta mission, launched in 2004 and orbiting the target comet from 2014 to 2016, and the planned Comet Interceptor Mission. Current and future missions also focus on the exploration of Mars and the question of whether life exists, or has ever existed, on the planet. The Mars Express mission has been in orbit since December 2003, while the ExoMars program includes the Trace Gas Orbiter launched in 2016, a rover and surface platform planned for 2022 together with the Russian space agency Roscosmos, and cooperation with NASA for a Mars sample return to Earth.

Cross-References

- [Astrometric Planets](#)
- [Cassini-Huygens Space Mission](#)
- [Comet Interceptor Mission](#)
- [CoRoT Satellite](#)
- [Exoplanets, Discovery](#)
- [Gaia Mission](#)
- [Giotto Spacecraft](#)
- [International Space Station](#)
- [Mars Express](#)

- [NASA](#)
- [Phylotype](#)
- [PLATO 2.0 Satellite](#)
- [Rosetta Spacecraft](#)

European Space Exposure Facility (ESEF)

- [COMET \(Experiment\)](#)

European Space Research and Technology Centre

- [ESTEC](#)

Euryarchaeota

Ricardo Amils

Departamento de Biología Molecular,

Universidad Autónoma de Madrid, Madrid, Spain

Definition

Euryarchaeota is one of the best characterized superphylum of the domain ► [Archaea](#). The extremophiles used by C. Woese to discover the existence of Archaea belong to this phylum. Euryarchaeota comprises a physiologically diverse group of Archaea: all known methanogens, extreme halophilic Archaea, ► [hyperthermophiles](#) such as *Thermococcus* and *Pyrococcus*, most acidophilic-thermophilic prokaryotes including *Picrophilus*, and the thermophilic-acidophilic cell wall-less *Thermoplasma*. A large number of Euryarchaeota produce methane (CH₄) as an integral part of their metabolism (see ► [methanogens](#)). It is considered a very ancient metabolism due to the unique set of enzymes involved. The extreme halophilic Archaea are a diverse group of Euryarchaea that inhabit highly saline environments (see [halophile](#)). Most species require 2–4 molar salt concentration for optimal growth, and they are able to

grow in the presence of saturating salt conditions. *Picrophilus* is capable of growing below pH 0. *Pyrococcus*, which literally means fireball, has an optimal growth at 100 °C.

Cross-References

- [Acidophile](#)
- [Archaea](#)
- [Halophile](#)
- [Halotolerance](#)
- [Hyperthermophile](#)
- [Methanogens](#)

EUV

- [Extreme Ultraviolet Light](#)

Euxinic Ocean

- [Sulfidic Oceans](#)

Evaporite

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Evaporitic rocks and minerals](#)

Definition

Evaporite is a class of sedimentary rocks and minerals precipitated from evaporating brines. Common evaporitic minerals calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), anhydrite (CaSO_4), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and halite (NaCl) precipitate out of solution in the reverse order of their solubilities

from evaporating seawater. Non-marine evaporites such as trona ($\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$) can be precipitated in soda lakes. The occurrence of evaporite minerals on planetary surfaces may record the past presence of water. The Mars Rover Opportunity has discovered gypsum and ► [jarosite](#) in the Burns Formation, *Meridiani Planum*, Mars, which are interpreted as deposits formed by the evaporation of acidic waters of likely hydrothermal origin (e.g., McLennan et al. 2005).

Cross-References

- [Evaporites, Archean](#)
- [Jarosite](#)
- [Mars](#)
- [Natron](#)
- [Oceans, Chemical Evolution of](#)
- [Soda Lake](#)
- [Thermonatrite](#)
- [Trona](#)

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Evaporites, Archean

Sami Nabhan

Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Keywords

Evaporites · Barite · Gypsum · Carbonate · Chert · BIF · Archean · Continental growth

Definition

Evaporites are chemical sediments and sedimentary rocks that form as result of an increasing concentration of ions in water as precipitates

either at the surface or at the base of the water body. The majority of evaporitic sediments and sedimentary rocks on Earth consist of carbonates, sulfates, or halides. Archean evaporites are, to their largest part, either of a restricted-marine facies or hydrothermally related. Open-marine evaporites are completely absent, terrestrial evaporites nearly so.

Overview

Evaporites compose a disproportionally small percentage of the Archean rock record because their preservation potential is generally low and because conditions for their formation may have been poor due to smaller and fewer emerged ► [continents](#), lower continental freeboard, a perceived hot and humid climate, and an unknown saturation state of the oceans. Ocean salinity and surface water temperature are major controlling factors for the precipitation of evaporites. Estimates of the Archean ocean temperature based on oxygen isotope composition of early diagenetic ► [chert](#) units are debated, as is the salinity of Archean ocean water. Archean ocean temperatures, as indicated by the isotope composition of Archean cherts, were approx. 55–85 °C (Knauth 2005), while a more recent reevaluation of data, based on both oxygen and silicon isotopes, provides Archean ocean temperature ranging between 35 °C and 55 °C (Marin Carbonne et al. 2014). Estimates of Archean ocean water salinity based on “adding back” the volume of halite in the geological record to the oceans would result in a salinity of 1.2–2 times the modern value (Knauth 2005). This number, however, is highly dependent on estimates of the size of subsurface salt deposits and of hypersaline brines in sedimentary basins. Other factors controlling evaporation include the ionic composition of Archean ocean water and its pH value. The suggestion of an early ocean saturated in sodium carbonate (the “soda ocean”) would result in a pH of ~10 (Kempe and Degens 1985; Gargaud et al. 2005). The presence of reduced iron (Fe^{2+}) in the Archean ocean, however, indicates a pH between 6 and 7 (Krissansen-Totton et al. 2018).

Archean evaporites are commonly preserved as pseudomorphs, silicified from their precursors (e.g., gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), nahcolite (NaHCO_3), and aragonite (CaCO_3)). Most evaporites are preserved as dolostones and limestone that originally precipitated as carbonate cements such as aragonite and magnesian calcite (Grotzinger and Kasting 1993) or as ► [stromatolites](#), a common component of Archean carbonate platforms (Grotzinger and James 2000). Most carbonates older than ~3 Ga are of peritidal sedimentary facies and found in ► [greenstone belts](#) of South Africa, Australia, and India (Harnmeijer 2010). The oldest known carbonate platform is the ~2.9-Ga-old Steep Rock platform in Ontario, Canada. At about 2.6 Ga, platform-type carbonates became established (Grotzinger and Kasting 1993; Harnmeijer 2010), substantially composed of original aragonite (now mainly dolomitized) and exemplified by the ~2.55-Ga-old Campbellrand-Malmani carbonate platform with individual beds of up to 65% encrusting carbonate. This suggests that seawater was supersaturated with respect to aragonite and calcite and that its pH was neutral to slightly alkaline (Sumner and Grotzinger 2004). In some Neoproterozoic carbonate platforms, the presence of pseudomorphs of carbonates and chert after halite (NaCl) crystals combined with an absence of sulfate pseudomorphs within supratidal lithofacies zones (Boulter and Glover 1986; Sumner and Grotzinger 2004; Eriksson et al. 2005; Gandin et al. 2005) has been interpreted to either reflect a generally low sulfate content or, as a consequence of extensive carbonate precipitation, a low calcium content of seawater (Boulter and Glover 1986; Grotzinger and Kasting 1993; Sumner and Grotzinger 2004; Eriksson et al. 2005). On the other hand, pseudomorphs after swallowtail gypsum and enterolithic gypsum have been described by Gandin et al. (2005). Some of the crystal fans interpreted as aragonite fans resemble gypsum domes in their structure (Hardie 2003; Gandin et al. 2005). Calcitization of former sulfate evaporites is interpreted as a result of bacterial sulfate reduction and the organic diagenesis of pyrite (FeS_2) (Gandin et al. 2005). Such a metabolic process would constitute a second link to

widespread microbial life in the Archean, aside from the abundant morphological evidence provided by stromatolites in carbonate platforms.

Sulfate deposits formed as thinly bedded barite (BaSO_4) of early and mid-Archean age are well represented in the ~3.3-Ga-old Sargur Group, ► [Dharwar Craton](#), central India (Jewell 2000); the ~3.45-Ga-old Onverwacht and the ~3.24-Ga-old Fig Tree Groups of the ► [Barberton Greenstone Belt](#), South Africa (Lowe et al. 2019); and the 3.45-Ga-old North Pole chert-barite unit of the Warrawoona Group, Western Australia (Jewell 2000). All of them are of marine origin and show primary sedimentary and secondary diagenetic structures (Buick and Dunlop 1990; Jewell 2000). For some deposits, their possible origin by volcanic-hydrothermal exhalation is discussed (Reimer 1980). Parts of the North Pole barite have been interpreted as pseudomorphosed gypsum, based on interfacial angles of individual crystals (Buick and Dunlop 1990; Jewell 2000; Shen et al. 2001). ► [Sulfur isotope](#) variations within these sulfates in microcrystalline ► [pyrite](#) suggest the existence of sulfate-reducing bacteria (Shen et al. 2001; Shen and Buick 2004; Dunlop 2015).

Overall, the presence of evaporitic sulfates in the 3.5–3.2 Ga Archean rock record may indicate a global sulfate-bearing, partly oxidized, and stratified ocean (Huston and Logan 2004). Aside from the three deposits mentioned above, only two additional bedded sulfate deposits are known in the geologic record prior to the GOE at ~2.4 Ga, after which they become more abundant (Huston and Logan 2004), possibly due to low concentrations of sulfate in the Archean ocean (Boulter and Glover 1986; Grotzinger and Kasting 1993; Sumner and Grotzinger 2004; Eriksson et al. 2005; Gargaud et al. 2005). However, a partly oxidized ocean may not be required to produce low seawater sulfate from volcanic SO_2 because SO_2 reacts with H_2O to H_2S and H_2SO_4 even in the absence of oxygen (Huston and Logan 2004; Gargaud et al. 2005).

Terrigenous evaporites are exceedingly rare in the Archean. Nabhan et al. (2016) describe widespread silicified former sulfate nodules from the vadose zone of fluvial to supratidal coastal plains

of the ~3.2-Ga-old Moodies Group, South Africa, and interpreted them to have formed pedogenic to early diagenetic by evaporating groundwater in semiarid conditions.

Some Archean cherts and possibly banded-iron formations (BIF) can be considered evaporites where the involvement of biologic processes is uncertain or unlikely. Some cherts may form abiogenically in subtidal environments due to silica oversaturation of pore waters during evaporation (Pufahl and Hiatt 2012). ► [Banded-iron formations](#) are composed of a mixture of silica with iron-bearing minerals such as hematite (Fe_2O_3), magnetite (Fe_3O_4), siderite (FeCO_3), and pyrite (FeS_2), which precipitate depending on ocean water chemistry (Huston and Logan 2004; Gargaud et al. 2005; Pufahl and Hiatt 2012). They are interpreted either as deep-water precipitates or as precipitates developed during times of restricted clastic supply.

Basic Methodology

- Field observations (mapping, documentation of sedimentary structures, construction of stratigraphic cross sections)
- Thin-section microscopy
- Analysis of major and trace element distribution
- Raman spectroscopy for fluid and gas inclusions
- Stable isotope fractionation (S, C, O, N, Sr, Fe)

Applications

Evaporites are sedimentary rocks that reflect atmospheric and hydrospheric conditions during the time of their formation. Therefore, Archean evaporites can be used to constrain Archean atmospheric and seawater composition. Terrestrial evaporites can also be used to provide information on Archean groundwater and to infer climatic conditions. Evaporites are often related to or aided by biogenic processes and may thus preserve traces of early life.

Cross-References

- [Archean Environmental Conditions](#)
- [Banded Iron Formation](#)
- [Campbellrand-Malmani Platform, South Africa](#)
- [Chert](#)
- [Evaporite](#)
- [Jaspilite](#)
- [Magnetite](#)
- [Moodies Group](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)
- [Oceans, Origin of](#)
- [Precambrian Oceans, Temperature of](#)
- [Pyrite](#)
- [Stromatolites](#)
- [Sulfate Minerals](#)
- [Sulfate Reducers](#)
- [Sulfur Isotopes](#)
- [Warrawoona Group](#)

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Evaporitic Rocks and Minerals

- [Evaporite](#)

Evidence in Astrobiology

Erik Persson

Department of Philosophy, Lund University,
Lund, Sweden

Keywords

Evidence · Justified belief · Reasons for belief ·
Proof · Biosignatures · Technosignatures

Synonyms

The term “proof” is sometimes used in common language as a synonym to “evidence,” though in philosophical and strict scientific jargon, proof is usually referred to mathematics and logic, and is not used in connection with empirical science. Contrary to proof, evidence is not a matter of either-or but of strength. Thus, evidence for X of strength Y justifies belief X to degree Y. Contrary to proof there can also exist evidence both for and against a belief.

Definition

‘Evidence’ is defined by the Cambridge dictionary as “one or more reasons for believing that something is or is not true” (The Cambridge Dictionary).

In philosophy, evidence is also often defined in terms of justification, rather than reason, for belief. A probabilistic definition would look as follows:

E is evidence for H if and only if $P(H|E) > P(H)$.
E is evidence against H if and only if $P(H|E) < P(H)$, though whether evidence is best described in probabilistic terms is controversial (The Stanford Dictionary of Philosophy 2014).

Overview

Astrobiology is an interdisciplinary field that tries to answer some connected yet different questions.

This makes the question of evidence slightly more complicated than in most other fields. The question is complicated further by the fact that the questions asked by astrobiology have strong relevance also outside of science, including among the general public.

Among the key issues, we find the following questions:

- “What counts as evidence in astrobiology?”
- “How do we assess the strength of evidence in astrobiology?”
- “Do different questions need different kinds/strength of evidence?”
- “What kind/strength of evidence do we need to establish that life has been found on a particular celestial body?”
- “What kind/strength of evidence do we need to establish that a particular body is uninhabited?”
- “What kind/strength of evidence do we need to establish that we are alone in the universe?”

Extraordinary Claims Require Extraordinary Evidence

The most commonly cited statement about evidence in astrobiology is “extraordinary claims require extraordinary evidence,” also known as the Sagan standard. The quote is from Carl Sagan’s TV-series *Cosmos* (Sagan 1980), but the idea behind the statement can be traced back most noticeably to Laplace (1812) and Hume (1748).

Though the statement makes intuitive sense, it also raises questions. How can different claims to truth require evidence of different strength; what makes a claim extraordinary; what kind of or amount of evidence counts as extraordinary, and in our case, what answers to what questions in astrobiology should count as extraordinary? Is for instance a claim that there is life on another world, more or less extraordinary than a claim that we are alone in the universe? Is an alleged finding of extraterrestrial intelligent life more or less extraordinary than an alleged finding of extraterrestrial microbial life?

The nature of these questions also makes the Sagan standard difficult to operationalize.

The need for extraordinarily strong evidence in astrobiology must also be balanced against the

need to avoid feeding into conspiracy theories. If the demand for extraordinary evidence leads to rejection of conclusions that under normal circumstances would be accepted by the scientific community or if the publication process takes an unusually long time, there is a risk that this will feed the myth that the scientific society knows more about extraterrestrial life than they want to admit to the public.

Biosignatures

Directly observing life on another world is difficult, especially outside our solar system. Evidence for life can, however, also be in the form of non-living phenomena, referred to as biosignatures. A biosignature is a non-living phenomenon that is closely enough associated with life to function as evidence for life.

A non-living phenomenon can be sufficient or necessary for life or life can be sufficient or necessary for the presence of a particular non-living phenomenon. A non-living phenomenon that does not fit into any of these categories can still be indicative of life.

Observation of a non-living phenomenon that is sufficient for life or for which life is necessary, would be conclusive evidence of life on the same level as observing actual life. Observation of a non-living phenomenon that is necessary for life would be weak evidence for life, while lack of any such phenomena on a given body is conclusive evidence that life does not exist on that body. Due to the great diversity of life and the lack of a generally accepted definition of life, it is very difficult to identify non-living phenomena as being necessary or sufficient for life as well as the other way around. A possible example of a physical condition necessary for life could be a temperature range within which chemical processes can take place. An example of a phenomenon for which (past or present) life is a necessary condition might be certain technosignatures such as Dyson-spheres (i.e., a megastructure around a star collecting a large proportion of the energy radiating from the star, see Dyson 1960) or translatable radio signals.

Non-living phenomena that do not fall into any of these categories can still provide important, though non-conclusive, evidence. The degree to which a certain non-conclusive biosignature can count as evidence in astrobiology depends not just on its own relation to life but also on the existence of alternative explanations (other than the presence of life) for the observation. The strength of O_2 as evidence of life on a particular world depends, for example, on the existence of other possible sources of O_2 on the world in question.

Collecting evidence for extraterrestrial life is thus a painstaking process that may not take the form of a discovery in the traditional sense but rather be a matter of increasing the amount and quality of evidence until we decide that we are certain enough. This means we have several problems to consider: How certain do we have the right to be given the evidence we have? What kind of evidence do we need in order to increase the certainty, and how do we collect such evidence? Where on the scale do we need to be in order to be certain enough to declare that we have actually found life?

How we answer the last question regarding when we can be certain enough, is not an empirical but a philosophical question Persson 2014. It depends, among other things, on the purpose of the question and the values at stake. For example, is it about being confident enough that we found life to publish a scientific paper or to hold a press conference, or is it about being confident enough that a world is uninhabited to move the planet to a different planetary protection category or to allow commercial exploitation of the planet?

The Evidence Value of Non-findings

If we, in spite of trying, do not find any reliable evidence for extraterrestrial life on a particular world, or anywhere, how shall we interpret that information? Is lack of evidence for life the same as evidence against life? The answer to this question is that the relation between positive findings and non-findings in terms of evidential value is asymmetric. The evidential value of non-findings is not comparable in strength to the evidential value of positive findings but that does not mean

they have zero evidence value (Achinstein 2003; Chalmers 1999; Noble 1975; Popper 1959). If we drop a stone 10,000 times and it falls to the ground every time, we can still not be as certain that it does not sometimes fly off on its own, as we can be that it sometimes falls to the ground. Even so, it is more rational to bet that it will fall to the ground than that it will fly away next time we drop it. This means we can successively increase our confidence that a world is uninhabited by gathering negative evidence, just as we can successively increase our confidence that a world is inhabited by gathering more and better evidence, even if none of the evidence is conclusive. The collective strength of any amount of non-conclusive evidence whether positive or negative, cannot reach the same level of confidence as one piece of conclusive evidence but we can get asymptotically closer by continuing to gather more and better evidence. (Note, however, that conclusive evidence means that we are justified in believing something beyond doubt. It is not the same as proof in mathematical or logical context.) Like with positive evidence, different non-findings can have different strengths depending on the quality of the study. A good study that does not find anything is stronger (though still in itself rather weak) evidence against life than a poor study that does not find anything. A certain number of non-findings from studies focusing on different places or biosignatures or use different methods are also, taken together, stronger evidence than the same number of studies with less variation. The problem of deciding where on the evidence scale we need to be to decide that we are certain enough and for what purpose, will be same as with positive evidence.

In principle, the same goes for evidence that we are alone in the universe, but due to the sheer size of the universe, the evidence value of each non-finding will be very small.

Cross-References

- Planetary Protection
- Sagan Carl

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Evo-devo

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Definition

“Evo-devo” is the term used to designate the relationship between evolution and developmental biology. It corresponds to the evolutionary developmental biology. This term “evo-devo” was created in the 1980s, after the discovery of the genes that regulate development of the animal body, notably the *Hox* gene complex.

During the last decades, the expansion, the distribution, and the changes in the embryonic expression of these genes in taxa have been associated to explain evolutionary changes in animal organization.

Evolution of Species, Islamic Ideas

Salman Hameed
Hampshire College, Amherst, MA, USA

Keywords

Evolution · The great chain of beings · Al-Jahiz · Brethren of Purity · Ibn-Miskawayh

Definition

There are few medieval Islamic scholars who speculated on the evolution of species (e.g., Al-Jahiz, Ibn-Miskawayh, and a group of writers using the pen name the Brethren of Purity). In most instances they believed in the creation of species by God and a hierarchy of God's creation from minerals, plants, and animals to humans, angels, saints, and prophets. Al-Jahiz, however, did comment on the interconnectedness of life and described an ecosystem based on the adaptation of species to local environment, but the Brethren of Purity considered adaptation as a gift from God rather than a process responding to environmental conditions.

Overview

There are diverse claims about medieval Islamic ideas on the evolution of species and there is limited scholarship available on this topic. Some of the uncertainty lies in the late nineteenth- and twentieth-century translations and interpretations of medieval works in light of Darwin's theory. Sarton (1927) and Bayrakdar (1983) made strong claims that Al-Jahiz (776–886 C.E.) in his book, *The Book of Animals* (*Kitab al-Hayawan*), came close to natural selection and some form of a theory of evolution. Egerton (2002) disputes the strong claim but attributes the origin of a detailed idea of a food chain to Al-Jahiz. According to Elshakry (2014), *The Book of Animals* was more a work of literature “written in a highly expressive

and ornate style...with its emphasis on philosophical and religious edification” rather than a zoological treatise. Al-Jahiz believed in spontaneous generation of life, but he commented on the interconnectedness of life and believed that every plant and animal had its place in the scheme designed by God. It is in this context that he described ecosystems and commented on adaptation of species, where stronger animals “feed upon weaker species than itself” and that “each animal is the food for a species that is stronger than itself” (Stott 2013). The works of Ibn-Miskawayh (940–1030 C.E.) and a group of tenth-century pseudonymous writers in Basra known as ► *Ikhwan al-Safa* (Brethren of Purity) drew on the idea of the *Great Chain of Being* that connected all life (and also minerals, with alum and vitriol being the lowest types) in a hierarchical structure, but then speculated on the possibility of transformation of species within the ladder. While apes are mentioned to be close to humans, their hierarchical structure also includes angels, saints, and prophets, thus making it hard to argue for a straightforward theory of evolution (Elshakry 2014). The *Ikhwan* are considered keen observers of the biological world, but consider adaptation as God's grace to the species rather than a process. Similarly, while they do identify some animals as intermediate species (e.g., they call the giraffe a cross between a camel and an ass), they still see these as stable forms of its kind (Goodman and McGregor 2009). Much of the uncertainty in the interpretations comes from the fact that the terms used in medieval literature are “change,” “stage,” and “transformation” and scholars have to interpret this in light of the use of “evolution” (Guessoum 2011).

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Evolution, Biological

Guillaume Lecointre and Pierre-Henri Gouyon
Département Systématique et Evolution, UMR
7138 CNRS-MNHN-UPMC-IRD, Muséum
National d'Histoire Naturelle, Paris, France

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Synonyms

[Biological evolution](#)

Definition

In Biology, evolution is the change of organisms through their variation, then transmission of these variations to their progeny (whatever the way they are transmitted), and, eventually, ► [selection](#) of some phenotypic variant in the long run as a result of environmental conditions.

History

Evolution: What's in a Word?

When speaking about evolution people can have different meanings in mind even within the field of Biology. Evolution is sometimes understood as a movie scenario, a big story to tell. Evolution is

also seen, in our imaginations, as a big tree: the tree of ► [life](#). Evolution is also more or less understood as a progress. Evolution is seen as a process by which living things do change over time. Last but not least, evolution is meant as the general theory of Biology, Palaeontology, and Anthropology. The two meanings of the word that scientists would like to retain are the last two. In the eighteenth century, evolution (from latin *evolutio*, from the verb *evolvere*) originally meant the deployment of an inner content, and was employed as we use today embryonic development. The famous geologist, Charles Lyell, used the term in the sense of transformation of ► [species](#) for the first time in the second volume of his *Principles of Geology* (1832). Herbert Spencer (1862) popularized the term in a very wide sense including transformation of species through times (Tort 1996). Charles Darwin did not use the word in the first editions of his famous book *The Origin of Species* (Darwin 1859), but did in the fifth and sixth editions.

However, in a more general context, evolution is a term used to designate a change. Evolution of the political situation of a country, evolution of the social condition of workers, evolution of the health of a patient following a treatment against a given sickness, evolution of the weather, evolution of the universe, etc., are examples of common uses of the term. The question of transferring the term “evolution” to designate precise phenomena in chemistry or astronomy is meaningless if the term is understood in that general sense of “change.” The whole physical world is, obviously, subject to change. The question becomes more interesting if, by “evolution,” a particular process of change is meant. Evolution would be “change” through heritable variation of physical entities and selection of some variants by the conditions of the environment – whether biological, chemical, or physical.

Basic Methodology

Evolution in Biology: Theory and Facts

Evolution is the general theory of Biology, Palaeontology, and Anthropology. The role of a

theory is to coordinate facts, laws, models, and hypotheses, and to maximize the global consistency of the whole. A theory explains facts and allows us to predict some yet unobserved facts. When a theory is corroborated, as highly as possible, it is still a theory. Unfortunately, scientists stop speaking about their favorite theories as “theories” when their reliability is maximal. But there’s no epistemological change to justify this. As a result the public has a kind of implicit hierarchy in mind: a theory is dubious, facts are serious. But evolution is still a good theory and its role as a theory has not changed since Darwin. Its degree of corroboration is today as high as the theory of chromosomal heredity or the theory of continental drift. Hierarchy distinguishing theories from facts is nonsense for Science in general. Theories are useful to organize facts, even to simply speak about facts. Everyone should remember that cars, planes, fridges, or phones are built according to theories and not facts. There are evolutionary facts, like fossil discoveries or DNA sequences, and at the same time there is a very good theory: evolutionary theory. A theory without facts is fantasy; facts without a theory are chaos. Such an embedment of facts within theories leads to the question of theoretical changes. If facts can only make sense through a given theory, how can we change that theory for an alternate one? Usually a given fact is evaluated within (at least) two competing theories. The parsimony of a theory is the same measurement as the coherence of facts (or global consistency): the more coherent is a set of facts the less ad hoc hypotheses we need to add to maintain the theory. This is why we prefer, among the competing theories, the most parsimonious theories. Claiming that evolution “is only a theory” is therefore meaningless for scientists.

Evolution Through Multiple Sciences

Sometimes scientists are asked to provide “evidence” for evolution. Evolution being understood as a scenario, they are expected to come back from the past with pictures and films captured with their camera. Speakers in creationist or intelligent design books, websites, or “museums” claim that scientists actually know nothing from the past.

This is not true. Two epistemological sides of evolutionary sciences must be distinguished here.

First of all, evolution is supported by many experimental proofs. Organisms with short generation times are grown in the lab (fungi, bacteria, fruit flies, etc.), variation can be measured, and, knowing parameters of selective pressures, changes of variant frequencies in populations can be measured and predicted. Famous examples of experiments in evolutionary sciences of the twentieth century involved the fruit fly *Drosophila melanogaster* or the fungi *Ascomyces*. Today, it is possible to make bacteria like *Escherichia coli* perform protein engineering just by introducing selective pressures at the lab. Hypothetico-deductive reasoning is at work: if the premises and the law (or the rule) are true, the result is true. Evolutionary mechanisms are therefore either experimented/reproduced at the lab or observed in the field, and can lead to short term predictions. However, products of evolution in the wild are contingent. Each population or each species is produced by laws of mutations, recombinations, genetic drift, and ► [natural selection](#), but the result is always historically singular and cannot be predicted in the long term. One of the reasons is that all parameters of the environment undergo changes in a contingent manner. This is why evolutionary sciences are also historical sciences.

Secondly, evolution is supported by historical proofs, which are another kind of scientific proofs. If the premises are true, the result is only probable. We have a number of signs and facts. We create a scenario that maximizes consistency of the whole set of facts, minimizing ad hoc hypotheses. This is the reasoning of historians, policemen, and phylogeneticists. The reasoning is called abductive: we infer what might have occurred in the past to explain the state of facts in the present. The scenario is made *to explain* the present facts and signs. Abduction is a “reverse deduction,” deduction being found in a situation where present facts and signs would explain the scenario. By using algorithms that maximize consistency, phylogeneticists do produce statements that can be tested, i.e., reproduced or refuted, even if the reasoning is abductive.

Key Research Findings

Evolution: Biological Processes

The general process of biological evolution is based on variation. Among a set of individuals that are able to interbreed, one can notice slight differences. In the hall of the airport, at a given time no two people have the same face. This is basically due to the fact that living matter is constantly altered. Individuals belonging to the same species are not identical, and they can differ and vary in traits that are inheritable. Indeed some of the variations can be transmitted to the offspring. These varying traits are those involved in evolution. Different versions of those traits can be present in a species. Each version is (or may be) represented by several individuals. Some individuals will have a high number of descendants, others only a few, others none at all, either because the variations influence the reproductive success (selection) or just by chance (drift). We shall now examine these two processes. When the variation does not influence the reproductive output of individuals, there is no selection. In this case, each generation represents a sampling among the hereditary diversity of the preceding one. As a result the frequency of a given version of the trait does vary with time. If the global number of individuals is small, these fluctuations can have a high effect on the relative proportions of the versions within the species. This is called a “drift” in frequencies of versions. Eventually, a given version will reach a frequency of 100% or disappear just by chance. The smaller the number of individuals that can give offspring, the faster drift is (a sample differs more from the original set when it is small). The species has thus changed. If the number of individuals is high, drift is very slow and mutations which introduce variation compensates for the loss of diversity. This process constantly maintains a number of different versions within the species – this is called polymorphism. We must keep in mind that once a version has disappeared, or once a version has reached a frequency of 100%, a new version of the same trait can appear again: life is constantly altered. For example, five centuries ago the Portuguese brought domestic mice (*Mus musculus*) to the

Madeira Islands with their ships. These islands have high mountains that separate valleys. Mice settled in the valleys in small populations, almost isolated from one another. Chromosomal changes did occur. Some of the resulting chromosomal formulae reached a frequency of 100% in one valley just by drift. Those formulae, once analyzed, show that mice from one valley cannot breed with mice from the neighboring valley anymore. Reproduction is impossible because, once fecundation has occurred, genetic material cannot be harmoniously distributed among daughter cells. Populations changed, and new species (as we conventionally limit species with obstacles in the interbreeding) appeared within the past five centuries.

Charles R. Darwin (1809–1882) introduced the notion of natural selection. Among versions of a given trait, some of them confer to the individual that bears them a certain advantage in terms of number of offspring. The version of the trait is advantageous within a certain environment. If the trait is heritable and if the environment is stable enough for a while, the version of the trait can easily reach a frequency of 100% in the species. This tendency to accumulate traits favored by a given environmental condition is called ► [adaptation](#). The process is acting on many traits at the same time, as organisms are made of multiple traits. The differential reproductive success among versions of a trait (disappearing of disadvantageous versions and increase of copies of advantageous versions) is called natural selection. Note that many versions are just neutral with regard to the environment: neither advantageous nor disadvantageous. Note that drift can fix slightly disadvantageous traits just by chance. Note that selection of a strongly advantageous trait can have side effects, i.e., be accompanied with disadvantageous consequences onto another trait. There is no “perfect” organism: natural selection is a permanent trade-off among traits that are not fully independent from each other. For instance, aggressiveness is very important among female spotted hyenas. The more aggressive they are, the more they eat, the more their daughter eats, and the higher their social rank, which is transmitted to daughters (not to sons).

Males are smaller and outside this competition. Cubs are aggressive right after their birth. They fight with each other until death. Young females keep being aggressive all through their lives. Their brain had been marked by high levels of testosterone in the very early period of their development. Indeed the placenta of spotted hyenas has enzymes that transform the circulating estradiol of the mother into testosterone that circulates in the blood of the fetus. The young maintain high levels of testosterone in utero which has the advantageous consequence of early aggressiveness, but also the disadvantageous side effect of having the female external sexual organs being deviated towards a male development. As a result adult females have a peniform clitoris, an obturated vagina, a pseudo-scrotum. They give birth through the clitoris, which is a unique case among mammals. Because of this anatomical curiosity they lose 60% of their first born progeny: the umbilical duct is shorter than the corridor they must go through, provoking the separation of the placenta before the cub is out, which sometimes dies from anoxia. This gives an example – among so many others – that organisms are far from perfect and then not “designed.”

Perfection is not a scientific notion anyway, but nested within the realm of individual values. François Jacob has compared evolution by natural selection to tinkering. Contrarily to an engineer who designs the final product he wants to achieve and produces the pieces in order to reach this goal, evolution transforms existing parts through random variation and just sorts out, through selection, those which are favored within a given context. This is as if planes had been built by transforming a car. In evolution, tinkering can be seen at work in different cases. A classic example is the feathers of birds, originally selected for their thermal properties, then used for flight. One can also cite the fact that the same organ can play the role of swim bladder in some fishes or of lungs in other animals, with some intermediate forms perhaps used at both roles. Any new form is a result of a transformation of a preceding one. The development of embryos is a complex process and minor changes in the timing or functioning of each step can have important consequences on

the shape of the future individual. These variations, occurring independently from the future needs of the organism but sorted out through the relative success (in terms of survival and reproduction) of the individuals issued from them (i.e., natural selection), explain the evolution of the shape of organisms and constitute the “evolutionary tinkering.”

Natural selection has many facets: the ways by which a given version can have a higher number of descendents are many. Let's call them modalities and let's list five of them. The *first* modality of natural selection is competition among individuals of the same species for resources (food, home). This is the first one we think about because Darwin himself emphasized the “struggle for life” in his main book, an idea coming from the simple comparison between the increase of resources and the potential increase of offspring of the species exploiting them. The second increase is exponential, the first one is arithmetic: all individuals cannot get the resources they need. In other words, the populating power of a species is by far higher than the actual state of populations: if every elephant could have all the food it needs, within a few decades Africa would be all covered with elephants. There must be a competition somewhere, leading to the fact that any inheritable version of a trait that favors the ability of individuals to get more food must have led to more offspring against versions that did not confer such an advantage. However, competition for food is by far not the only modality.

A *second* modality is competition among individuals of the same sex for sexual intercourse, called sexual selection. Any change of traits favoring sexual attraction, if heritable, must have led to more offspring and must have been rapidly spread through the species. Darwin wrote an entire book about sexual selection (Darwin 1871). It is clear that there is often a trade-off between natural selection and sexual selection. A classical example is the magnificent caudal feathers of the male of the peacock. Observations and experiments led to the conclusion that such an apparatus has a real impact on females' preferences: the bigger the feathers, the higher the chance for the male to be chosen as a sexual

partner. However, the whole bulk of caudal feathers is a very long and embarrassing burden that does not allow the male to escape rapidly from predators. Such a characteristic is thus the result of a compromise between the advantage in seducing females on one side and the disadvantage in escaping from predators in the given environment.

The *third* modality of natural selection is linked to predation. The more we escape from predation, the higher the chance to transmit our traits to the offspring. Any version of any heritable trait that favors a quick escape from predators should have been selected. Here we have the origin of mimicry. The more individuals resemble their substrate, the higher their chance of survival against predation and thus the higher the size of their expected progeny. Cryptic individuals (like the famous chameleon which can adjust its color to the substrate's one, or the stick insects which are hardly distinguishable from stems or leaves) transmit their heritable traits that favor resemblance, which must have been rapidly spread if the predation pressure was high.

A *fourth* modality is the association of species. There is a gradient of situations between parasitism (association of species with a strong disequilibrium in benefits) and mutualism (association of species with mutual benefits). Our fleas are parasites. We have no benefit in hosting them. Our mitochondria are mutualist (endo)symbionts: we could not live without them inside our cells; they could not live without us. They are actually bacteria whose ancestors got associated with eukaryotic cells more than 2000 million years ago. Almost all eukaryotes are symbiotic: they have mitochondria in their cells. ► **Symbiosis** is far more spread through life than we usually think. All plants and photosynthetic algae are symbiotic: they host mitochondria and chloroplasts (another organelle produced by bacterial endosymbiosis) in their cells. All vertebrate animals are symbiotic: we harbor a variety of bacterial species in our digestive tract and we could not live without them. Symbiosis must be understood as the association of individuals from different species having both more offspring when associated than when separated. Any change that could favor

such phenomena must have been spread through generations.

A *fifth* modality of natural selection is partnership within the species. This could explain the origin of multicellularity. Traits are transmitted to the progeny – to a wide extend – through the transmission of genetic material. Any phenotypic trait inducing a behavior which increases the transmission of the ► **genotype** coding for it will increase in frequency within a group of individuals. Consequently, it has been shown that cooperation between individuals increases with the genetic relatedness of the individuals. The different cells composing a multicellular organism are genetically identical – we all are clones from the egg from which we were issued. Thus, in sexually reproducing multicellular eukaryotes, selection has produced a developmental system in which most of our cells will not reproduce in the long run because they die with the organism (the somatic cells constituting our body) while only a small part of the individual's cells, the sexual (or germinal) cells will survive through producing offspring. From an evolutionary perspective, the fact that one cell or another within the organism produces a progeny makes no difference. Indeed, there can be competition among cells within an organism, but since only the germinal cells produce progeny, this process will not influence directly the hereditary make-up of the next generation. It can, however, be important in the determination of the success of the individuals in terms of survival or reproduction. For instance, if some cells behave independently from the others a cancer arises, with potentially immortal cell lineages but resulting in the death of the organism.

The same reasoning discussed in the above paragraph can easily explain parental care, since the hereditary traits of the parents will reproduce through the success of their progeny. It is interesting to note that in most species, the genetic relatedness between parents and offspring and between siblings is equal. Consequently, in several groups of organisms (termites, mole rats), the individuals raise their sibs instead of producing their own progeny. In some species (insects hymenoptera including bees, ants, wasps, etc.) however, the genetic relatedness is greater between

sisters than between a mother and her progeny. Hymenoptera are thus, not surprisingly, composed of a very high proportion of social species where most individuals raise their sisters and do not produce any progeny on their own. The family is thus a unit of selection as well as the individual.

Higher levels of selection also exist, but heated debates have been maintained concerning its application at the population level. One could think that populations that act in a coordinated manner better face the changes of threats of the environment than those that do not act so. Populations that protect their young can better transmit their traits to the offspring than those that do not. Populations that are more cohesive through help provided to the older or the weaker, through compassion, better face environmental changes. But theoretical models have shown that, because individuals can migrate from one population to another, this process can only act in very particular cases. Indeed, imagine a population of animals where everyone helps the others. If a migrant from a population where this trait does not exist arrives, he will benefit from the help without paying the cost of helping the others. This issue is still debated.

Selection at the family level or at higher levels can be considered as providing an insight into the natural origin of love, mutual help, compassion, and moral rules, given that such behaviors are transmitted to the next generation, whatever the nature of the transmission. Although it is too often forgotten, Darwin also wrote almost an entire book (Darwin 1871) about this topic. The ways by which our versions of our traits can be better spread through generations are diverse and we should not reduce natural selection to a “struggle for life” understood as a competition among individuals. This probably does not reflect the main factors by which natural selection plays, and this surely does not reflect the richness of Darwin’s thinking and contemporary evolutionary thought.

When considering a structure in an organism, we must be careful when evoking adaptation right away. Indeed organisms as wholes are compromises among traits. All traits are not under the same selective regime and “conflicts” occur. As discussed above, there is no “optimal organism”

to be understood as “perfect organism.” Perfection is not a scientific concept. Above all, the trait considered may not be present for direct selective reasons, but the by-product of a selection of another trait of the same organism (see above). The side effect is obtained through chemical or physical constraints of organism construction as consequences of a selection at another level or trait. But there is another reason for adaptation and side effects for a trait to be present: history. A trait can be present as heritage or “frozen accident” that has never been counter-selected. The pathway of our phrenic nerve is an example. That nerve connects the diaphragm to our spinal cord. The pathway is not the shortest possible. It passes through the thoracic cage, the neck and connects the spinal cord at the level of the first cervical vertebra. This long nerve is sometimes irritated, provoking hiccup. That pathway is a heritage of the ancient times, similar to the pathway of the homologous nerve in teleosts (modern fish) that starts under the skull and innervates some muscular blocks of the branchial basket situated just underneath. With the rise of tetrapods (animals with limbs) some 360 Ma ago, the neck separated the muscular blocks from the skull and throughout evolution the length of the nerve increased. It is easy to understand that the position where the nerve is getting inserted in the spinal cord is more anatomically constrained than the progressive lengthening of the nerve as the muscular block it serves is getting farther from the neck. The result is far from optimal but the interaction between selection and historical constraints have made it that way; one of the effects of the above cited “evolutionary tinkering.”

Evolution: Structures and History

The processes described above explain why generations flow and change through time. That flow of generations is genealogy. A genealogy is a network exhibiting ancestor-descendant relationships between individuals. In the theoretical scheme those relationships are among virtual individuals. In the empirical field those relationships are not accessible – except in the framework of a few generations – because ancestors have definitively disappeared. That flow of generations is

sometimes interrupted by extinctions, sometimes divided by obstacles. Obstacles can be mountains (case of the domestic mice in the Madeira Islands), chromosomal changes, pheromone changes, behavioral changes, etc. For a while, members of the genealogy of each part cannot meet and give rise to offspring. If the obstacle stays for long enough, alterations are going to produce divergence. Divergence can be strong enough to lead, sooner or later, to the impossibility for the two sets to give rise again to offspring. The genealogy is a continuous flow of changing individuals through times; at a small scale it is a network but at a larger scale there are diverging branches (we will see later on that there can be connections among those branches under certain circumstances). Now we have to manage another problem: we cannot speak about living things by giving a surname to each individual we meet. We need names at wider scales. We use these branches to give names to sets of individuals that are able together to give rise to offspring. These sets are called species. The “concept” of species is more complex than it seems and an important literature has been produced concerning it. Species has a definition: by convention, a species is a set of individuals collectively able to give rise to offspring, delimited from one point of divergence in the genealogy to the next point of divergence. In other words, a species is an inter-node in the theoretical genealogical tree of life. A species seems to be real in synchrony but is just conventional in diachrony (i.e., considered through a significant time span): today we know that cats do not make babies with dogs, but by considering the depth of times the theoretical genealogy does connect them and an arbitrary limit must be set somewhere. Species is therefore defined as a convention of language mapped onto a theoretical genealogical continuum. Note that branches or the tree of life can go extinct, or expand by producing new branches. There is thus a selection at this level, but it can only act by sorting out those lineages which do possess characteristics making them sustainable. These characteristics result from the processes described above. Natural selection in its usual sense is about the relative success of a given variation possessed by

individuals, not about the relative success of species. Natural selection can thus be seen as producing “locally optimal” organisms in terms of survival, or reproduction, or of transmission of their hereditary material, not in terms of survival of the species.

Species definition should not be confused with criteria of assignment – both having been too often confused into the single term of “species concept.” When we find an individual organism and we do not know *what it is*, we have criteria to assign the individual to an already known species: similarity (most often), interbreeding, and fertile offspring. Note that sex, seen as gene exchange between two individuals, exists in all groups of organisms including Bacteria and Archaea so that, even if the concept is less clear in some groups, it is still possible to recognize lineages which can, or cannot, mix their hereditary material.

Today we see sets of living beings that are separated by the impossibility of producing offspring: in the history of biology species have often been considered as real. The general theory predicts that we must consider in the deep times that these sets are connected to each other: their members do not produce offspring together but they should have done it in the past. This will be useful to reconstruct degrees of kinship among a given set of individuals. A cat has hair and a dog has hair. Why do they have hair? Is it because they live here under this climate? No: the white bear and the giraffe have hair and they do not live here. Do they have hair because they produce offspring together? No: everyone knows that dogs and cats, together, do not produce offspring. But there has been a time when they did it. The answer is in the past. Hair must have been inherited from common ancestors. By comparing organs, shape, metabolism, DNA sequences, whatever feature that can be recognized as *the same* in several individuals of different species, it can be interpreted as a sign of common ancestry. By comparing many features, a tree can be reconstructed, showing degrees in sharing features. Such a tree shows “who shares what with whom.” It is not a genealogy because there are no ancestor-descendant relationships. When such a tree is read with the theory of evolution in mind,

it becomes a ► **phylogeny**, a tree expressing “who is more closely related to who than others.”

A phylogeny does not express ancestor-descendant relationships between the actual individuals we have at hand, but expresses relative degrees of relationships among them. There can be ancestors in a phylogeny, but they are virtual. This is also true for fossils. Within a phylogeny, fossils of extinct species are treated like we treat extant species. They are just a collection of features gathered in a past organism. Fossils are at the tip of branches just like extant organisms. A given fossil can be the ancestor of some part of today's ► **biodiversity**, but we have no empirical mean to approach that kind of relationships. Modern phylogeny is not practiced anymore in terms of “who is descending from whom” but in terms of “who is closely related to whom,” which is more empirically powerful. Phylogenies are used in a wide variety of scientific investigations. Among them are classifications in natural history. Classifications are conventional and classification is the construction of a concept under the form of a virtual box. Here outside there is no “bird.” Here outside there are only individuals. “Bird” is a name associated with a box in my mind, gathering millions of individuals, themselves being gathered in some 10,000 species (themselves gathered in hundreds of genera, etc.). There are reasons why we created that box: a classification reflects properties of organisms we decided to point out. Did we decide to put all these species in a same box because they are good to eat? Because they are beautiful? Because they do the same things in their environment? Because they share the same features? A “good” or “efficient” classification is the one that is self-consistent, i.e., that is successful in organizing things according to the criteria we set. Today, systematists classify living organisms together because they do share features in common. The feature must define the group and must not be present at the same time outside the group. Because sharing features among species is interpreted by the theory of evolution as common ancestry, our classifications by shared features will be naturally extracted from phylogenies. A virtual “box” or “group” containing real organisms is a taxon. By mapping our boxes onto nodes

of a phylogeny, we produce complete taxa, i.e., taxa that contain one ancestor and all its known descendants. This is what we call monophyletic groups. In modern systematics – science of classifications – classification of organisms is related to the theory of evolution by the fact that the only valid groups are monophyletic groups.

The “tree of life” is a genealogical metaphor. We will never have the full genealogy of life, just because ancestors have disappeared. But a theoretical scheme of genealogy is required by scientific evolutionary thinking. The shape of that theoretical tree is changing. Divergences of branches are best constrained for most of the animals; however for other eukaryotes, bacteria, or archaea there can be exchange of material among well separated branches of the genealogy. They are horizontal (also called lateral) transfers of genetic material. In bacteria it can be so powerful that we are not sure that the shape of the tree is still the best scheme as a theoretical framework. Another phenomenon we must be careful about is multiple symbioses. When partners of a symbiosis are associated together for long enough, phylogenies reconstructed from each partner are expected to be the same. This is why we use mitochondrial DNA to trace the phylogeny of eukaryotes. But when associations are recent, genetic traces of kinship can be different for each of the partners.

Applications

Evolution Exported

The discovery and understanding of evolution has had a number of consequences in the thought of our societies. It has changed the perception of the world in many respects, influenced a number of different scientific fields, and even been at the origin of new technologies. The fields where evolution was exported are of two kinds. The first one is philosophical and sociological, i.e., outside scientific activity *sensu stricto*. It concerns philosophy, eugenics, and social Darwinism. The second field is purely scientific: evolutionary thought was exported into already developed scientific fields where it was initially absent. This concerns evolutionary psychology, Darwinian medicine,

cellular Darwinism, biochemistry, neural Darwinism, and genetic algorithms in computer sciences. It would be too long to develop these fields here but it is certainly necessary to give some insights into some of them.

From a philosophical point of view, once it is recognized that all living organisms are the result of a natural process, the perception of Nature (including human nature) is profoundly influenced. One of the major changes is that the fact that something exists does not anymore indicate that it is good (because it is the will of the Creator). The “Natural theology,” developed before Darwin (and which he was extensively taught), loses its justification. As Thomas Huxley (zoologist, friend of Darwin) stated, “Nature is neither moral nor immoral, but non-moral.” At first sight, there are thus no moral rules to be found in nature. However, since we are issued from an evolutionary process, the sense of justice, equity, and help could have something to do with the way the human lineage has evolved: there is a natural origin of our moral rules, a fact that is perceived as contradicting their presumably transcendental origin. Philosophical debates about these points have been going on for a century and a half and we shall not enter them here. Science is a collective activity whose first aim is just to rationally explain phenomena and objects of the real world. As such it has no program to contradict or confirm any theological or moral statement.

From a social point of view, the Darwinian theory, when fused with ► [genetics](#) under the name “NeoDarwinism,” was first applied to the human species. In the dark years following the 1929 economic crisis, the idea that the wonderful social and intellectual qualities or the “race” were due to natural selection led the scientific community to declare that there was a danger of degeneration due to the social laws adopted during the nineteenth century. The mix of political, sociological, and scientific considerations led to the birth of an applied science: eugenics. It developed and was strongly supported by the scientific community. In the USA and in Scandinavian countries, thousands of people were sterilized in order to prevent their genes from spreading. The Nazi

government in Germany used this theory to sterilize hundreds of thousands of people. These practices disappeared more or less slowly after Nuremberg. Another social application was more economic, it was called “social Darwinism” in 1880 by Emile Gautier, a French journalist referring to the political philosophy of Herbert Spencer. It proposed the idea that the social system should respect the principle of selection and let the best succeed and the others remain desperately poor in order to respect the laws of nature. Note that, among the various modalities mentioned above by which natural selection can play, Spencer considered only inter-individual competition. This theory is still supported among the theoreticians of neo-liberal economy. Darwin himself never took a position in favor of Spencer’s ideas. Indeed, Darwin’s personal writings show that his political ideas were rather different. On the left side of the political continuum, Kropotkin (1902) also referred to Darwin’s scientific writings when he tried to justify the naturalness of mutual help in human societies. It is important to point out that in either case we have an ideological work at play, picking up into science what is interesting for socio-political purposes. These intellectual by-products are not born by the sole will of the scientific community trying to explain the natural world.

On a more positive side, in the second category of fields that have imported the idea of evolution, the modern theory of evolution can help us understand psychology and the health questions in humans; this has led to the development of evolutionary medicine and psychology. Moreover, the Darwinian concept of variation selection has been imported into robotics, evolutionary algorithms, protein engineering, linguistics, biochemistry, neurosciences, cellular biology, etc. Such fecundity leads to the question of whether, outside its initial field, the use of the word “evolution” should be restricted to the process of variation of entities and selection by their environment, or the word should still be used in the wider vernacular sense of “a story to tell about change.” In the second sense there is no doubt that the word “evolution” can be used to mean the change of our Universe and all objects it contains from

galaxies to isolated molecules. In the first – more restrictive sense – applying the word evolution in the field of astronomy implies the identification of extraterrestrial objects susceptible to variation and the transfer of structure to similar entities, a transfer subject to environmental conditions. Thus, this process has not been used to describe the change of most of the large-scale objects we find in the Universe. However the word “evolution” has been used to describe changes in macromolecules that could be present in meteorites or planets, like amino acids or nucleotide polymers. Biological macromolecules were, whatever the ways by which they transfer their variations in sequence or conformation to others, probably the very first step of (precellular) evolution in the restrictive sense. As at least small precursors of the macromolecules are present in our extraterrestrial Universe, “evolution” is a rightful and suggestive concept in astrobiology.

Evolution Everyday

Evolution is not only a matter of fossils or DNA sequences. Evolution is needed to feed the entire human kind. There would be no agriculture without evolution. Artificial selection helped us to survive by domesticating various animals and plants. Often, one species has yielded very different varieties. The sole species *Brassica oleracea* yielded cabbage, broccoli, cauliflower, Brussels sprouts, and flowering kale. The different breeds of dogs (the species *Canis lupus familiaris*) differ much more in morphology and behavior than do other mammalian species. This is also evolution: just artificial selection among variants that humans used to produce differential demographic success in their offspring.

Evolution shapes medicine. A well-known example is the rapid spread of antibiotic resistance among different strains or species of bacteria by ► [lateral gene transfer](#). It is produced by the interchange of fragments of DNA (called plasmids) coding for proteins, able to degrade an antibiotic used in the clinical setting. The plasmid that confers the antibiotic-resistant ► [phenotype](#) in the recipient bacteria will be inherited by the progeny, allowing the resistant cells to evolve in the presence of such a selective

pressure. A second example: when people infected by the human immunodeficiency ► [virus](#) (HIV) are treated with antiviral drugs, the population of viruses that infects them evolves multiple amino acid substitutions that confer drug resistance in few months. As a consequence of HIV evolution, the antiviral drug combination must be changed.

Usually, evolution is not directly accessible to our senses, since large animals have long generation times and require very long periods to exhibit spectacular changes or speciation events. In turn, organisms with very short generation times, such as *Escherichia coli* and other bacteria, evolve very fast but we cannot see them with our sole eyes. Nevertheless, the evolution of fast-growing viruses or bacteria is easily monitored in the lab. Additionally, thanks to the advances in molecular biology, in vitro evolution is currently used to mimic and speed up the evolutionary processes at the molecular level.

Last but not least, evolution does not mean nor justify anything in terms of political or moral issues. Evolution is just the scientific approach to understand the origin of living beings and their changes through time. The approach uses amoral procedures, and our moral considerations do not have to be transferred to the living world (and reciprocally). Each time that such a transfer occurred along the history of our evolutionary sciences, it was a source of obstacles. Moral and political issues must be managed in the philosophical and political realms that surround scientific activity. They can give directions to research; however, scientific reasoning itself must stay out of these constraints.

Cross-References

- [Adaptation](#)
- [Biodiversity](#)
- [Cell](#)
- [Darwin's Conception of the Origins of Life](#)
- [Earth's Atmosphere, History of the Origins](#)
- [Evolution, In Vitro](#)
- [Fitness](#)

- [Genetics](#)
- [Genotype](#)
- [Lateral Gene Transfer](#)
- [Life](#)
- [Multicellular Organisms](#)
- [Mutation](#)
- [Natural Selection](#)
- [Phenotype](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Selection](#)
- [Species](#)
- [Symbiosis](#)
- [Taxonomy](#)
- [Virus](#)

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Evolution, Chemical

André Brack
Centre de Biophysique Moléculaire CNRS,
Orléans Cedex 2, France

Keywords

Autotrophic life · Cellular world · Primitive life · Primordial soup · RNA world

Synonyms

[Prebiotic chemistry](#)

Definition

Chemical evolution refers to the suite of natural reactions that led to the first living systems from abiotically synthesized molecules on the primitive Earth. Since this was a historical process and we have no relics of the compounds formed in this process, chemists can only model chemical evolution by running experiments, chemical reconstructions also known as prebiotic chemistry.

Overview

Although primitive life is generally believed to have been organic, that is, based on ► [carbon chemistry](#), the precise sequence of steps that allowed for the formation of living systems from abiotic chemistry remains poorly constrained and somewhat speculative. Chemical evolution is the study of the processes that led from simple molecules to biochemistry.

There are presently numerous scenarios for this process which scientists consider plausible. Among them is the idea of a genetic mineral material presenting suitable properties such as the ability to store and replicate information (Cairns-Smith 1982). Another hypothesis favors a heterotrophic origin of life in a ► [“primordial soup”](#), involving self-assembling, preformed carbon-based molecules. An autotrophic origin of life via direct reduction of carbon oxides in a “metabolism-first” scenario has also been proposed (Wächtershäuser 2007).

While it is clear that all contemporary life shares a common heritage, it is possible that there were earlier, more primitive states that life evolved through which might have borne little resemblance to modern biochemistry. Some believe that primitive life emerged as a cell-like system requiring at least pre-RNA molecules capable of storing and transferring the information needed for reproduction, pre-enzymes providing

the basic chemical work, and pre-membranes able to isolate the system from the aqueous environment. Since RNA has been shown to be able to act as an information molecule and also as a catalytic molecule, RNA has been considered as a candidate for the first living system that preceded the cellular world. The spontaneous organization of amphiphilic molecules to form vesicles has also been postulated as the first step toward the origin of life (Morowitz 1992). Chemists are also tempted to consider that primitive self-replicating systems depended on simple autocatalytic molecules adsorbed on solid surfaces, which could solve some of the problems of the likely high dilution of organics in the primitive oceans.

Cross-References

- [Abiotic](#)
- [Carbon](#)
- [Earth's Atmosphere, History of the Origins](#)
- [Origin of Life](#)
- [Prebiotic Chemistry](#)
- [Primordial Soup](#)
- [RNA World](#)

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Evolution, In Vitro

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

Amplification · Aptamer · Combinatorial nucleic acid library · Deoxyribozyme ·

Evolution · Molecular evolution · Mutation · Ribozyme · RNA world · Selection · SELEX®

Synonyms

[Artificial evolution](#); [Directed evolution](#); [Experimental evolution](#); [In vitro evolution](#)

Definition

In vitro evolution is an experimental method that allows the screening of large random-sequence libraries of nucleic acids – ► [RNA](#) or ► [DNA](#) – for a specific function, such as catalysis or binding. In vitro evolution experiments have led to the selection of novel or improved RNA enzymes, called ► [ribozymes](#), as well as artificial DNA enzymes – DNAzymes or deoxyribozymes – and target-binding nucleic acid molecules, ► [aptamers](#). The iterative in vitro process involves serial cycles of amplification and selection of the functional nucleic acid until the desired activity is reached. The outcome of directed evolution can be monitored through the analysis of the genotype and phenotype of the evolved molecules.

History

The first experiments aimed at determining if Darwinian evolution was possible in cell-free systems involved the in vitro replication of the RNA genome of the bacteriophage Q β – a ► [virus](#) that infects *Escherichia coli* – by the viral RNA replicase protein. Serial dilution experiments allowed the transfer of an aliquot of the replication mixture into a new reaction tube containing fresh enzyme and RNA monomers. The inherent mutation rate of the viral polymerase ensured genetic variation during the experiment, and the ► [phenotype](#) under selective pressure was the replication speed of the RNA genome. After several serial transfers, the Q β genome evolved by deleting sequences not required for its recognition by the polymerase, thus shortening the replication time (Mills et al. 1967).

A quarter century later, the availability of reverse transcriptase enzyme – RT, which catalyzes the conversion of RNA into DNA – and PCR technology, as well as the possibility to chemically synthesize nucleic acid pools of random sequence, opened a new era in in vitro evolution experiments. This field was also reinforced by the discovery of natural ► [ribozymes](#), what underlined the functional capabilities of RNA and its hypothesized key role in pre-cellular evolution. By 1990, directed evolution allowed the – artificial – selection of functional RNA molecules from random pools in two independent experiments that used the ability of RNA to bind a target molecule as the selective pressure. The stepwise process of amplification-selection was termed “Systematic Evolution of Ligands by Exponential Enrichment” or SELEX (Tuerk and Gold [1990](#)), and the term “aptamer” was coined to denote the in vitro evolved, target-binding RNA (Ellington and Szostak [1990](#)).

The next milestone in experimental cell-free evolution was the development of a system for continuous in vitro evolution of nucleic acids. In contrast to stepwise in vitro evolution, it combined the processes of selection, amplification, and genetic diversification within the same reaction mixture, thus allowing the continuous directed evolution of ribozymes (Wright and Joyce [1997](#)). In parallel, a new method termed “mRNA display” was set up for the in vitro selection of peptides and proteins (Roberts and Szostak [1997](#)).

Overview

The starting point of a stepwise in vitro evolution experiment is a large pool of nucleic acid molecules, in general, 10^{12} – 10^{16} , with a central region of random or mutagenized sequence, usually 20–100 nt long, flanked by two primer-binding sites of defined sequence. The successive amplification-selection rounds increase the ratio of active:inactive RNA – or DNA – and the pool finally becomes dominated by molecules with the desired ► [phenotype](#). Within each round, RNA amplification involves successive steps of reverse

transcription, PCR amplification, and ► [transcription](#). ► [Selection](#) is introduced by choosing for the next round only the nucleic acid molecules able to bind the target – aptamers – or to perform the desired activity – ribozymes – while non-functional molecules within the pool are discarded. The whole cell-free process occurs in vitro, and all the experimental variables can be controlled and fine-tuned. In vitro evolution can be distinguished from in vitro selection in that the former includes a continuous introduction of genetic variation in the molecular population, through mutation – usually, by error-prone PCR – and/or recombination (Wilson and Szostak [1999](#); Joyce [2004](#)).

In vitro evolution and in vitro selection have been used to obtain artificial nucleic acid enzymes and to engineer natural ribozymes to expand or improve their current functionality. The unveiled functional plasticity of RNA has increased the plausibility of the ► [RNA World](#) hypothesis for the origin and early evolution of life (Joyce and Orgel [2006](#)). In parallel, directed evolution of nucleic acids has generated new families of aptamers with diagnostic and therapeutic applications (Klussmann [2006](#)). Microfluidic chip technology and computer-assisted control have been incorporated to the biochemical process in order to automate the system and to monitor in real time the population size, its composition, and the performance of the evolved molecules (Paegel and Joyce [2008](#)).

Cross-References

- [Aptamer](#)
- [DNA](#)
- [Evolution, Biological](#)
- [Evolution, Molecular](#)
- [Genotype](#)
- [Phenotype](#)
- [Polymerase Chain Reaction](#)
- [Quasispecies](#)
- [Ribozyme](#)
- [RNA](#)
- [RNA World](#)
- [Selection](#)

- [Transcription](#)
- [Virus](#)

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Evolution, Molecular

Peter Schuster

Institut für Theoretische Chemie der Universität
Wien, Wien, Austria

Keywords

Adaptive evolution · Applied molecular evolution · Error threshold · Evolutionary biotechnology · Genome · Genotype · Neutral evolution · Phenotype · Phylogenetics · Quasispecies · SELEX[®]

Synonyms

[Directed evolution](#); [Molecular phylogenetics](#)

Definition

Molecular evolution deals with the application of knowledge from biophysics, biochemistry, and molecular biology to biological evolution with the focus on understanding evolutionary phenomena at the molecular level. Two branches of molecular evolution are established fields of research: (1) reconstruction of phylogenetic trees by comparing genomic DNA sequences and (2) modeling evolution in vitro and in silico (i.e., by computer simulation), using simple models like populations of RNA molecules, simple viruses, or bacteria.

History

Molecular evolution originated from the vision of an evolutionary molecular clock by Linus Pauling and Emile Zuckerkandl in 1962 (Morgan 1998). Reconstruction of phylogenetic or evolutionary trees by comparison of biomolecular sequences became an established method through the works of Walter Fitch, Emanuel Margoliash, and Margaret Dayhoff in the 1960s, and the evolutionary clock (Kumar 2005) became an established tool in evolution research for dating speciation events. In vitro evolution of RNA molecules from bacteriophages was initiated by Sol Spiegelman in the 1960s (Spiegelman 1971). He showed that Darwinian evolution occurs in cell-free systems. At the same time, Manfred Eigen developed a kinetic theory of evolution at the molecular level (Eigen 1971). Since 20 years, molecular evolution has been applied to the evolutionary design of molecules with predefined properties and given rise to a new branch of biotechnology.

Overview

Evolution is based on the interplay of reproduction (providing the basis for inheritance, either by variation or ► [mutation](#) as a result of imperfect copying or recombination of genetic modules) and selection (choosing from the phenotypes present in the population). Insights into the molecular

machinery of life reveal the specific chemistry of reproduction initiated by replication of a nucleic acid molecule – DNA, or rarely RNA – which carries the genetic information in the form of a one-dimensional string of digits. Mutation occurs in three different forms: (1) single nucleotide incorporation errors commonly called point mutations, (2) insertions, when a part of the sequence is copied twice or several times, and (3) deletions, when a part of the sequence is missing in the copy. The unfolding of the genetic information, the ► **genotype**, or the genome, yielding the ► **phenotype**, is the key to understanding evolution, because it creates the repertoire upon which selection operates. The genotype-phenotype map is the source of complexity and varies from sequence-structure relations for in vitro evolution of molecules to the entire process of development leading from the fertilized egg to the adult organism in case of higher organisms.

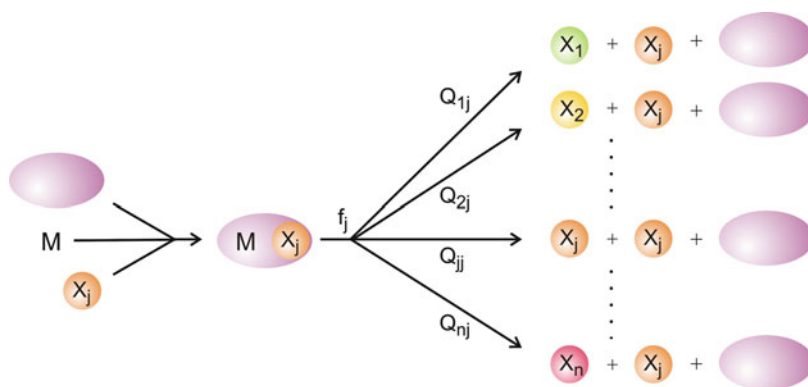
Every organism carries information on its own history in the form of the DNA or RNA sequence that originates through mutation events. Molecular phylogenetics reconstructs the tree of life from present-day sequences of species (Graur and Li 2000) in which the proper alignment of sequences is an important part of the procedure (Mount

2004). Comparing sequences from vertebrates reveals the molecular clock of evolution (Morgan 1998; Kumar 2005; Takahata 2007), which implies that the number of single point mutations per nucleotide site and time is approximately constant for a given protein molecule. Further investigations have shown substantial vagaries of the clock, but in the age of genomics, the molecular clock turned out to be a valuable device for dating historical events. The last 40 years have seen a heavy debate between selectionists and neutralists about the role of mutations that have no influence on the ► **fitness** values of their carriers. Data on the evolution of entire genomes are ending this controversy through the discovery of new mechanisms dominating genome evolution (Nei 2005).

In the language of chemical kinetics, the evolution of molecules through correct replication and mutation under controlled conditions (Fig. 1) is cast into a first-order differential equation:

$$\frac{dx_j}{dt} = \sum_{i=1}^n Q_{ji} f_i x_i - x_j \varphi(t) \quad \text{with} \quad (1)$$

$$\varphi(t) = \sum_{i=1}^n f_i x_i \quad \text{and} \quad \sum_{i=1}^n x_i = 1.$$



Evolution, Molecular, Fig. 1 An example of a reaction mechanism for replication and mutation according to Eq. 1. An enzyme binds the template molecule (X_j) and the building blocks for polynucleotide synthesis (M). Correct replication and mutation are parallel chemical reactions with a rate parameter f_j , individual reaction channels lead to correct replication with frequency Q_{jj} and to a variety of

mutants with frequency Q_{ji} with $i \neq j$. Stable inheritance requires $Q_{jj} > Q_{ji}$ and sufficiently large (see the error-threshold shown in Fig. 2). Since every replication product is either correct or a mutant, a conservation relation $\sum_i Q_{ji} = 1$ holds. After the replication is completed both polynucleotide molecules, template and copy, are released from the enzyme, which is free for the next replication round

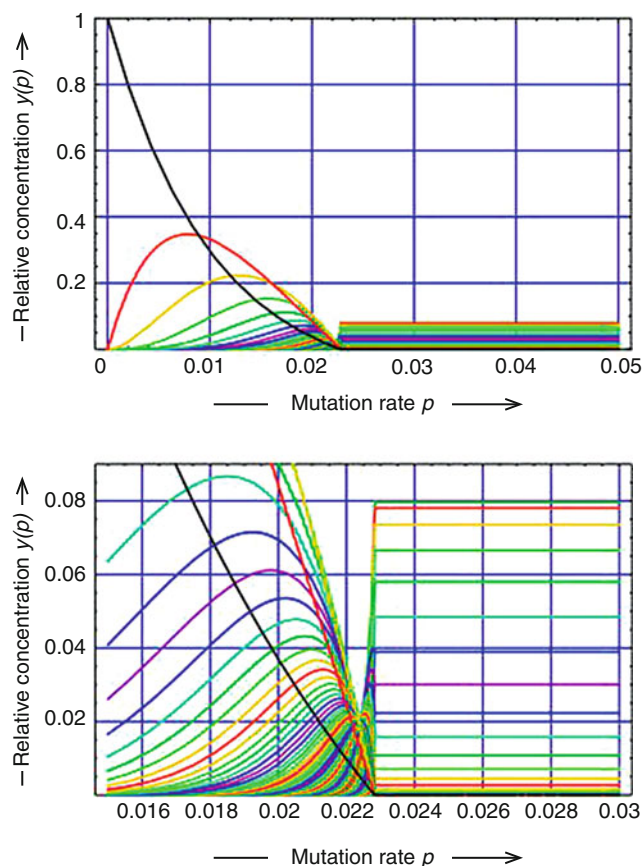
This equation describes the changes in genotype distribution of a population that consists of n different genotypes $X_1, X_2, \dots, X_n$. The variables are relative concentrations: $x_j = N_j / \sum_{i=1}^n N_i$ with $N_i = [X_i]$ being the number of molecules of type X_i . The parameters in Eq. 1 are (1) the replication rate parameters or fitness values for the individual genotypes, f_i , and (2) the mutation frequencies, Q_{ji} representing the frequency at which X_j is obtained as an error copy of the template X_i . The first term in Eq. 1 describes the production of X_j either as a correct copy, $Q_{jj}f_jx_j$, or as an error copy from another genotype X_i , $\sum_{i=1, i \neq j}^n Q_{ji} f_i x_i$. The second term, $\varphi(t)$, is a flux compensating for the excess production of genotypes. Mathematical analysis of the solutions of Eq. 1, which are obtained by integrating factor transformation and solution of an $n \times n$ eigenvalue problem (Eigen et al. 1989), yields two results that are relevant for biology:

1. The long time or stationary solution is given by the largest eigenvector ξ_0 of the matrix $W = QF$, where $Q = \{Q_{ij}; i, j = 1, \dots, n\}$ and $F = \{F_{ij} = f_i \delta_{ij}; i, j = 1, \dots, n\}$, the diagonal matrix of fitness values (δ_{ij} is Kronecker's symbol, $\delta_{ij} = 1$ if and only if $i = j$ and 0 otherwise). All elements of ξ_0 are positive by Perron-Frobenius theorem and hence no genotype will vanish. The largest eigenvalue λ_0 is nondegenerate and hence the result of the mutation selection process is unique. No matter what the initial conditions were, the population will converge toward a unique distribution of genotypes called *quasispecies* (Eigen and Schuster 1979), which consists of a fittest genotype, the *master sequence* X_m , and its mutant cloud.
2. Consideration of quasispecies as a function of the mutation rate p , $\xi_0(p)$, reveals a critical mutation rate p_{cr} at which the genotype distribution changes abruptly from the quasispecies centered around the master sequence into the uniform distribution (Fig. 2). Neglecting mutational backflow from mutants to the master sequence, the critical mutation rate is obtained as

$$\begin{aligned} p_{cr} &= 1 - \sigma_m^{-1/\ell} \quad \text{with} \\ \sigma_m &= \frac{f_m}{\bar{f}_{-m}} \quad \text{and} \\ \bar{f}_{-m} &= \frac{1}{1 - x_m} \sum_{i=1, i \neq m}^n f_i x_i \end{aligned} \quad (2)$$

In this equation, the chain length of the genotype is denoted by ℓ , x_m is the relative concentration of the master sequence, σ_m is the superiority of the master sequence, and $\bar{f}_{-m}$ is the mean fitness of the population except the master sequence. Equation 2 has two important consequences: It defines (1) a maximal chain length for constant replication accuracy $(1 - p)$, $\ell_{\max} \approx \ln \sigma_m / p$, and (2) a maximal error rate for constant chain length ℓ , $p_{\max} \approx \ln \sigma_m / \ell$. Both limitations have immediate consequences in biology: (1) In classes of organisms, the spontaneous mutation rates determined by the accuracy of the replication mechanism are inversely proportional to genome lengths (Drake et al. 1998; Gago et al. 2009), and (2) for RNA virus replication, which occurs at mutation rates as close to the error threshold as possible in order to guarantee maximal variability in fighting the defense system of the host, a drug-induced increase of the mutation rate can drive the population into extinction (lethal mutagenesis; Domingo et al. 2008).

Molecular evolution experiments starting with the seminal work of Sol Spiegelman (Spiegelman 1971) and continued by Christof Biebricher, Jack Szostak, Gerald Joyce, and others (Watts and Schwarz 1997; Joyce 2004, 2007) represent experimental realizations of the theory. Evolution experiments under controlled conditions were also carried out with bacteria, and radical innovations induced by mutations were interpreted successfully at the molecule level (Blount et al. 2008). The molecular approach to evolution is completed by introducing a relation between genotypes and phenotypes in the form of a mapping or fitness landscape, which in the simplest system, in vitro evolution of RNA, deals with RNA sequences and structures (Schuster 2003, 2006). Evolutionary phenomena, for example,



Evolution, Molecular, Fig. 2 The accuracy limit for replication. The two plots show solution curves of Eq. 1 as functions of the mutation rate p . In order to illustrate the phase transition-like change in the mutant distribution at the error threshold (2) the relative concentration of error classes $y_k(p)$ are plotted against p : $y_0(p)$ represents the concentration of the master sequence, $y_1(p)$ is the sum of the concentrations of all one-error mutants, $y_2(p)$ is the sum of the concentrations of all two-error mutants, $y_3(p)$ is

the sum of the concentrations of all three-error mutants, etc., and in general $y_k(p)$ is the sum of the concentrations of all k -error mutants. At the error-threshold the quasispecies changes abruptly into the uniform distribution, and the concentrations of the mutant classes become equal to the binomial coefficients. The lower part of the figure represents an enlargement of the curves around the error-threshold. Parameters used in the calculations: chain length $\ell = 100$, fitness values $f_0 = 10, f_n = 1$ for all $n \neq 0$

the existence of error thresholds, are highly sensitive to the fitness landscape and commonly applied. Oversimplified models based on the unrealistic assumptions that mutations contribute to fitness additively or in a multiplicative way give wrong results (Phillipson and Schuster 2009). Neutrality is a fundamental property of realistic fitness landscape, and neutral evolution (Kimura 1983) in parts of the sequence space is indispensable for the success of the Darwinian mechanism (Schuster 2006).

Molecular kinetics of evolution and most of population genetics are based on modeling by means of differential equations. The limitations of this approach primarily come from small particle numbers – every mutant has to start from a single copy; uniform distributions are completely unrealistic since there are orders of magnitude less molecules in the population than possible genotypes. Proper stochastic treatments and computer simulations were performed, but a universal model of finite population size effects in evolution is not at hand.

Basic Methodology

The methodology of molecular evolution is shared with molecular genetics, genome research, population genetics, bioinformatics, and biochemical kinetics. Specific developments concern the construction of special flow reactors and other equipment for evolutionary biotechnology (Watts and Schwarz 1997).

Key Research Findings

The phylogenetic tree of conventional biology has been approved independently by molecular phylogenetics. The molecular clock of evolution yields a genetic measure of time. In vitro evolution has provided evidence that Darwinian evolution does not require reproduction at the cellular level. Quasispecies theory and existence of error thresholds for replication provide a solid theoretical basis for virus evolution at the molecular level.

Applications

In vitro evolution of molecules was applied to the design of molecules with predefined properties in biotechnology and became a popular tool for systematic evolution of ligands by exponential enrichment (SELEX[®], which is a registered trademark of the company Gilead Sciences, Foster City, CA). Examples are the evolutionary design of nucleic acid molecules (Joyce 2004; Klusmann 2006), proteins (Brakmann and Johnsson 2002; Jäckel et al. 2008), and synthetic compounds (Wrenn and Harbury 2007). Quasispecies theory and the concept of error propagation in successive replication gave rise to new antiviral strategies known as lethal mutagenesis (Domingo et al. 2008). Together with rational design, evolutionary biotechnology represents a core technique of synthetic biology.

Future Directions

The promising and challenging future program for molecular evolution is the integration of data from genomics and systems biology into the currently

used methods. Whereas phylogenetics on the whole genome level is more or less solved, upscaling of modeling evolution from RNA molecules and viruses to cells and organisms will require new experimental and computational tools. Learning how genotypes are mapped into phenotypes represents the key for understanding evolution at the molecular level.

Cross-References

- [Evolution, Biological](#)
- [Evolution, In Vitro](#)
- [Fitness](#)
- [Flow Reactor](#)
- [Genotype](#)
- [Hypercycle](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Phenotype](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Quasispecies](#)
- [Replication \(Genetics\)](#)

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Evolutionary Sequence of Young Stellar Objects

- [Spectral Classification of Embedded Stars](#)

Evolutionary Tree

- [Enantiomeric Excess](#)
- [Phylogenetic Tree](#)

Exergonic

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

The term exergonic refers to a chemical reaction that releases free energy as it proceeds. An exergonic reaction may also be ► [exothermic](#), but does not need to be (see ► [entropy](#)). An example of exergonic reaction is gasoline ► [oxidation](#) in the Earth's atmosphere; burning gasoline releases sufficient free energy (work) to propel a car.

It is important to make a clear distinction between thermodynamics and kinetics. A spontaneous reaction can be characterized by a rate so small that no change can be observed, as is the case with gasoline in the presence of oxygen at normal temperature. A temperature increase by a flame or spark is sufficient to initiate a combustion reaction which, being not only exergonic but also exothermic, then proceeds without any additional supply of heat. Many biochemical reactions are exergonic but extremely slow in the absence of a catalyst (for example an enzyme). In the presence of enzymes, however, the reactions proceed at an appreciable rate at low temperature.

Cross-References

- [Entropy](#)
- [Exothermic](#)
- [Oxidation](#)

Exobiologie Experiment

Michel Viso

Innovaxiom, Paris, CX, France

Definition

During the ► [CNES](#) sponsored mission “Perseus,” the experiment “exobiologie” was

flown in 1999 onboard the Russian MIR space station and exposed for 97 days outside the station (April 16–July 9). Samples containing chiral ► [amino acid](#) (► [leucine](#) and alpha-methyl leucine) and peptides (leucine-diketopiperazine and trileucine thioethylester), mixed or not with montmorillonite or meteoritic powder, were deposited on windows of magnesium fluoride and exposed directly to the solar UV flux. Spores of *Bacillus subtilis* mixed with meteoritic powder were also exposed in cooperation with the DLR. As references, duplicates of the samples were placed in the instrument but hidden from the solar light as ground-based experiment was conducted.

Analysis of the material after the flight did not reveal any racemization or polymerization of the amino acids but did provide information regarding photochemical pathways for the degradation of leucine and of the tripeptide. Very thin layers of inorganic material did not protect spores against the deleterious effects of energy-rich UV radiation in space to the expected amount. Surprisingly, self-formed layers of UV radiation inactivated spores serve as a UV shield by themselves. The

hypothetical interplanetary transfer of life by the transport of microorganisms inside rocks through the solar system cannot be excluded but requires the shielding of a substantial mass of inorganic substances (Rettberg et al. 2002; Fig. 1).

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Exobiology

- [Astrobiology](#)

Exogenetic

- [Exogenous](#)

Exogenic

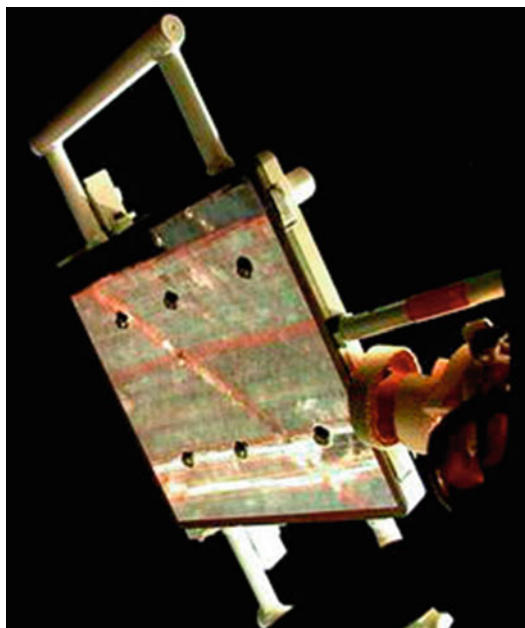
- [Exogenous](#)

Exogenous

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Exogenetic](#); [Exogenic](#)



Exobiologie Experiment, Fig. 1 Experiment “exo-biologie” as seen from the interior of the Kvant module of the MIR space station. (Photo: CNES)

Definition

In geology, exogenous (from Greek *exo*, outside) refers to all the geodynamic processes that are produced on the surface of the Earth (and other planets). Weathering, erosion, transport, and sedimentation are the main exogenous processes. The result of these processes is the formation of sediments and sedimentary rocks and the morphological transformation of the planetary landscape. The main source of energy is the Sun, its radiation leading to atmospheric heating, wind circulation, and climate changes. Internal heat of the planet can contribute in a very minor amount to exogenous processes.

Cross-References

- [Endogenous](#)
- [Sedimentary Rock](#)
- [Weathering](#)
- [Weathering Profile](#)

ExoMars

Jorge L. Vago, Elliot Sefton-Nash and Håkan Svedhem

European Space Agency – ESA/ESTEC (SCI-S),
Noordwijk, The Netherlands

Keywords

ESA · Habitability · Life on Mars · Mars evolution · Mars Express · Mars geology · Mars missions · Mars rovers · MER · MSL · Methane on Mars · MRO · Roscosmos · NASA Pathfinder · Viking · Water on Mars

Definition

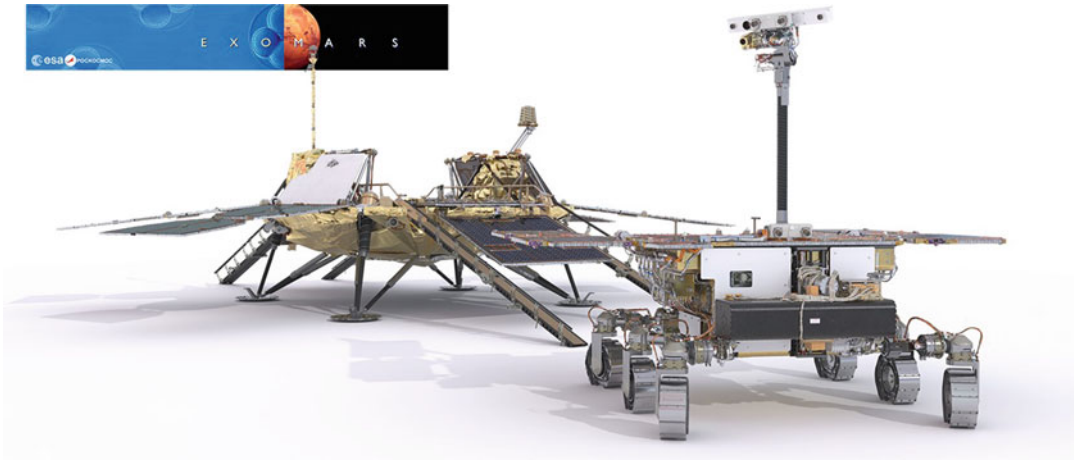
ExoMars is a cooperative program of the ► [European Space Agency](#) (ESA) and the Russian Space Agency, Roscosmos, to develop and launch two missions.

The first ExoMars mission was launched on 14 March 2016 and arrived at the red planet on 19 October 2016. ExoMars 2016 included two elements: (1) the Trace Gas Orbiter (TGO), to study subsurface water and atmospheric trace gases with the goal to acquire information on possible ongoing biological or hydrothermal processes; and (2) Schiaparelli, a European Entry, Descent, and Landing (EDL) demonstrator equipped to perform measurements during descent and on the Martian surface. Schiaparelli was able to transmit much valuable information during EDL, but unfortunately the last phase of the sequence did not work and the lander crashed. After performing a series of atmospheric aerobraking passes lasting approximately 1 year, TGO reached its science orbit in early 2018 and began performing its science mission. TGO also provides data communication services for surface landers and rovers.

The second ExoMars mission will deliver two science elements to the Martian surface (see Fig. 1): (1) *Kazachok*, a surface platform (SP) instrumented to perform environmental and geophysics measurements; and (2) *Rosalind Franklin*, a 300-kg rover tasked with conducting a search for signs of life (Vago et al. 2017).

History

ExoMars was originally conceived as a rover mission carrying a drill capable to collect small samples from the subsurface and analyze them. The initial work aiming to define the scope of the rover mission and its payload started in 1996. A group of scientists was tasked by ESA to make recommendations for future search-for-life missions on Mars. Their findings were collected in the so-called ESA “Red Book” report of 1999. During 2001, the nascent ESA Aurora program for Solar System exploration decided to pursue the Mars exobiology rover concept. In 2003, ESA issued a call for instruments to be accommodated on the 2009 ExoMars rover. The ExoMars mission was approved in 2005. A last-minute request to add a lander station resulted in a more complicated mission concept,



ExoMars, Fig. 1 Artist depiction of rover and surface platform. (Credit: ESA/Mlabspace)

requiring a larger launcher, which could not be realized within the available budget. A number of studies were necessary to redefine the mission, and thus the launch date was postponed, first to 2011 and then to 2013. At the same time, NASA was experiencing cost overrun problems with their ► [Mars Science Laboratory \(MSL\)](#) mission that affected their capability to independently realize a mission in 2016. In the course of 2009, ESA and NASA decided that they could accomplish more by joining forces. A scenario was defined for an ESA-NASA joint program that had as ultimate goal the realization of an international ► [Mars Sample Return \(MSR\)](#) mission in the mid to late 2020s. Within this program, ESA and NASA defined the first two missions, in 2016 and 2018. In late 2011, budget constraints in the USA forced NASA to scale down its participation. ESA, NASA, and Roscosmos started a dialogue aiming to realize the program as a tripartite collaboration. However, in early 2012 NASA informed ESA and Roscosmos that they would not be able to contribute major elements. Following a program reassessment phase, in 2013 ESA and Roscosmos signed a cooperation agreement to work in partnership to develop and launch two ExoMars missions in 2016 and 2018. The first mission was launched in time. The second one

had to be postponed to 2022, initially due to implementation delays and later because of the COVID-19 pandemic crisis.

Overview

Establishing whether life ever existed, or is still active on Mars today, is one of the outstanding scientific questions of our time. The ExoMars program seeks to address this important scientific goal and to demonstrate key flight and in situ enabling technologies underpinning European and Russian ambitions for future exploration missions.

The ExoMars scientific objectives are the following:

- To search for signs of past and present life on Mars
- To investigate the water/geochemical environment as a function of depth in the shallow subsurface
- To study Martian atmospheric trace gases and their sources
- To characterize the surface environment

In support of these objectives, the following technologies will be achieved:

- Entry, Descent, and Landing (EDL) of a payload on the surface of Mars
- Surface mobility with a rover
- Access to the subsurface to acquire samples
- Sample acquisition, preparation, distribution, and analysis

The 2016 TGO includes two scientific instruments for the detection of atmospheric trace gases, the study of their temporal and spatial evolution, and the localization of their source regions (NOMAD and ACS). It also has a neutron detector for the mapping of shallow subsurface ice (FREND), and a color stereo camera (CaSSIS).

The ExoMars 2022 launch period opens on 20 September 2022 and extends until 1 October. The landing will take place on 10 June 2023.

Basic Methodology

The Surface platform (SP) will conduct environment and geophysics investigations for a nominal period of one Martian year. The large majority of the meteorological SP measurements will be periodic in nature, e.g., sample temperature and humidity at regular intervals throughout the day and seasons. Other measurements will be decided

on the basis of opportunity and resources. SP investigations can be programmed several sols in advance.

The nominal duration of the rover search-for-signs-of-life mission is 211 sols. In contrast to the SP, rover operations require twice-daily interactions with ground control. This is because precise knowledge of yesterday's results (e.g., rover final drive position) is needed to plan today's activities (e.g., obtaining a sample for analysis). Typically, the rover will be instructed using a morning satellite overflight and report back on an evening telecommunications pass.

After landing, once the SP and rover status have been stabilized (Fig. 2), the next important stage will be the descent of Rosalind Franklin onto the Martian surface. The rover will remain in the vicinity of the SP for a few weeks. The rover and SP can image each other, assist with commissioning activities, and conduct proximity science measurements. Once this proximity phase will have finished, the rover will drive off. The two surface elements will then begin their individual missions.

If life ever arose on the red planet, it probably did when Mars was wetter, sometime within the first billion years following planetary formation. Conditions then were similar to those when microbes gained a foothold on the young Earth.



ExoMars, Fig. 2 Artist view of mission after landing. (Credit: ESA/Mlabspace)

Both planets had the necessary environmental conditions and ingredients for life, namely, liquid water, carbon, and other essential elements, as well as a source of energy. Life could have arisen in suitable locations, such as in the vicinity of hydrothermal activity, where all requirements could have existed, even if the standing bodies of water were ice-covered. This marks Mars as a primary target for the search for signs of life in our Solar System.

The rover will use a drill to collect samples from outcrops and at depth. The drill can reach down to 2 m below the surface. Such depth range has never been probed on Mars before. ExoMars' subsurface sampling capability will provide the best chance yet to access and analyze sedimentary deposits, possibly containing molecular biosignatures, that may have been shielded from the ravages of ionizing radiation prevailing at the surface.

The rover's Pasteur payload includes the following: panoramic instruments (PanCam (Coates et al. 2017) wide-angle and high-resolution cameras; ISEM (Korablev et al. 2017), an infrared spectrometer; WISDOM (Ciarletti et al. 2017), a ground-penetrating radar; and ADRON (Mitrofanov et al. 2017), a neutron detector); a subsurface drill to acquire samples; contact instruments for studying rocks and collected material (CLUPI (Josset et al. 2017), a close-up imager; and Ma_MISS (De Sanctis et al. 2017), an infrared spectrometer in the drill head); a Sample Preparation and Distribution System (SPDS); the analytical laboratory, the latter including Micro-mega (Bibring et al. 2017), a visual and infrared imaging spectrometer; RLS (Rull et al. 2017), a Raman spectrometer; and MOMA (Goesmann et al. 2017), a Laser-Desorption, Thermal-Volatilization, Derivatization, Gas Chromatograph Mass Spectrometer (LD + Der-TV GCMS).

The ExoMars 2022 mission will land at Oxia Planum, an ancient location with strong potential for past habitability and for preserving physical and chemical biosignatures (as well as abiotic/prebiotic organics). Oxia Planum is situated on the eastern margin of the Chryse basin, along the Martian dichotomy border, and at the outlet of the Coogoon Valles system. The coordinates

for the nominal touchdown location are 18.159°N, 24.334°W. The approximately 100 km × 9 km dispersion ellipse lies in the lower part of a wide basin, where extensive exposures of Fe/Mg-phyllosilicates (>80% of the ellipse surface area) have been detected with OMEGA and CRISM hyperspectral and multi-spectral data. The Fe/Mg-rich clay detections are associated with early/middle- to late-Noachian layered rocks (with layering thickness ranging from a few meters to <1 m for several tens of meters). They may represent the southwestern expansion (lowest member) of the Mawrth Vallis clay-rich deposits, pointing to a geographically extended aqueous alteration environment, perhaps an ocean.

No previous mission will have landed at such an ancient location. The Oxia Planum clay deposits are dated at 4.1 Ga, from the epoch when Mars' surface was crisscrossed by plentiful liquid water systems. The oldest landing sites so far have been that of Perseverance (Jezero Crater, 3.8 Ga) and Curiosity (Gale Crater, 3.6 Ga).

In the case of a possible biosignature discovery, independent confirmation of the results will require more thorough analyses than can be performed by remote robotic means. The ExoMars 2022 mission will contribute to determining what types of samples we should return to Earth for further studies.

The Martian Environment and the Need for Subsurface Exploration

For organisms to have emerged and evolved, liquid water must have been present on Mars. Without it, most cellular metabolic processes would not be possible. In the absence of water, life either ceases or slips into a quiescent mode. Hence, the search for extinct or extant life automatically translates into a search for liquid water-rich environments, past or present.

The strategy to find traces of past biological activity rests on the assumption that any surviving signatures of interest will be preserved in the geological record, in the form of buried/encased remains, organic materials, and fossil communities. Because current Martian surface conditions

are hostile to most known organisms, when looking for signs of extant life, the search methodology must focus on investigations in protected niches: in the subsurface and within surface outcrops. Therefore, the same sampling device and instrumentation can adequately serve both types of studies.

The rover's surface mobility and the 2 m vertical reach of the drill are both crucial for the scientific success of the mission.

The ExoMars rover will search for two types of life-related signatures: morphological and chemical. This will be complemented by an accurate determination of the geological context. Morphological information related to biological processes may be preserved on the surface of rocks. Possible examples include the biomediated deposition of sediments, fossilized bacterial mats, stromatolite mounds, etc. Essential for these studies are mobility and an imaging system capable of covering from the meter scale down to submillimeter resolution (to discern microtextural information in rocks).

Effective chemical identification of biosignatures requires access to well-preserved organic molecules. Because the Martian atmosphere is more tenuous than Earth's, three important physical agents reach the surface of Mars with adverse effects for the long-term preservation of organic compounds: (1) The ultraviolet (UV) radiation dose is higher than on our planet and will quickly damage potential exposed organisms or biomolecules; (2) UV-induced photochemistry is responsible for the production of reactive oxidant species that, when activated, can also destroy organics; the diffusion of oxidants into the subsurface is not well characterized and constitutes an important measurement that the mission must perform; and (3) finally, ionizing radiation penetrates into the uppermost meters of the planet's subsurface. This causes a slow degradation process that, over many millions of years, can alter organic molecules beyond the detection sensitivity of analytical instruments. Please note that the ionizing radiation effects are depth dependent: The material closer to the surface is exposed to a higher dose than that buried deeper.

A major goal of ExoMars is to study ancient (older than 3.8 billion years) sedimentary rock

formations. However, the chemical record of early Martian life, if it ever existed, is likely to have escaped radiation and damage only if it is trapped in the subsurface for long periods. Studies show that a subsurface penetration in the range of 2 m is necessary to recover well-preserved organics from the very early history of Mars.

Additionally, it is essential to avoid loose dust deposits distributed by eolian transport. While driven by the wind, this material has been processed by UV radiation, ionizing radiation, and potential oxidants in the atmosphere and on the surface of Mars. Any organic biosignatures would be highly degraded in these samples.

For all the above reasons, the ExoMars drill will be able to penetrate and obtain samples from well-consolidated (hard) formations, at various depths, from 0 down to 2 m.

Key Research Findings

In spite of their sensitivity (1000 to 10,000 higher than that of instruments on previous missions), TGO observations using the NOMAD and ACS instruments have not detected atmospheric methane at the altitudes they can explore using the Sun occultation technique (typically between 5 and 25 km) down to a minimum detection limit of ~ 0.01 ppbv (Korablev et al. 2019). This is in contradiction with reports from Curiosity's team who claim to have measured in situ levels between 0.2 and 0.8 ppbv as continuous background and more during putative peak emissions. This difference remains to be explained.

Another important finding of TGO has been the role that atmospheric heating and subsequent inflation during large dust storms have on boosting atmospheric and especially water vapor escape (Vandaele et al. 2019; Fedorova et al. 2020).

The FREND neutron detector on TGO has discovered numerous areas of shallow buried water ice deposits (local regions with suppressed neutron flux that indicate the presence of considerable hydrogen) in the Mars tropical band (Malakhov et al. 2020). These permafrost oases

have water mass fractions varying between 30% and 100%.

The CaSSIS camera on TGO has obtained more than 20,000 color images of the Martian surface, many of which are stereo pairs.

Future Directions

TGO will continue its science and data relay mission. The next challenge is to launch, land, and perform ExoMars 2022. Beyond this, ESA and NASA are working on Mars Sample Return.

Cross-References

- [Mars Express](#)
- [Mars Sample Return Mission](#)
- [Mars Science Laboratory](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)

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Exomoon

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Definition

An exomoon is a natural satellite (as opposed to an artificial satellite) of an extrasolar planet. In analogy to the solar system where many of the planets have moons around them, it is expected that extrasolar planets will host moons as well. No exomoon has yet been firmly discovered (as of 2021), as the detection of exomoons is a very complicated task with all current detection techniques.

In 2018, Teachey and Kipping announced the detection of a Neptune-size exomoon candidate around the giant planet Kepler-1625b. However, this discovery was challenged by several studies (e.g., Kreidberg et al. 2019) and the detection was not confirmed.

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Exon

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

In interrupted (split) ► [genes](#), exon refers to each of the sequences in the primary transcript present

in the mature ► [RNA](#) sequence after removal of the ► [introns](#) (intervening sequences separating the exons) by the splicing process.

Cross-References

- [Gene](#)
- [Intron](#)
- [RNA](#)

Exoplanet Simulation Chamber

- [Simulation Chambers](#)

Exoplanet, Detection, and Characterization

Therese Encrenaz¹ and Nader Haghighipour²

¹Observatoire de Paris – PSL, Section de Meudon, Meudon, France

²Institute for Astronomy, University of Hawaii-Manoa, Hawaii, HI, USA

Keywords

Astrometry · Coronagraphy · Microlensing · Planets · Radial velocity · Transit

Synonyms

[Extrasolar planets detection and characterization](#)

Definition

An exoplanet, or extrasolar planet, is a planet in orbit around another star. The first of such objects was discovered in 1992 and about 5,200 exoplanets have been identified today (November 2021). Because an exoplanet's reflected visible light is (in the case of a system comparable to ours) $\sim 10^{-9}$ times weaker than the stellar flux, indirect methods such as Doppler velocimetry

(radial velocity technique) and transit photometry have first been used to detect these objects. Before the first discoveries in 1995, astrometry was tried without success, as the available instrumental means were not sensitive enough to detect such small motions. The velocimetry technique was later successfully used, and, since 1995, this has led to the discovery of about a thousand exoplanets. Since 2000, the transit photometry technique has been especially successful, in particular with the CoRoT space mission, launched in 2006, and even more with the Kepler space telescope which provided a very large amount of data. The number of planets detected by this method is close to 3500. Other methods have also been successful, in particular microlensing surveys, and, more recently, direct imaging (see ► [Direct-Imaging, Planets](#), and ► [Transiting Planets](#)).

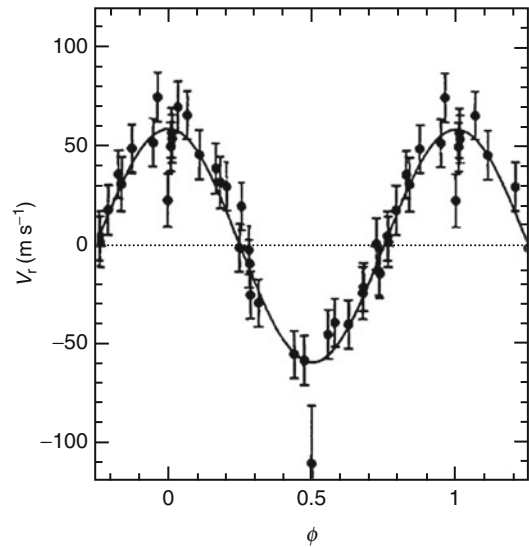
History

The question of the plurality of worlds is probably as old as humanity. In Antiquity already, some philosophers suggested the possible existence of inhabited worlds outside the solar system. In the Middle Ages and later, the question was very much under debate among philosophers and scientists. Astronomical programs for detecting exoplanets started at the beginning of the twentieth century. Following the work of Friedrich Bessel (1784–1846) who had discovered a low-mass companion around Sirius, the ► [astrometry](#) technique was favored. In 1944, Piet Van de Kamp announced the discovery of a planet around Barnard's star. After many studies, it turned out that the apparent star motion was due to an artifact, caused by systematic instrumental errors. In the 1980s, astronomers came to the view that, in light of the performances of the available instruments, astrometric techniques were not sufficiently accurate for detecting exoplanets.

The first true exoplanet was discovered in 1992 around a pulsar, using the method called pulsar timing. Pulsars, first detected in 1967 by J. Bell and A. Hewish, are neutron stars, at the very last stage of their lifetime. These stars rotate extremely rapidly and have a very strong magnetic field. As a

result, they emit a periodic radio signal which can be detected from Earth. If a planet is present around the pulsar, it creates a perturbation in the radio signal. In the 1970s, several tentative detections were announced but none of them was confirmed until, in 1992, Alexander Wolszczan discovered the presence of two planets around the pulsar PSR1257 + 12; this object has an especially fast rotation period of 1.5 ms. Over 40 objects around pulsars have been detected since 1992. These first detected exoplanets have of course no resemblance at all with solar system planets and bear little interest for astrobiology (the intense and periodic radiation may not be favorable for life as we know it).

Still in the 1970s, astronomers started developing another indirect method, called velocimetry or radial velocity measurement. The idea is, like astrometry, to detect the motion of the star with respect to the center of mass of the system, but this time the velocity is measured using the Doppler technique. At the beginning of the 1980s, three teams were especially active in carrying out such long-term programs: M. Mayor for the Observatory of Geneva, the team led by G. Marcy and P. Butler in the USA, and the team led by G. Walker and B. Campbell in Canada. After over a decade with no result, the first discovery was announced in 1995 by M. Mayor and D. Queloz, using the 1.93 m telescope of Saint-Michel Observatory (Fig. 1). An exoplanet was detected around a solar-type star, 51 Pegasi. More surprisingly, the object was a giant exoplanet (with a mass at least half of Jupiter), orbiting at only 0.05 AU from its star, with a revolution period of only 4 days! This outstanding discovery was followed by many others. In 1996, G. Marcy announced the detection of two other exoplanets, around 47 UMa and 70 Vir. The following detections confirmed the strange nature of the exoplanets: most of them were ► [giant planets](#) orbiting in the close vicinity of their star. This situation was completely unexpected: at the time, the formation scenarios of the solar system suggested that planets, formed by the accretion of solid particles within the ► [protoplanetary disk](#), should be small and rocky objects near their star, and gas- or ice-giants at larger distances. The first implication of the discovery of extrasolar



Exoplanet, Detection, and Characterization, Fig. 1 The velocity curve of 51 Pegasi, measured by Mayor and Queloz (1995) at the Haute Provence Observatory. The sinusoidal shape of the curve is the signature of the presence of a planet which orbits the star at the same period. (After Ollivier et al. 2009)

planets was that indeed exoplanets do exist around solar-type stars, but their formation scenario – or at least their evolutive process – may be very different from that of the solar system.

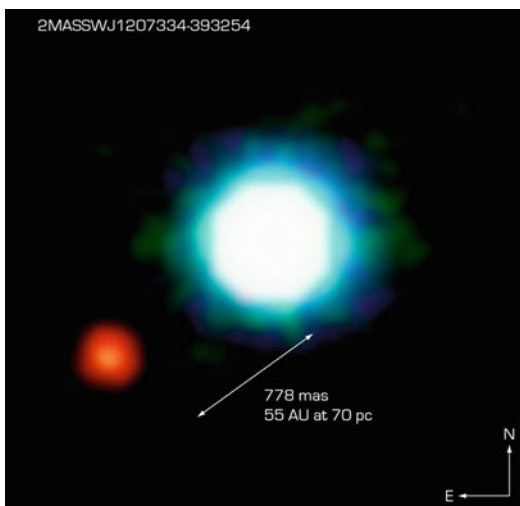
The second major step in the exploration of exoplanets was the detection of planets by the method of transits. When a planet transit in front of its host star, the stellar flux slightly decreases, and this small variation may be detected using very stable photometry. The method has been used since the beginning of the twenty-first century, both from the ground and from space, and is responsible for the majority of exoplanet discoveries.

Overview

The main problem for detecting exoplanets is the huge contrast between the reflected planetary flux and the stellar flux, and the very small angular distance between the planet and its host star. As mentioned above, for a Jupiter-like planet located at 5 AU from a solar-type star, the flux contrast is

10^{-9} in visible light. As the planet is a cold object, the situation improves in the infrared with a contrast of about 10^{-6} at $10\text{ }\mu\text{m}$. For a star located at 10 pc for the Sun (a typical distance for a sample of nearby stars), the star-planet angular separation is 0.5 arcsec . With the present means, it is extremely difficult to obtain a direct image of a Jupiter-like planet around a solar-type star, even in the infrared.

Direct imaging can be considered for star-planet systems with a more favorable contrast and a larger separation. This implies looking for cooler and smaller stars, that is, M-type dwarfs, and large exoplanets far from their host stars, or highly luminous stars such as A stars and very large exoplanets at very large separation (e.g., tens of AU). The first direct image of an exoplanet was obtained by G. Chauvin and his team from the Observatoire de Grenoble (Fig. 2). The star, 2MASS1207, has a mass of 0.025 solar masses. Its planet, located at 55 AU from the host star, has a mass of five Jovian masses. The observation was performed in the near-infrared range at the **VLT**, using adaptive optics; the detection was made easier by the fact that the host star is a **brown dwarf**, much cooler than typical stars. This discovery was the first one of a promising research field.



Exoplanet, Detection, and Characterization, Fig. 2 The planetary system 2MASS1207 observed from the ground in the near-infrared range by the NACO instrument on the VLT (Chauvin et al. 2005). (Figure from ESO)

A more prominent and highly studied planetary system detected by direct imaging is the four-planet system of the A star HR 8799.

The Indirect Detection Techniques

Astrometry and Velocimetry

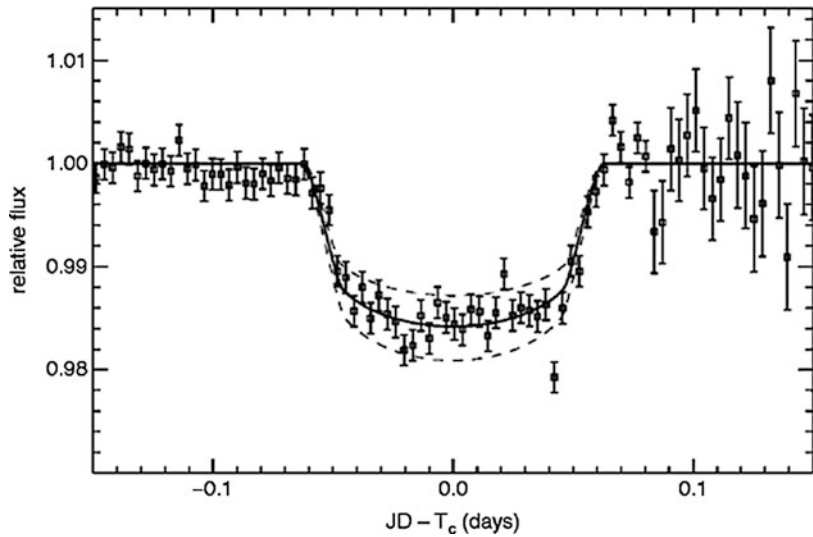
As mentioned above, both astrometry and velocimetry have been used for measuring the stellar motion around the center of mass of the system. In the case of the solar system, the motion induced on the Sun by Jupiter corresponds to a velocity of 12.5 m/s ; in the case of the Earth, it is only 9 cm/s . In the case of astrometry, as seen by the observer, the motion of the star is an ellipse, which becomes a line segment if the observer is located in the plane of the planetary system. In the case of velocimetry, the situation is reversed. The observer measures the projection of the stellar motion along the line of sight (called the radial velocity). As a result, the velocity curve is sinusoidal and maximal if the observer is in the plane of the system, but is zero if the observer is aligned with the rotation axis of the system. As the viewing angle of the system is unknown, only a lower limit of the planet's mass is retrieved, in addition to its period.

The detection of exoplanets by the astrometry method from the ground has been so far beyond instrumental capabilities. In the near future, it could become feasible from the ground for giant exoplanets with the interferometric instrument PRIMA at the VLTI. However, the main instrument for exoplanet detection is the Gaia astrometry space mission, launched by the European Space Agency in 2013, which should lead to the detection of a huge number of exoplanets, especially massive objects at large distances from their host stars.

As mentioned above, velocimetry has been the first tool of exoplanets' detection. The success of this method is due to the unexpected fact that massive objects are found very close to their stars, which is especially favorable for this technique. In the case of 51 Pegasi b (the first exoplanet found around a solar type star) and other exoplanets of this kind (also called **hot Jupiters**), the motion of the star was close to 50 m/s .

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Fig. 3 The transit of HD209458b, as observed from the ground (After Charbonneau et al. 2000. (The figure is taken from Ollivier et al. 2009))



Thanks to the improving performances of high-resolution spectrographs, it is now possible to measure velocities smaller than 1 m/s, which allows a mass limit not far from a terrestrial mass. The extension of the velocimetry data base over two decades also allows searches for planets located at a few AU to a few tens of AU from their host star, that is, searches for planetary systems which might be more similar to the solar system.

The Method of Transits

Under favorable circumstances, the observer may be located close to the plane of a planetary system. In this case, the exoplanet periodically crosses the stellar disk. During this event, the flux of the star is reduced because of the presence of the occulting planet, and this flux variation can be measured if the stellar flux is continuously monitored with a very high stability. In the case of the solar system, the occultation of the Sun by Jupiter, as observed from a nearby star, would lead to a flux decrease of 1% (this is simply the square of the ratio between the planetary and solar radii). In the case of the Earth, the flux decrease would be only 0.01%.

The detection of hot Jupiters is very favorable to the transit method, as the occultation events repeat over a short timescale (a few days). Measuring flux variations of 0.01% is not achievable from the ground, but variations of the order of a

percent can be monitored from the ground. However, photometric data with exquisite accuracy can be obtained from space. The first observation of a planetary transit was achieved using a ground-based telescope by D. Charbonneau and his team in 2000 (Fig. 3). The hot Jupiter, HD209458b, was later observed with the Hubble Space Telescope (HST) with a much higher precision.

The great advantage of the transit method is that, combined with velocimetry, several planetary parameters can be derived: the radius (from the flux extinction), the mass (from the velocimetry), and thus the density. Physical characterization of the planet thus becomes possible, as will be discussed below.

Several ground-based monitoring programs have been developed for the systematic search for transits using small, robotic, wide-field telescopes. These programs are well designed for the search for giant exoplanets close to their stars. The Earth-like exoplanets, or even the rocky exoplanets, with a mass less than ten terrestrial masses, cannot be detected from the ground because the photometric stability is limited by the turbulence of the Earth's atmosphere and also by potential seismic activity. This is why space missions have been developed. Launched by the French space agency CNES in December 2006, the CoRoT space mission was the first

satellite designed for this project (and a complementary program of asteroseismology) which actually detected exoplanets. The instrument consisted of a 27-cm diameter telescope equipped with four CCDs (two for the exoplanet survey) which image a 7 square-degree field for a maximum period of 5 months. CoRoT had detected several tens of exoplanets of all kinds, and many more candidates which remained to be confirmed by velocimetry.

The next transit space mission was Kepler. This mission was launched in March 2009 and ended its primary operation in 2013. (The Kepler telescope has been used in the NASA K2 mission until 2018.) The instrument consisted of a 95-cm telescope equipped with 42 CCDs which observed a field of about 100 square degrees. Kepler was able to detect terrestrial size and smaller planets. Nearly 1,000 exoplanets have been detected, and over 4,000 unconfirmed candidates had been reported, among which some exoplanets with a mass close to the terrestrial one.

Following the Kepler mission, two new space telescopes, dedicated to the detection of transiting exoplanets, are currently in operation: TESS (Transit Exoplanet Survey Satellite), launched by NASA in 2018, and CHEOPS (Characterizing Exoplanets Satellite), launched by ESA and Switzerland in 2019. TESS is equipped with four 10-cm telescopes and can detect stars weaker than Kepler by a factor between 30 and 100, and its objective is to detect low-mass exoplanets. CHEOPS is using a 35-cm telescope and is searching for transits of already known exoplanets, in order to better characterize these systems.

The Microlensing Technique

The phenomenon of gravitational lensing is a peculiar aspect of Einstein's theory of relativity. As a consequence of the energy/matter equivalence, a photon is subject to gravitation just as classical baryonic matter. As a result, a photon approaching a stellar object is deflected relative to its direction of propagation. If a massive object is located on the line between the observer and the distant object being observed, the image of the latter is modified. In the case of a massive

deflecting object (usually a galaxy), the result is the well-known gravitational lensing effect observed on distant quasars.

When the mass of the deflecting object is low, the effect, called microlensing, is observed as a magnification of the signal of the source being observed. This magnification effect can be used to detect remote stars which were not observable before. The time of transit of the nearer object (the "lens") in front of the distant star lasts typically a few tens of days. Using this method, several groups have undertaken ground-based surveys to search for a population of brown dwarfs and thus to try to detect dark matter in the Galaxy.

This method is also of interest for exoplanets' detection, as the presence of a planet around the lensing star can be inferred from a special signature in the amplification curve of the distant (source) star. This method is very sensitive and has led to the detection of over 30 objects among distant stars. A peculiar object is the very small planet (OGLE-05-390L) of 5.5 terrestrial masses, located at 2.6 AU from its star (Fig. 4). The main disadvantage of the microlensing technique is that the method is neither predictable, nor repeatable. So, no physical characterization can be undertaken on these presumably planetary objects.

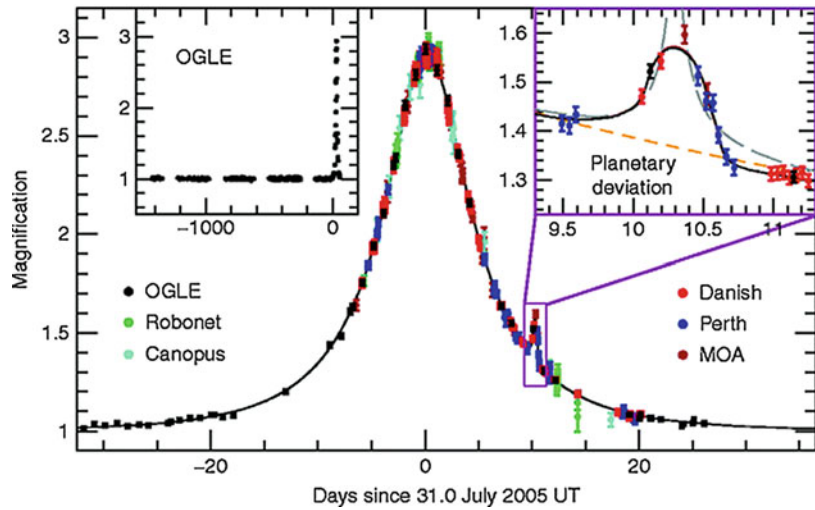
Comparison of the Different Indirect Methods

The advantages and limitations of the indirect detection methods can be summarized as follows:

- Astrometry is well adapted for the detection of massive exoplanets far from their stars. The method has been not so far usable from the ground, however much progress is expected from the ► [Gaia mission](#).
- Velocimetry has been the first tool for exoplanets' detection. Constant improvements in the instrumental performances have allowed the detection of exoplanets close in mass to terrestrial analogs. Mostly short-period exoplanets were detected in the first decade, but the time extension of the database has allowed the detection of more and more solar system giant-planet analogs with longer periods, as well a new class of planetary bodies with masses between 2 and 10 Earth-masses known as super-Earths.

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Fig. 4 Light curve of a microlensing event for OGLE-2005-BLG-390Lb



- The transit method is well adapted to the detection of massive objects close to their star; ground-based observations are possible for giant exoplanets and are performed in the frame of several ground-based systematic campaigns. The limitation lies in the peculiar geometry of the planetary system which must be observed edge-on. The probability for such a geometry is about 10% for hot Jupiters. The transit method, when coupled with velocimetry, provides the confirmation of the planetary nature of the candidate detected by transit. The combination of both methods allows for characterization of the exoplanet with the determination of its period, mass, radius, and density. The detection of rocky planets by transit has been possible using space missions CoRoT and Kepler.
- The microlensing technique is very sensitive, and well adapted to low-mass objects distant from their stars. Exoplanets are found around distant stars, located in the halo of our Galaxy, and a statistical analysis of this population can be obtained from the ground by this method. However, there is no possible physical characterization of the detected objects, as the observations are not repeatable.
- Finally, the pulsar timing which led to the first detection of exoplanets is extremely sensitive to low-mass objects. However, the method is

limited to a small number of cases (pulsars with planets).

Direct Detection Methods

The direct detection of an exoplanet implies the detection of photons, at any wavelength, emitted by the exoplanet itself. The problem is thus to separate these photons from the stellar ones.

Spectrophotometric Measurements: Secondary Transits

We have mentioned above the transit observations as an indirect method of exoplanet detection. In addition, when the planet's flux is strong enough, the same observations can be used for a direct measurement of the exoplanet's flux during the secondary transit, when the planet passes behind the star. By measuring the total flux of the system, before, during, and after the secondary transit, it is possible to retrieve by difference the flux emitted by the planet's dayside, and even to measure its spectrum. The method has been successfully used in the infrared range on a few objects, mostly hot Jupiters. Spectroscopy has been achieved between 1 and 20 μm using ground-based observations, the HST and Spitzer (see below).

Imaging Techniques

Optimizing the spectral range of the observation results from a compromise between the

planet/star flux ratio (higher in the infrared) and the spatial resolution (higher in the visible range). Two spectral domains have been considered:

- In the near-infrared range, the star-planet pair can be resolved, using ► [adaptive optics](#) and coronagraphic techniques; the first image of an exoplanet, 2MASS1207b, was obtained using adaptive optics (see above).
- In the thermal infrared range, between 5 and 20 μm , the planet/star contrast is optimal; however, interferometry must be used to obtain the required angular resolution. A method has been proposed, called “nulling interferometry,” which allows the elimination of the stellar flux, by combining destructive interferences along the line of sight; if a planet is present at some distance from the line of sight, its signal can be detected if it corresponds to a bright fringe. These observations will have to be performed from space and still require important technological developments.

Significant developments have been achieved over the past 10 years in the near-infrared imaging technique. New instruments combining adaptive optics, coronagraphic masks, and sophisticated data processing algorithms have been mounted on very large telescopes (Keck, Gemini, VLT...). About 150 exoplanets have been detected by this technique (Fig. 5).

Radio Detection

The radio range, and in particular the decametric range, is especially favorable in terms of planet/star flux ratio. Indeed, planets like Jupiter which possess a strong magnetic field emit a nonthermal auroral emission, coming from the interaction between charged particles and the magnetic field in the polar regions. In the case of Jupiter, the intensity of this emission is comparable to that of the Sun. These emissions have special characteristics: in the case of Jupiter, they have durations shorter than 1 s, and their spectrum extends from about 20–40 MHz. There are, however, sources of noise at the same frequencies, coming both from the Galactic emission and from the Earth itself, including human activities. Still, radio-astronomers are studying the possibility of detecting radio emissions from exoplanets using large arrays of radio antennae like LOFAR in Europe, UTR-2 in Ukraine, and later SKA (the proposed Square Kilometer Array). Calculations predict that the radio emission of a Jupiter-like exoplanet at 0.2 pc could be detected with UTR-2; however, there is no nearby star closer than 1 pc. In the case of hot Jupiters, close to their stars, the radio signal would be accordingly enhanced and such objects could possibly be detected up to distances of 20–25 pc. This would open the possibility of actually detecting exoplanets with this technique. A search for radio emissions from three exoplanetary systems (55 Cancri, ν Andromedae, and τ Bootis) has been undertaken using the LOFAR low-beam



Exoplanet, Detection, and Characterization, Fig. 5 Detection of a newly formed exoplanet within the disk of a young star, PDS 70. The K7 star is 5 My old,

located at 113 pc. The exoplanet is located at 22 AU from the star, and its mass is about 7 jovian masses. (Source: Müller et al. 2018)

antenna. A tentative signal has been detected from τ Bootis, which remains to be confirmed (Turner et al. 2021).

An Inventory of Exoplanets, over 25 Years After the First Discovery

January 2023 marks 28 years after the discovery of 51 Peg b. About 5,200 exoplanets have been detected. Most of the objects have been found by transit photometry and velocimetry. About 16% of the objects belong to multiple systems.

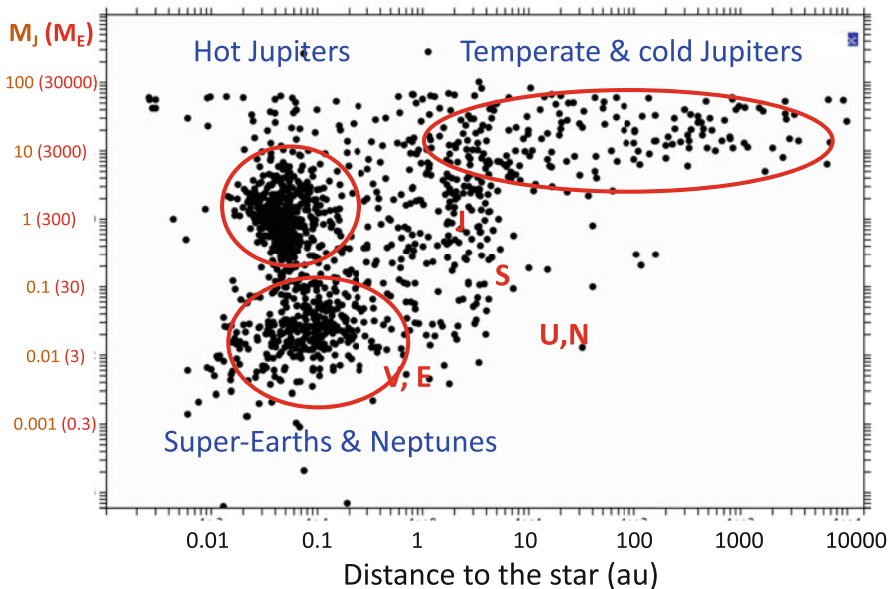
Exoplanets are common in the Galaxy. Following Kepler statistics, it appears that the probability for a star to have an exoplanet is close to 1. This first estimate will have to be refined in light of more complete samplings, including the M dwarfs, by far the most numerous stars in the Galaxy. Also, there are still observational biases toward short-period and massive exoplanets, which are easier to detect.

The (Mass, Distance) Diagram of Exoplanets

Figure 6 shows a diagram of the exoplanets as a function of the distance to their host star

(in abscissa) and their mass (in ordinate). It can be seen that they can be assembled in three categories which correspond to the three major detection techniques.

There is a compact group of massive planets close to their host star. They are the hot Jupiters, which were first detected with the radial velocity method. Many of them are orbiting within 0.05 AU from their star (i.e., with a period of 4 days or less). These objects are so close to their star that, most likely, they are tidally locked with their star, in synchronous rotation, showing always the same hemisphere to it (as in the case of the Earth-Moon system). In view of the short distance between the star and the planet, strong temperature contrasts are expected between the day side and the night side of the planet. The second group includes smaller objects (super-Earths and Neptunes) close to their star. Most of them have been detected by the method of transits, at distances from their stars ranging between 0.03 and 0.3 AU. As in the case of hot Jupiters, they are expected to be in synchronous rotation. Finally, the third group includes massive objects at distances from their stars larger than a few UA. The most distant ones have been recently detected by



Exoplanet, Detection, and Characterization, Fig. 6 The mass-distance diagram of exoplanets. (Source: exoplanet.eu)

the direct imaging technique, and their number is rapidly increasing.

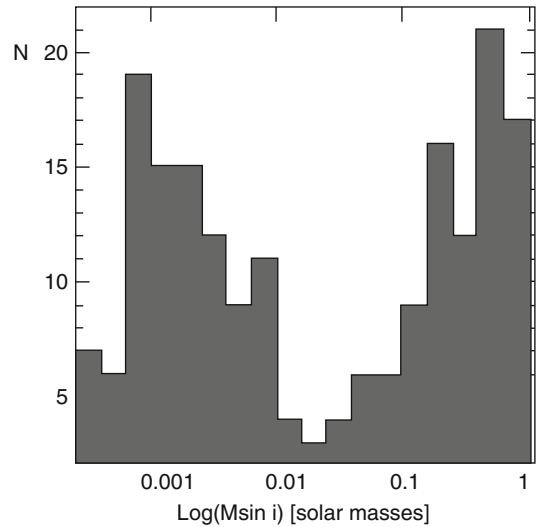
The absence of small objects distant from their stars is obviously an observational bias: they are the most difficult targets to identify, whatever detection method is used.

The Mass Distribution of Exoplanets and the “Brown Dwarf Desert”

The velocimetry method allows the detection of exoplanets, but also the detection of more massive stellar companions. If the object has a mass lower than 0.01 solar mass (or 13 Jupiter masses), its internal energy is not sufficient to generate the thermonuclear reactions leading to stellar nucleosynthesis; the object is called a planet. If its mass is between 0.01 and 0.08 solar masses (between about 13 and 80 Jupiter masses), the central temperature is sufficient for initiating the first cycle of thermonuclear reactions which destroys deuterium, but not the next cycle which would transform hydrogen into helium; the object is called a brown dwarf. Beyond a mass of 0.08 solar masses, the object is a star. Several stellar types are defined (O, B, A, F, G, K, M) as a decreasing function of their mass and temperature. The brightest and hottest stars have the shortest lifetime. The Sun, a G-type star, is a very ordinary star, in the middle of the range; its lifetime is about 10 Gy.

If we consider the distribution of stellar companions detected by velocimetry, we observe a bimodal distribution (Fig. 7), with a first peak between 0.001 and 0.01 solar masses (the exoplanets) and the other beyond 0.1 solar mass (the stars). The absence of objects between the two peaks is known as the “brown dwarf desert.” It probably illustrates the two different formation scenarios of these two classes of objects. Stars are formed from the collapse of a cloud fragment of interstellar matter; planets are formed by accretion of solid particles within the protoplanetary disk formed after the collapse of this cloud.

Inside the exoplanet population, the mass distribution also exhibits a bimodal distribution (Fig. 8). A first maximum appears around 0.03 Jovian masses (i.e., one terrestrial mass) and the



Exoplanet, Detection, and Characterization, Fig. 7 The bimodal mass distribution of stellar companions. The quantity $[M \sin i]$ is determined by velocimetry. The exoplanet population appears on the left side, and the stellar population is on the right side. The hole at the center is known as the brown dwarf desert. (The figure is taken from Ollivier et al. 2009)

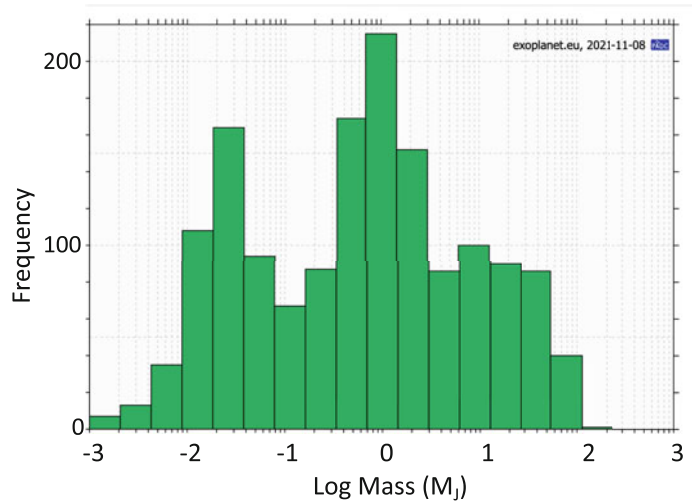
second one is centered around one Jovian mass. This bimodal distribution could possibly be the result of the core accretion scenario, assumed to be valid for the Solar system; according to this scenario, planets are formed within the protoplanetary disk from the accretion of solid embryos (see below). However, it must be kept in mind that this curve may still be affected by observational biases.

A Wide Range of Eccentricities

Within the solar system, we are used to planets on almost concentric orbits, that is, with low eccentricities. Exoplanets are very different. With the exception of hot Jupiters whose orbits are very circular (possibly as an effect of strong tidal forces), exoplanets exhibit a large variety of eccentricities, in some cases as high as 0.90. A possible explanation could come from various types of interaction, especially between the planet and the protoplanetary disk. There is no clear apparent correlation between the masses of exoplanets and their eccentricities.

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Fig. 8 The mass distribution of exoplanets.
(Source: exoplanet.eu)



A Large Number of Multiple Systems

Many multiple systems have been detected, and more are to be found. So far, the nearly 4,900 confirmed exoplanets have been found in about 3,600 planetary systems, including more than 800 multiple systems, with a number of planets ranging from 2 to 7. However, in view of the observational bias, multiple systems might be as common as single ones. Thus, in this view, the solar system is not an exception. Multiple systems are of special interest for dynamicists who can study their stability with numerical simulations.

The most famous of multiple planetary systems is the system of the star Trappist 1, discovered by the method of transit. This very small, 0.08 solar-mass M8 star is host to seven planets, all with a size comparable to the Earth. All orbits are coplanar. The whole system is very small, as all planets are located within 0.05 AU from their star. For comparison, in the Solar system, the closest planet, Mercury, is located at about 0.4 AU from the Sun.

The Effect of Metallicity

It is interesting to study the probability for a star to host a planet as a function of its relative fraction of heavy elements (i.e., elements heavier than helium), also called its metallicity. According to the scenario most commonly accepted for planetary formation, planets formed within a protoplanetary disk from the accretion of solid

particles. The higher the metallicity of the star, the more solid material should be available for planetary embryos; we should thus expect a positive correlation between the metallicity and the frequency of planets. This correlation is indeed observed in the case of giant exoplanets; it is not clear in the case of rocky exoplanets, and a larger sample will be needed before any firm conclusion can be reached. It should be also noted that the Sun, in spite of its low metallicity, hosts a system of eight planets, including four giant ones.

Scenarios for Planetary Formation

It is generally accepted that planets formed within a protoplanetary disk, resulting from the collapse of a rotating fragment of an interstellar cloud. These early phases of star formation have been observed on many young stellar objects, and this scenario is also believed to be responsible for the solar system formation. Within the disk, planets form from the accretion of solid particles. In the vicinity of the Sun, the temperature is such that only metallic compounds and silicates are in solid form. Because these elements are not very abundant in the Universe, the planets formed near the star are expected to be relatively small and dense: they are the rocky planets. In contrast, at farther distances from the star, where the temperature drops below about 200 K, most of the simple

molecules (H_2O , NH_3 , CO_2 , CH_4 , H_2S , ...) are in the form of ices. These compounds can thus be incorporated in planetary nuclei which can reach a mass of 10–15 terrestrial masses. Calculations show that beyond this limit, the gravity field of the nuclei is sufficient to capture by gravitational collapse, the surrounding material, which is mostly composed of hydrogen and helium. The process leads to the formation of giant planets, with a large volume (mainly of gas) and a low density. The collapse of the nebula surrounding such a planet leads to the formation of a small disk, which explains the presence of satellites and ring systems in the equatorial plane of the giant planets. In the case of the solar system, this nucleation formation scenario is fully consistent with the presence of terrestrial planets within 2 AU from the Sun and giant planets beyond 5 AU.

How can we then explain the presence of giant exoplanets in the immediate vicinity of their star? The most common explanation proposed by theoreticians is planet migration. As an effect of interactions between the planet and the protoplanetary disk (mostly the gaseous disk), a planet can migrate from the outside to the inside and come in the vicinity of the star. A question is still open: what is the mechanism which stops the migration at 0.05 AU from the star? According to some dynamical models, after a period of high [▶ eccentricity](#), the planet could come into an approximately circular orbit; the strong gravity field of the star would tidally lock the planet to it.

Another question is to be raised: why was there no major migration in the solar system? According to dynamical simulations, a moderate migration of giant planets has also occurred in the solar system (Tsiganis et al. [2005](#)). According to these models, the small mass of Mars could be the result of the inward migration of Jupiter from 3.5 to 1.5 AU and its subsequent outward migration due to the pull of Saturn to orbits beyond 3.5 AU.

From Detection to Characterization

After 25 years of intense observing campaign, we have discovered a wide variety of exoplanets, with different masses and orbital properties. We

are now entering a new research era, the one of exoplanet characterization. The aim is to understand the nature of their atmospheres, and the main tool for it is infrared spectroscopy of transiting exoplanets.

What Kind of Exoplanets Can We Expect?

We can have a first guess of the possible nature of an exoplanet's atmosphere, knowing its mass and its distance to the star, just by analogy with solar system planets and satellites. The most important parameter is the stellar distance, as compared with the line of ices of the system (the "[▶ snow line](#)"). This limit corresponds to water condensation and occurs at a temperature of about 180 K. Within this limit, we expect rocky exoplanets; beyond it, we expect either icy planets, if their mass is below ten terrestrial masses, or giant planets (i.e., with some fraction of protostellar gas) if they are bigger. In the first case, we would expect a (CO_2 , N_2) atmosphere, with some amount of H_2O and CO ; in the latter case, we would expect a reduced atmosphere, dominated by hydrogen and helium, with a minor contribution of CH_4 , NH_3 , and other hydrogenated molecules. Of course this "first guess" classification is extremely simplified, as many parameters (albedo, rotation period, obliquity, possible greenhouse effect, magnetic field, etc.) might be involved. Even more importantly, no migration is assumed in the above scenario, and we know that it is a common process encountered in planetary systems.

The Infrared Spectrum of an Exoplanet

As in the case of any solar system object, the infrared spectrum of an exoplanet shows two main components, the reflected stellar radiation which peaks in the visible range for a solar-type star, and a thermal component with peaks in the infrared range corresponding, to first order, to the blackbody radiation at its effective temperature. The balance between the two components depends upon the albedo (reflectivity) of the exoplanet. For solar system objects, the albedo ranges typically between 0.05 (comets) and 0.3–0.6 (planets and icy satellites). In the solar reflected regime, atmospheric signatures are observed in absorption in front of the stellar flux. In the

thermal regime, the situation is more complex, as the molecular features may appear in absorption or emission, depending upon the thermal vertical gradient in the atmosphere. For solar system planets, the signatures are in absorption if they are formed in the troposphere (where the temperature decreases with increasing altitudes), and in emission in the stratosphere (where the temperature increases with altitude). Understanding the thermal emission of an exoplanet thus simultaneously requires the determination of its thermal vertical structure.

Infrared Spectroscopy of Transit Exoplanets

There are two ways of measuring the spectrum of a transiting exoplanet. During the primary transit, when the planet passes in front of the stellar disk, its atmospheric constituents can be observed in absorption in front of the stellar flux. Before and after the secondary transit, when it passes behind the star, the planet can be observed in emission. In both cases, the planetary flux is retrieved by difference with the stellar flux without the planet.

Over the past 20 years, spectroscopic observations of a few hot Jupiters (HD209458b, TrES-1, HD439733b) have been obtained in both modes. Using primary transits, transmission spectra have been obtained in the visible and near-infrared

ranges, using the Hubble Space Telescope and ground-based observations. Atomic lines of H, O, C, Na have been observed, as well as emission bands of CH₄ and H₂O. Secondary transits have been used to measure the exoplanets' emission spectra with the Spitzer satellite in the near- and mid-infrared range. Using both primary and secondary transits, many signatures have been identified, including those of CH₄, H₂O, CO₂, CO, NH₃, HCN, C₂H₂, and some radicals (Fig. 9). This field of research is rapidly exploding and more discoveries are expected in the coming decade.

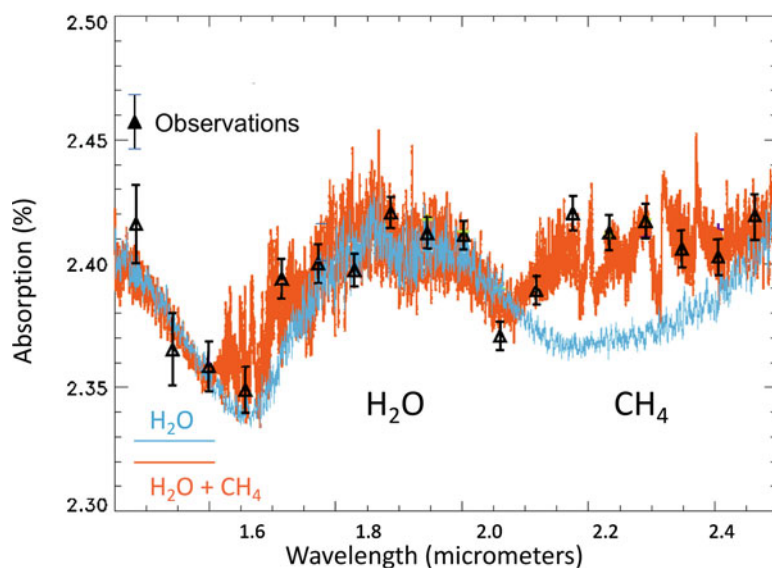
In addition to transit spectroscopy, the imaging technique is more and more associated with spectroscopic capabilities. This is the case of the SPHERE instrument on the VLT, which is equipped with a low-resolution spectrometer in the near infrared, thus allowing the characterization of young and warm planets located at several AU from their host star.

Future Directions

The number of known exoplanets – about 5,200 – now allows statistical studies to be performed, and the characterization of their atmospheres is becoming technically feasible. In the future,

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Fig. 9 Detection of H₂O and CH₄ in the atmosphere of a hot Jupiter, HD189733 b, using the near-infrared spectrometer of the Hubble Space Observatory. The black triangles are the data. The curves show atmospheric models including H₂O (in blue) and (H₂O + CH₄) in orange. Both molecules are clearly detected. (Source: Swain et al. 2008)



studies will use both indirect and direct detection techniques.

The radial velocity method will take advantage of the advent of extremely large telescopes, expected to get their first light within the coming decade. In parallel, the extension of the spectral range to the near infrared range will give access to K and M stars, more numerous than the Sun. Large telescopes will also be precious for the development of imaging techniques, as well as the transit spectroscopy of large exoplanets around bright stars in the infrared spectral windows accessible from the ground.

In space, the astrometric Gaia mission, in operation since 2013, is expected to bring revolutionary results by making possible, within a few years, the detection of thousands of exoplanets by astrometry. In December 2021, the launch of the James Webb Space Telescope, with its two spectrometers, in the near infrared (NIRSpec) and the mid-infrared range (MIRI), has been a major step forward for the spectroscopy of transiting exoplanets. However, in view of the long exposure times and the strong competition for observing time, the number of potential targets will be limited. Other space missions devoted to exoplanet detection and characterization have been scheduled for the coming decade and beyond. Following TESS and CHEOPS, presently in operation, the European PLATO mission, with enhanced capabilities, is expected to be launched around 2026. Two years later, the Ariel mission, also developed by ESA, is expected to bring a complete inventory of the spectral characteristics of about 1000 exoplanets.

Cross-References

- [Brown Dwarf](#)
- [Coronagraphy](#)
- [CoRoT Satellite](#)
- [Direct-Imaging, Planets](#)
- [Eccentricity](#)
- [Exoplanets, Discovery](#)
- [Gaia Hypothesis](#)
- [Giant Planets](#)
- [Habitable Zone](#)

- [Hot Jupiters](#)
- [Hubble Space Telescope](#)
- [Late Heavy Bombardment](#)
- [Metallicity](#)
- [Nulling Interferometry](#)
- [Planet Formation](#)
- [Planetary Migration](#)
- [PLATO 2.0 Satellite](#)
- [Protoplanetary Disk](#)
- [Pulsar Planets](#)
- [Radial-Velocity Planets](#)
- [Snow Line](#)
- [Spitzer Space Telescope](#)
- [TPF/Darwin](#)
- [Transiting Planets](#)
- [VLT](#)
- [Water in the Solar System](#)

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Exoplanets, Discovery

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[Extrasolar planets](#)

Definition

Exoplanets, also known as extrasolar planets, are planets beyond the solar system, orbiting around stars other than the Sun. The discovery of the first exoplanet happened in 1992 when three planets were discovered around the pulsar PSR 1257+12 (Wolszczan and Frail 1992). The first planet around a Sunlike star (hence the name *extrasolar* planet) was discovered in 1995 by Mayor and Queloz.

Overview

The quest for planets beyond the solar system has achieved spectacular progress during the last 25 years. In the few years to come, astronomers

will discover tens of thousands of planets (thanks to Gaia for instance). Many of which will be similar to Earth, orbiting Sun like stars, and some of which could possibly support life as we know it.

After the discovery of the planetary system around pulsar PSR 1257+12 in 1992, the initial discoveries of extrasolar planets involved giant planets with enough mass to induce measurable reflex motions in the stars they orbited, thus implying the presence of unseen planets. Unlike what many had anticipated that planets would be detected by astrometry through identifying stellar motion in the plane of the sky and across the line of sight, it was the stellar motions along the line of sight (i.e., perpendicular to the plane of the sky) based on measurements of the changes in radial velocities using Doppler spectroscopy at optical wavelengths that opened the exoplanet floodgates. The conventional thinking was dominated by the architecture of the solar system, with the giant planets in wide circular orbits out past the ► [snow line](#), where conditions were cold enough for them to form. The first radial-velocity orbit for an unseen companion that could be called a giant planet (if the orbit happened to be oriented nearly edge on) was published in 1989, but it defied conventional wisdom on three counts. The orbital period of only 84 days placed it far inside the snow line, where conditions would have been too hot for a gas giant to form; the orbit was eccentric, unlike any of the giant planets in the solar system, and the mass was at least ten times that of Jupiter, which was uncomfortably large (and close to the mass of a small ► [brown dwarf](#)). Thus, most astronomers dismissed the unseen companion of HD114762 (Latham et al. 1989) as a star or brown dwarf in an orbit seen nearly face on (thus minimizing the observed Doppler effect, which only measures the velocity along the line of sight). It was assumed that the observed orbital amplitude of 0.5 m/s was small because of projection effects and not because the mass of the companion was small enough to be a planet.

In 1992, the detection of a system of unseen planets orbiting the pulsar PSR B1257+12 was

announced (Wolszczan and Frail 1992). Unlike the case of HD114762, these planets were detected based on periodic variations in the arrival times of the radio pulses from their rotating neutron host star. Follow-up observations, using the detection of perturbations in the pulse arrival times consistent with gravitational interactions involving planetary-mass objects, soon demonstrated that the masses were indeed small and similar to the mass of Earth. Astronomers were puzzled how planets could survive the ► [supernova](#) event that created the neutron star or alternatively how they might have formed from the leftover debris, but it seemed clear that if planets could find a way to live around a pulsar, maybe they would prove to be common around normal stars similar to the Sun.

That is how the search for planets around Sun like stars stood. Because our solar system was used as a template, the search for giant planets (which could induce larger reflex motion on their host stars) was focused on distances beyond the snow line. It was in 1995 when an orbit for 51 Pegasi was announced that implied an unseen companion with a mass similar to Jupiter and a remarkably short period of only 4.2 days (Mayor and Queloz 1995). Soon after this announcement, many argued that because of the uncertainty in the inclination of the planet's orbit and therefore the value of its actual mass, the unseen object may in fact be a more massive body such as a brown dwarf. The initial resistance was, however, overwhelmed by the announcement of several other low-Doppler-amplitude orbits implying giant planets, often in eccentric orbits close to their parent stars, some of them quite massive. Too many were being found for them all to lie in orbits facing the Earth and thus to possibly be brown dwarfs. A population of extrasolar planets was being revealed, although for any particular candidate the mass could not be pinpointed until the inclination of the orbit to the line of sight could be established.

Ambitious Doppler surveys of hundreds and even thousands of solar-type stars rapidly expanded the known population of radial-velocity planet candidates. As the surveys were sustained

over longer durations, planets with longer periods were discovered. As the instrumental techniques improved and the velocity precisions improved, the discoveries were extended to smaller masses as well. As richer data sets were accumulated, systems with more than one planet were discovered. Finally, in the search for habitable planets, the surveys were focused on cool, low-mass stars. By now, a new class of bodies known as *super-Earths* has been identified, some of which with masses only a few times that of Earth, orbiting in the habitable zones of their host stars. These accomplishments are described in more detail in the entry ► [“Radial-Velocity Planets”](#).

To remove the ambiguity in the actual mass of an unseen companion revealed by a radial-velocity orbit (traditionally termed as a ► [spectroscopic orbit](#) by astronomers), the inclination of the orbit to the line of sight must be established so that the observed orbital velocity can be corrected for projection effects. Astrometry of the orbital motion on the plane of the sky can in principle resolve this ambiguity because of the extra information provided by the motion in two dimensions across the line of sight. Indeed, in a few cases, astrometry has provided orbital inclinations for radial-velocity planets. However, the real breakthrough for deriving actual masses for planets (and therefore confirming their planetary nature) came with the discovery of systems with orbits oriented close enough to be edge on as seen from the Earth so that the planets transited across the face of their host stars. The first of such transiting planets was HD209458 (Charbonneau et al. 2000; Henry et al. 2000). Detection of planets using transit photometry opened a new chapter in the exoplanetary science. Not only does this technique allow the actual mass of the transiting planet to be determined (the orbital inclination with respect to the plane of the sky is now known and is near 90°), it also enables one to determine the radius of the planet. The amount of stellar light blocked by the shadow of the planet allows the area, and therefore planet's radius, to be measured. Knowing the mass and radius of a planet, its bulk properties such as the density and surface gravity can be calculated.

It turns out that transiting planets also provide a rich variety of opportunities to learn additional planetary astrophysics. This includes observations of planetary atmospheres during both the transits and the secondary eclipses (sometimes called occultations), when the planet disappears behind its star, yielding the temperature and chemical composition of the planet's atmosphere. In some cases, the thermal emission from the planet has been tracked as it moves around in its orbit, thus revealing the changes in temperature as more of the dayside comes into view and providing insights into the weather on the planet. The degree of the alignment of the planet's orbit with the equator of its host star can also be determined in transiting system. Using the ► [Rossiter-McLaughlin effect](#), one can determine the tilt of the stellar spin axis to the planetary orbit which can provide important clues about the history of the formation and evolution of the planet. Similar to planetary systems detected by radial velocity, additional planets may exist in transiting systems (which may or may not transit). These planets may reveal their presence by perturbing the times at which transits of other planets are observed. Known as *transit-timing variation (TTV)* method, these variations have been used to detect several planets by the *Kepler* space telescope. Perhaps surprisingly, the detailed shape of a transit can pin down the density of the host star, and if the shape is determined with sufficient precision, details such as the oblateness of the planet due to rotation can also be determined. These topics are treated in more detail in the entry ► [“Transiting Planets”](#).

An entirely different approach to the detection of unseen planets orbiting distant stars takes advantage of an effect called gravitational microlensing. When the line of sight to a distant star (the source) is intersected very precisely by an intervening star (the lens), the light of the distant star is magnified by the lensing effect of the gravity of the intervening star. As the relative motion of the two stars changes the exact alignment, the changing magnification produces a light curve that first brightens and then dims in a way that can reveal information about the

lensing star (e.g., its mass). If a planet is orbiting the lens in such a way that it passes close to the line of sight, it can affect the brightening and introduce a feature in the light curve. Although the precise alignment needed to produce a microlensing event is very rare, and the alignment to reveal an orbiting planet is even more rare, surveys to monitor hundreds of millions of stars have detected and characterized several microlensing planets. These results and some details of the technique are described in the entry [“Microlensing Planets”](#).

An attractive way to study the characteristics of an extrasolar planet would be to isolate its light from that of the host star to produce a direct image for further studies such as astrometry to reveal the planet's orbit or spectroscopy to explore the structure and chemical composition of its atmosphere. Such experiments present daunting technical challenges because of the extreme brightness ratio and the tiny angular separation between the planet and its host star, even for the nearest systems. Direct images of a few giant planet candidates in wide orbits around hot stars have now been obtained both with special techniques from the ground and with the *Hubble Space Telescope*. Earth-sized planets will be much more difficult to image and will require specialized space missions or ground-based “extremely large telescopes.” More details can be found in the entry ► [“Direct-Imaging, Planets”](#).

Cross-References

- [51 Pegasi B](#)
- [Astrometric Planets](#)
- [Beta Pictoris b](#)
- [Coronagraphy](#)
- [Direct-Imaging, Planets](#)
- [Exoplanet, Detection, and Characterization](#)
- [HD 209458b](#)
- [Nulling Interferometry](#)
- [Pulsar Planets](#)
- [Radial-Velocity Planets](#)
- [Snow Line](#)
- [Spectroscopic Orbit](#)
- [Transiting Planets](#)

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Exopolymers

Lucas J. Stal
Department of Marine Microbiology, Royal
Netherlands Institute of Sea Research (NIOZ),
Yerseke, The Netherlands

Keywords

Biofilm · Cyanobacteria · Diatoms ·
Microalgae · Polymers

Synonyms

EPS; Extracellular polymeric substances; Extracellular polymers; Extracellular polysaccharides

Definition

Exopolymers are polymers that are deposited outside the (microbial) cell. These polymers are predominantly composed of carbohydrates, but many contain various other components such as proteins, DNA, and glycolipids. Some exopolymers consist of neutral sugars such as glucose, while others are acidic in nature and contain a variety of charged groups such as the uronic acids, carboxy groups, sulfated sugars, or pyruvate groups. The molecular structure and composition of exopolymers is therefore highly diverse and complex. Exopolymers form the matrix of biofilms in which the microorganisms are embedded but also serve a plethora of other functions.

Overview

Exopolymers are by definition polymers that are deposited outside the cell wall. These include sheaths or investments in which the cell, but often also aggregates or chains or threads of cells, are wrapped and represent a more or less structural part of the organism. Such sheaths may be highly structured and may have a typical morphology, while other infestations are more diffuse. Other exopolymers do not have a close association with the cells that produce them. They are exuded into the environment and “dissolve” as colloidal exopolymers in the water or form in the benthic environment the biofilm matrix in which the microorganisms are embedded.

Exopolymers that are exuded into the environment are usually the result of unbalanced growth, for instance, when photosynthetic organisms fix CO₂ but are limited by nutrients. In that case, the fixed carbon cannot be accommodated by the synthesis of structural cell material and will be deposited as polysaccharide. Part of it will be stored intracellularly as a reserve compound but the bulk will find its way as colloidal exopolymers. The same may be the case with chemotrophic microorganisms that live at the expense of energy-rich but nutrient-poor resources.

Exopolymers can also exude as a result of the gliding motility by some bacteria, notably by ► [cyanobacteria](#). The exopolymers are exuded through specific pores in the cell wall and interact with the substrate on which the organism glides, leaving behind a trail of exopolymer. The mechanism of gliding motility is still poorly understood.

Exopolymers are not just waste products. They may serve a variety of important functions for the organism that produces them as well as for the ecosystem as a whole. It has been shown that benthic diatoms metabolize the exuded exopolymers as a carbon and energy source in the dark. Exopolymers form the matrix of biofilms. They may be important for attachment of microorganisms to surfaces. This may be important for the success of the organism but represents also a problem known as fouling. Exopolymers form coherent networks and matrixes that may interact

covalently with mineral particles, resulting in sediments with a high erosion threshold. Hence, exopolymers have found application in sediment stabilization. Exopolymers may bind calcium and magnesium ions, thereby controlling calcification. It may act as an anti-calcification agent, but it may also allow local calcium carbonate precipitation and hence the tertiary structure of the polymer may determine the morphology of the calcium carbonate. This is the case with the calcium carbonate platelets known as coccoliths, which are produced by certain marine microalgae. Exopolymers protect the microorganisms from being grazed and immobilize (heavy) metals and other toxic compounds and antibiotics. The latter is an important problem for curing infections by pathogenic bacteria, while the former has found application in bioremediation of polluted soils. Many exopolymers may form a gel through the absorption of large amounts of water. This gel protects the organism from desiccation. Exopolymers can also scavenge important nutrients from the environment, thereby providing the biofilm organisms with an important advantage compared to free-living pelagic microorganisms. Finally, exopolymers can act as flocculants. Some benthic cyanobacteria have been shown to produce it in order to bind mineral particles, thereby clearing in the water column above them.

Cross-References

- [Archaeal Traces of Life](#)
- [Biomarkers, Morphological](#)
- [Cyanobacteria](#)

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Exothermic

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

The term exothermic refers to a reaction or a physical transformation which releases energy if it takes place at constant volume or which releases ► [enthalpy](#) if it takes place at constant pressure. A familiar exothermic reaction is the ► [combustion](#) of coal. The enthalpy change (ΔH) during an exothermic reaction or transformation taking place at constant pressure is negative by definition. The enthalpy release takes the form of a heat release.

Cross-References

- [Combustion](#)
- [Endothermic](#)
- [Enthalpy](#)

Exozodi

- [Exozodiacal Light](#)

Exozodiacal Light

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Dust particles · Exoplanet · Interplanetary
dust · Scattering

Synonyms

Exozodi

Definition

The exozodiacal light is the analog in extrasolar planetary systems of the ► [zodiacal light](#) seen in the solar system. It corresponds to the light emitted by the central star, scattered – or reemitted in the infrared – by interplanetary small dust particles concentrated in the mean orbital planetary plane, that is, the local ► [ecliptic](#). It is often abbreviated as *exo-zodi*. This may be a strong emission that can prevent direct detection of planets belonging to the system.

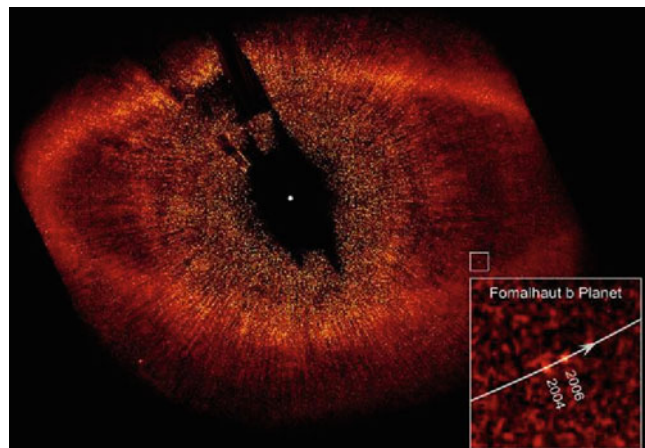
Overview

In the solar system, the zodiacal light appears as a flame-shaped glow just above the horizon, visible

to the naked eye in good atmospheric conditions and when the moon has not risen. It is seen only toward the west after sunset or in the east before sunrise and is aligned along the zodiacal belt, hence its name. It is due to sunlight reflected by dust particles of 1–100 μm in size, concentrated in the plane of the ► [ecliptic](#), mainly in its central region (approximately up to the asteroid belt). Because the dust particles are heated by the sunlight to a temperature comparable to the Earth's (300 K), they also emit in the infrared. It is generally admitted that extrasolar planetary systems must harbor a similar content of dust and thus exhibit an analog of the zodiacal light in the visible and infrared. The origin of this dust can be primitive material in the ► [protoplanetary disk](#), but more often in mature systems, it corresponds to debris left after planet formation when the remaining ► [planetesimals](#) suffered collisions and evaporation. The question of the intensity of the exozodiacal light is extremely important when dealing with the direct detection and characterization of planets in the ► [habitable zone](#), because exozodiacal light intensity may be so large that it would dominate by several orders of magnitude the signal from a planet. In the solar system, for instance, the zodiacal light is 300 times stronger than the emission of the Earth at a wavelength of 10 μm . The name exozodi was proposed as an abbreviation when its importance was realized and discussed in its details. It is generally assumed that the detection of an earthlike planet should be possible, provided that the exozodi does not exceed ten times the solar system value. A consequence is that before launching an

Exozodiacal Light,

Fig. 1 HST coronagraphic image of the star Fomalhaut at 0.6 μm , showing together the dust belt responsible for the exozodiacal light emission and the planet Fomalhaut b (*white square*) just within the inner boundary of the dust belt, at two different dates



expensive space mission that aims at direct detection of exoplanets, precursor missions or possibly measurements from the ground should assess the relative frequency of large and medium exozodi intensities in the visible and in the infrared. Figure 1 shows an image of the exosystem Fomalhaut where the exozodi is resolved as a ring and contributes to the background against which a planet has been directly detected (Kalas et al. 2008). A few stars have been identified as exhibiting an exozodiacal light, at least in the infrared domain: Beta Pictoris and 51 Ophiuchus are two examples.

Cross-References

- [Debris Disk](#)
- [Exoplanets, Discovery](#)
- [Zodiacal Light](#)

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Experimental Evolution

- [Evolution, In Vitro](#)

Explosive Nucleosynthesis

- [Nucleosynthesis, Explosive](#)

EXPOSE

Hervé Cottin

Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, Créteil, France

Keywords

Exposure facility · International Space Station · Low Earth orbit · Photobiology · Photochemistry · Space radiations

Synonyms

[EXPOSE-E](#); [EXPOSE-R](#); [EXPOSE-R2](#)

Definition

EXPOSE-E, EXPOSE-R, and EXPOSE-R2 are exposure facilities developed by ESA in the 2000s and 2010s to investigate the effect of the space environment (especially energetic radiations) on various chemical and biological samples. EXPOSE-E was installed on the ► [International Space Station](#) outside of the European Columbus module on the European Technology Exposure Facility (EuTEF) from February 2008 to August 2009, while EXPOSE-R was installed outside the Russian module Zvezda from March 2009 to March 2011. EXPOSE-R2 was a reload of EXPOSE-R with new experiments, which was exposed (also outside Zvezda) from October 2014 to February 2016.

Overview

A picture of one of the EXPOSE facilities is shown in Fig. 1. Data from six temperature sensors connected to the three trays, four UV-B sensors, and one radiometer were recorded.

Experiments selected by ESA to be implemented on EXPOSE-E, EXPOSE-R, and



EXPOSE, Fig. 1 The EXPOSE-R2 facility (480 × 520 × 327.5 mm) outside the International Space Station. EXPOSE facilities are made of three experiment trays into which four square sample carriers

(77 × 77 × 26 mm) are fitted (Credit Roscosmos). In most of the experiments, one layer of samples is exposed to space, while another layer is fitted just below the first one to be used as flight controls

EXPOSE, Table 1 Astrobiology experiments selected after the first call of ESA in 1996 and finally accommodated on EXPOSE-R

Experiment	Topic of research	Principal investigator
AMINO	Photochemical processing of organic compounds, including amino acids, RNA fragments, and samples relevant to cometary and Titan chemistry	H. Cottin, LISA/UPEC – Créteil (France)
ORGANIC	Study of the evolution of organic matter in space (PAHs)	P. Ehrenfreund – Leiden Observatory (NL)
ROSE-1/ENDO	Study of the impact of extraterrestrial UV radiation on microbial primary producers (algae and cyanobacteria)	C. Cockell – Open University (UK)
ROSE-2/OSMO	Study of the protective effects of osmophilic microorganisms enclosed within gypsum-halite crusts	R. Mancinelli – SETI Institute, NASA Ames (USA)
ROSE-3/SPORES with R3D	Study of the protection of spores by meteorite material against space conditions: UV, vacuum, and ionizing radiation/radiation dosimetry	G. Horneck – DLR (Germany)
ROSE-4/PHOTO	Study of the photoproducts resulting from exposure of dry DNA samples or bacterial spores to solar UV radiation	J. Cadet – CEA Grenoble (France)
ROSE-5/SUBTIL	Study of the mutational spectra of <i>Bacillus subtilis</i> spores induced by space vacuum and/or solar UV radiation	N. Munakata – University of Tokyo (Japan)
ROSE-8/PUR	Study of the biologically effective dose of solar extraterrestrial UV radiation by biological dosimetry	G. Rontó – Research Lab. for Biophysics, Budapest (Hungary)

EXPOSE-R2 are presented in Tables 1, 2, and 3 (Rabbow et al. 2009; Cottin et al. 2017).

EXPOSE experiments series have provided a large amount of data about the photostability of organic compounds in the context of the study of extraterrestrial environments such as comets, (micro)meteorites, the surface of Mars, the atmosphere of Titan, or interstellar medium (see, e.g.,

Stalport et al. (2019) or Baratta et al. (2019)). Furthermore, results are helping to build strategies of detections of the targeted samples or their photoproducts with telescopes, space probes, or rovers. Regarding biology, it has allowed exploring the limits of life in extreme environments and how bacteria can cope with high doses of radiation for a long duration. Enlightened hypotheses about

EXPOSE, Table 2 Astrobiology experiments selected after the second call of ESA in 2004 and finally accommodated on EXPOSE-E

Experiment	Topic of research	Principal investigator
ADAPT	Study of molecular adaptation strategies of microorganisms to different space and planetary UV climate conditions	P. Rettberg – DLR (Germany)
DOSIS/ DOBIES	Passive radiation dosimetry at the sample sites	G. Reitz – DLR (Germany)/F. Vanhavere – SCK CEN (Belgium)
LIFE	Study of the resistance of lichens and lithic fungi at space conditions	S. Onofri – Università degli studi della Tuscia di Viterbo (Italy)
PROCESS	Study of photochemical organic chemistry relevant to comets, meteorites, Mars, and Titan	H. Cottin, LISA/UPEC – Créteil (France)
PROTECT	Study on the resistance of spacecraft isolates to outer space for planetary protection purposes	G. Horneck – DLR (Germany)
R3D-2	Active radiation dosimetry (VIS, UV-A, UV-B, UV-C, and LET spectra of cosmic radiation)	D-P. Häder – University of Erlangen (Germany)
SEEDS	Study of plant seed as a terrestrial model for a Panspermia vehicle and as a source of universal UV screens	D. Tepfer – CNRS, Versailles (France)

EXPOSE, Table 3 Astrobiology experiments selected by ESA in 2010 to be accommodated on EXPOSE-R2

Experiment	Topic of research	Principal investigator
BIOMEX	Study of the stability of pigments, cellular components, and extremophiles under space and Mars-like conditions	J.P. de Vera – DLR (Germany)
BOSS	Study of the stability of bacteria exposed as biofilms and microbial mat communities under space and Mars-like conditions	P. Rettberg – DLR (Germany)
PSS	Study of the stability of organic compounds with a prebiotic relevance under space and Mars-like conditions	H. Cottin, LISA/UPEC – Créteil (France)

how microorganisms could survive in the Martian environments, or in meteorites ejected from one planet to another, can be derived from EXPOSE results (see, e.g., Billi et al. (2019), de Vera et al. (2019)).

One of the main limitations of EXPOSE was that scientists only had information about the samples before shipping them to space and then after their return in laboratories. This is one of the reasons why EXPOSE experiments series were discontinued by ESA after EXPOSE-R2 to be replaced by a new generation of exposure facilities allowing to monitor the samples during the exposure.

Cross-References

- [BIOPAN](#)
- [International Space Station](#)
- [Ionizing Radiation, Biological Effects](#)

- [Lyman Alpha](#)
- [Photolysis](#)
- [Radiation Biology](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [UV Radiation](#)

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Exposed Surface Bioburden

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

The term “exposed surface ► [bioburden](#)” is used to indicate the number of viable ► [microorganisms](#) that are carried on internal and external spacecraft surfaces that are available for particulate and gas exchange, and from which microorganisms could reach a planetary environment following the nominal landing of a spacecraft.

Cross-References

- [Bioburden](#)
- [Microorganism](#)
- [Planetary Protection](#)

EXPOSE-E

- [EXPOSE](#)

EXPOSE-R

- [EXPOSE](#)

EXPOSE-R2

- [EXPOSE](#)

Exposure Facilities

Gerda Horneck
German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Outer space parameters · Photochemical reactions · Space experiments · Survival

Synonyms

[Exposure platforms](#); [Exposure trays](#)

Definition

Exposure facilities are technical devices attached to the outer shell of a spacecraft with the purpose to expose ► [organic molecules](#), ► [microorganisms](#), and other small biological systems to outer space or to selected parameters of this extreme environment.

History

Soon after the advent of space flight, the accessibility of space has been used to study specific questions of astrobiology, such as the role of stellar ► [UV radiation](#) in the evolution of potential precursors of life, the role of the UV radiation climate in prebiotic and biological evolution on Earth or any other celestial body, and the likelihood of viable interplanetary transfer of life and the limiting factors of ► [Panspermia](#). First attempts were already performed during the Gemini program (Hotchin et al. 1968); they were continued in a more sophisticated manner during the Apollo program and up to the present studies on the ► [International Space Station \(ISS\)](#) (Horneck et al. 2010).

Overview

To expose chemical or biological samples to outer space or selected parameters of this extreme environment, several exposure facilities were developed for attachment to the outer shell of spacecraft (Table 1).

The first sophisticated exposure device was built in 1972 by ► [NASA](#), the Microbial Ecology Evaluation Device (► [MEED](#)) for the Apollo 16 mission (Taylor et al. 1974). MEED was mounted to the distal end of the TV boom of the Command Module during the extravehicular activity phase of the trans-Earth coast. It was composed of 798 sample cuvettes with quartz windows as optical filters with the optional provision of ventilation holes for access to space vacuum (Fig. 1). Using a solar positioning device, MEED was oriented directly perpendicular to the sun. In 1983, Spacelab 1 (SL 1) carried the exposure facility ES029 in its cargo bay (Horneck et al. 1984). ES029 consisted of an exposure tray partitioned in four square quartz-covered compartments (Fig. 2). Two of the compartments were vented to the outside, allowing access to space vacuum. The other two compartments were hermetically sealed with a constant pressure of 10^5 Pa. Each compartment accommodated 79 dry samples in the upper layer, allowing UV

exposure, and the same number was kept in the bottom layer as flight dark controls. UV-irradiated samples were placed beneath an optical filtering system composed of interference filters for narrow wavebands (220 nm, 240 nm, 260 nm, and 280 nm) and neutral density filters. A non-transparent shutter with optical windows was used to achieve precise irradiation intervals during the “hot phase” of the mission, when during several orbits the cargo bay of the shuttle was perpendicularly pointing towards the sun. The samples were exposed to space vacuum for 10 days and for predefined periods (from 19 min to 5 h 17.5 min) to solar UV radiation. The temperature ranged from 17 °C to 35 °C, the highest values occurring during the “hot phase” of the mission. A similar device was flown in 1993 with the experiment UVRAD during the German SL D2 mission that provided a “hot phase” during two orbits at the end of the mission.

Long-term exposures of organic chemical compounds and microorganisms to space started with the NASA ► [Long Duration Exposure Facility \(LDEF\)](#) and were continued with the European Retrievable Carrier (EURECA) mission (Fig. 3) (Innocenti and Mesland 1995), and the French PERSEUS mission on the Russian MIR station (Rettberg et al. 2002). The longest exposure of microorganisms to space, about 6 years (1984–1990), was achieved during the LDEF mission within the German experiment Exostack (Horneck et al. 1994). Frequent opportunities for short-duration exposure experiments (up to 15 days) of molecules and biological systems were provided by ESA’s Biopan facilities, cylindrical pan-shaped containers with a deployable lid mounted on the outer surface of the descent module of a Russian Foton satellite (Fig. 4) (Demets et al. 2005). The Foton satellite was also used to study the mineral decomposition and microbial survival during atmospheric reentry within the ► [STONE](#) experiments (Brandstätter et al. 2008; Cockell et al. 2007; de la Torre et al. 2010).

Advanced exposure facilities with up to four times the capacity of the ES029 experiment of SL 1 were developed by the ► [European Space Agency \(ESA\)](#) with the Exobiology Radiation Assembly (ERA) for the ► [EURECA](#) mission

Exposure Facilities, Table 1 Exposure facilities used on space missions to study the stability of organic molecules and the survival of biological systems in outer space (Horneck et al. 2010)

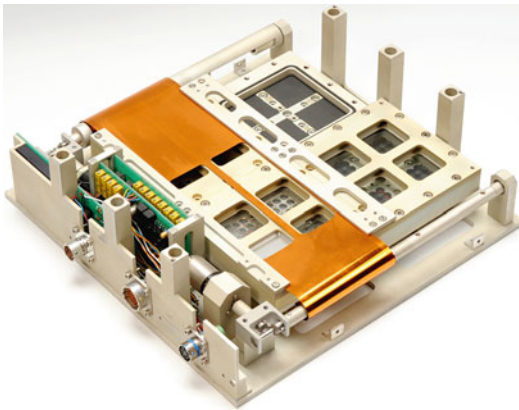
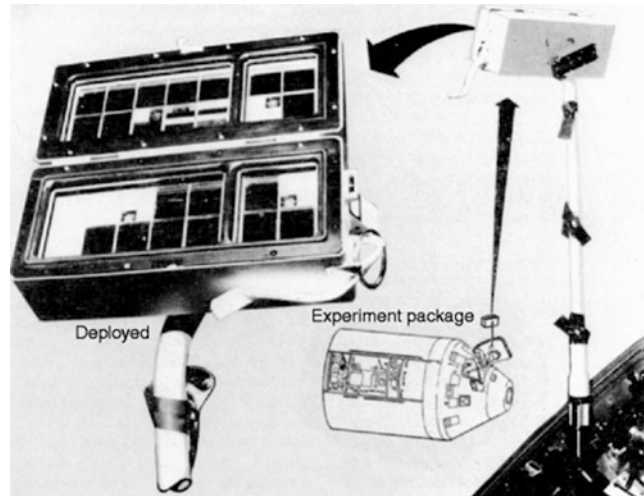
Year	Mission name	Mission characteristics	Exposure facility	Exposure duration	Space parameter studied
1966	Gemini IX and XII	Earth orbit (300 km alt)	Collecting/exposure device	16 h 47 min (GIX) 6 h 24 min (GXII)	Space, solar UV
1972	Apollo 16	Lunar mission	MEED	Vacuum: 1 h 20 min, UV: 10 min	Space vacuum; solar UV: 254, 280 nm
1983	Spacelab 1	Earth orbit (240 km alt.)	ES029	Vacuum: 9 days, UV: 19 min–5 h 17.5 min	Space vacuum; solar UV: >170; 220; 240; 260; 280
1984–1990	LDEF	Earth orbit (500 km alt.)	Exostack	2107 days	Space vacuum; solar UV
1992–1993	EURECA	Earth orbit, sun pointing	ERA	327 days	Space vacuum; solar UV: >110; >170; >280; >295; 220; 230; 260; 290 nm
1993	Spacelab D2	Earth orbit	RD-UVRAD	Vacuum: 10 days; UV: 5–120 min	Space vacuum; solar UV: 190; 210; 220; 230; 260; 280; >190; >304; >313; >314; >315; >316; >317 nm
1994	Foton 9	Earth orbit	Biopan-1	14.8 days	Space vacuum; solar UV
1997	Foton 11	Earth orbit	Biopan-2	10 days	Space vacuum. solar UV
1999	Foton 12	Earth orbit	Biopan-3	12.7 days	Space vacuum. solar UV
1999	MIR-Perseus	Earth orbit	Exobiologie	98 days	Space vacuum, solar UV
1999	Terrier Black Brant Rocket	Ballistic flight <304 km alt.	SERTIS	395 s	Space vacuum, solar EUV (30.4 nm)
2004	Terrier Mark 70-Improved Rocket	Ballistic flight <304 km alt.		350 s	High speed atmospheric entry
2005	Foton-M2	Earth orbit	Biopan-5	14.6 days	Space vacuum; solar UV: >170; >280; >320; >400 nm
			Stone-5		Meteorite entry in Earth's atmosphere
2007	Foton-M3	Earth orbit	Biopan-6	10 days	Space vacuum, solar UV: >110; >200; >290; >400 nm
			Stone-6		Meteorite entry in Earth's atmosphere
2008–2009	ISS-EuTeF	Earth orbit	EXPOSE-E	1.5 years	Space vacuum; solar UV: >110 nm; simulated Martian atmosphere and UV climate: >200 nm
2009–2011	ISS	Earth orbit	EXPOSE-R	~2 year	Space vacuum, solar UV: >110; >200 nm

(Fig. 3) and the ► **EXPOSE** facilities attached to the ISS (Rabbow et al. 2009). One EXPOSE unit consists of three trays (Fig. 5), each housing four compartments similar to those of the SL exposure

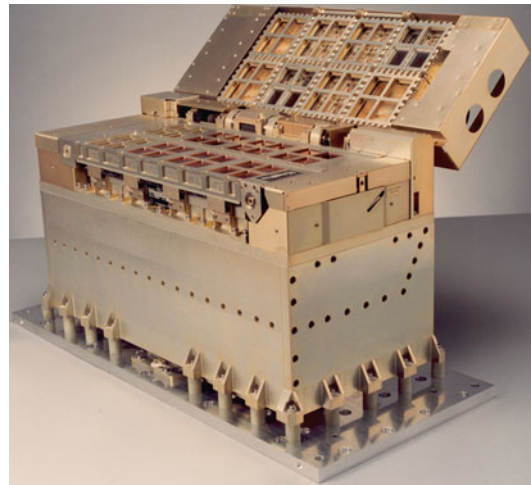
trays and of ERA. The EXPOSE-E facility was mounted during extravehicular activity to the European Columbus Module of the ISS as part of the European Technology Facility (EuTeF)

Exposure Facilities,

Fig. 1 Exposure facility MEED, which was mounted on the camera beam of the lunar orbiter of the Apollo 16 mission. (Credit: NASA)



Exposure Facilities, Fig. 2 Exposure tray of the ES029 experiment, which was mounted on a cold plate in the cargo bay of SL 1



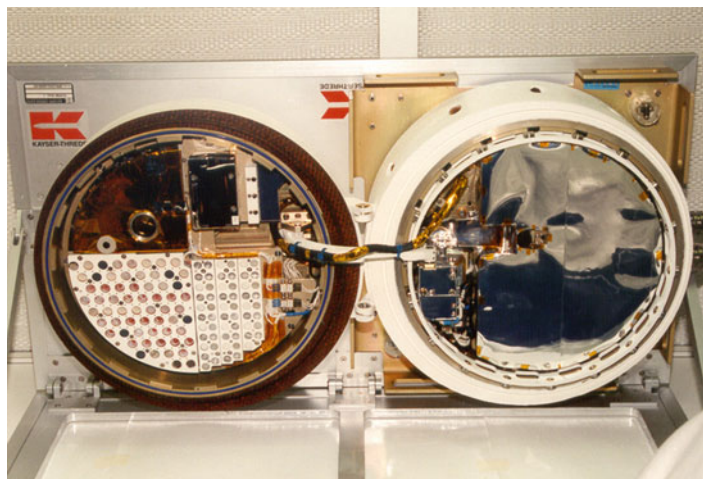
Exposure Facilities, Fig. 3 Exposure tray of the Exobiology Radiation Assembly (ERA), which was mounted on the EURECA platform. (Credit: ESA, from Horneck et al. 2010)

platform in February 2008 and retrieved in September 2009. Experiments on prebiotic chemical evolution were located in one tray of EXPOSE-E; the other two trays accommodated different microbial systems, either exposed to outer space conditions (space vacuum and solar UV spectrum of $\lambda > 110$ nm) or to simulated Mars surface climate (600 Pa pressure, 95% CO₂, and solar UV of $\lambda > 200$ nm). The second EXPOSE facility, EXPOSE-R, was launched in November 2008 and will remain attached to the URM-D platform, an external ISS facility at the Russian Zvezda module, for about 2 years. EXPOSE-E

and EXPOSE-R house a total of 13 different experiments that are performed in international cooperation (Baglioni et al. 2007). Before launching into space, all EXPOSE experiments were tested in carefully designed ground simulation experiments and in an experiment sequence test using the Planetary and Space Simulation Facilities (PSI) at the ► [German Aerospace Center DLR](#). The EXPOSE experiments will be continued with EXPOSE-R2.

Exposure Facilities,

Fig. 4 Biopan facility with lid opened, which was mounted on the outside of Foton satellites. (Credit ESA, from Horneck et al. 2010)



E

Exposure Facilities,

Fig. 5 EXPOSE-E facility (arrow), which was mounted on the EuTef platform of the ESA Columbus facility of the ISS. (Credit ESA)

**Cross-References**

- BIOPAN
- Exobiologie Experiment
- EXPOSE
- Extreme Environment
- Foton Capsule, Spacecraft
- Inactivation
- International Space Station
- Lichens
- Lithopanspermia
- Long Duration Exposure Facility
- Mars
- MEED

- Panspermia
- Spore
- STONE

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Exposure Trays

► Exposure Facilities

Extended Red Emission

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

ERE

Definition

The broad emission band observed in some interstellar environments (e.g., ► [reflection nebulae](#), ► [planetary nebulae](#), ► [HII regions](#), interstellar “► [cirrus clouds](#)”) extending between about 600 and 800 nm is referred to as extended red emission (ERE). It is thought to be the result of photoluminescence from ► [interstellar dust](#), although it is not clear whether the carrier is carbon-rich or silicate-rich material. The spatial distribution of ERE is, in many cases, similar to that of ► [polycyclic aromatic hydrocarbons](#) (PAHs).

Cross-References

- [Cirrus Cloud](#)
- [HII Region](#)
- [Planetary Nebula](#)
- [Polycyclic Aromatic Hydrocarbon](#)
- [Reflection Nebula](#)

Exposure Platforms

► Exposure Facilities

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Extensive Plain

- [Vastitas, Vastitates](#)

Extinct Radionuclides

Daniele L. Pinti
GEOTOP Research Center for the dynamics of
the Earth system, Université du Québec à
Montréal, QC, Canada

Synonym

[Short-lived radionuclides](#)

Definition

Extinct radionuclides are atoms with unstable nuclei that have undergone radioactive decay into atoms of another element in a geologically short time; usually, half-lives of parent nuclides range from 80.8 Myrs (Plutonium-244 decay to xenon isotopes) down to 60,000 years (Lanthanum-137 decay to Barium-137). These elements, which originated from processes of stellar nucleogenesis in supernovas, are now extinct in nature because of their short half-lives, relative to the age of the Earth (4.5 Ga). A parent nuclide is considered as extinct after seven half-lives. An example is ^{26}Al , with a half-life of 0.7 Ma, which decays into ^{26}Mg . After 3.5 Myrs, the ^{26}Al could be considered as extinct. These radionuclides allow dating of objects formed early in the history of the solar system. Indeed, these objects contain traces of the daughter elements produced by decay of the incorporated parent nuclides, prior to their extinction. Intense decay heat generated by these radionuclides is thought to have allowed the total melting of medium- to small-size planetary bodies, driving early planetary differentiation.

Cross-References

- [Earth, Age of](#)
- [Geochronology](#)
- [Radioactivity](#)

Extinction Event

- [Mass Extinctions](#)

Extinction, Interstellar or Atmospheric

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The extinction is the decrease of the light intensity of a celestial object due to scattering and/or absorption by an intervening medium. The medium can be of telluric origin (molecules, aerosol in the atmosphere) or astrophysical (small dust particles in the ► [interstellar medium](#)); in the later case one speaks of interstellar extinction. Extinction is measured in ► [magnitudes](#) and the wavelength at which it applies should be indicated. The interstellar extinction is larger in the blue than in the red and becomes less and less important as the wavelength increases in the infrared domain. Because of this differential effect, extinction is responsible for the so-called *reddening* of distant stars. Reddening is characterized by the ► [color excess](#). The radio domain is essentially not affected by extinction. Interstellar extinction is generally noted A_F , where F is the symbol of the wavelength considered (U, B, V, etc.), defined by a passband filter. When no indication is given, it is assumed that the extinction is in the visible band (V). Typical extinction by the average ► [interstellar medium](#) in the plane of our Galaxy is $A_V = 2 \text{ mag/kpc}$ (1 kpc is about 3000 light-years).

Cross-References

- [Color Index](#)
- [Dust Grain](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Magnitude](#)
- [Reddening, Interstellar](#)

Extinction-Level Event

- [Mass Extinctions](#)

Extracellular Polymeric Substances

- [Exopolymers](#)

Extracellular Polymers

- [Exopolymers](#)

Extracellular Polysaccharides

- [Exopolymers](#)

Extrachromosomal Genetic Element

- [Plasmid](#)

Extrasolar Planets

- [Exoplanets, Discovery](#)

Extrasolar Planets Detection and Characterization

- [Exoplanet, Detection, and Characterization](#)

Extraterrestrial Delivery of Organic Compounds

André Brack

Centre de Biophysique Moléculaire CNRS,
Orléans, France

Keywords

Amino acids · Chirality · Comets · Impacts · Meteorites · Micrometeorites · Prebiotic compounds · Space experiments

Definition

The primitive Earth experienced a large spectrum of impactors ranging from the huge Mars-sized impactor which created the Moon to cosmic dust less than 1 μm in size. A great number of organic molecules, including amino acids, have been found in carbonaceous chondrites. Micrometeorite collection and analysis from the Greenland and Antarctic ice sheets suggest that the Earth accreted large amounts of extraterrestrial complex organic molecules. Intense bombardment probably caused some chemical reprocessing of the Earth's primitive atmosphere. Laboratory and space experiments support plausibility of the extraterrestrial delivery of organics to the primitive Earth.

Overview

Delivery of Extraterrestrial Organic Matter

Comets

Comets are the richest planetary objects in organic compounds known so far. Ground-based observations have detected hydrogen cyanide and formaldehyde in the coma of comets. In 1986, on board analyses performed by the two Russian missions Vega 1 and 2, as well as observations obtained by the European mission Giotto and the two Japanese missions Suisei and Sakigake, demonstrated that the Halley comet shows substantial amounts of organic material. On average, dust particles ejected

from the Comet Halley nucleus contain 14% of organic carbon by mass. About 30% of cometary grains are dominated by light elements C, H, O, and N, and 35% are close in composition to carbon-rich meteorites. The presence of organic molecules, such as purines, pyrimidines, and formaldehyde polymers, has also been inferred from the fragments analyzed by the Giotto Picca and Vega Puma mass spectrometers. However, there was no direct identification of the complex organic molecules probably present in the cosmic dust grains and in the cometary nucleus. Many chemical species of interest for exobiology have been detected in Comet Hyakutake in 1996, including ammonia, methane, acetylene (ethyne), acetonitrile (methyl cyanide), and hydrogen isocyanide. In addition, the study of the Hale-Bopp comet in 1997 led to the detection of methane, acetylene, formic acid, acetonitrile, hydrogen isocyanide, isocyanic acid, cyanoacetylene, formamide, and thioformaldehyde.

The Stardust mission collected samples of Comet Wild 2 and returned them to Earth in January 2006 for laboratory analysis. Unexpectedly, most of the comet's rocky matter formed inside the solar system at extremely high temperature. The grains contain organic functions (alcohol, ketone, aldehyde carboxylic acids, amides, and nitrile). The protein-building amino acid glycine has also been discovered.

Comets orbit on unstable trajectories and sometimes collide with planets. The collision of Comet Shoemaker-Levy 9 with Jupiter in July 1994 gave a recent example of such events. Such collisions were probably more frequent 4 billion years ago, the comets orbiting around the Sun being more numerous. Comets may therefore be an important source of organic molecules for the primitive Earth (Ehrenfreund and Charnley 2000; Despois and Cottin 2005). However, it is unlikely that whole comets could have safely delivered organics to Earth. They exploded either while entering the atmosphere or when impacting Earth's surface.

The European Rosetta probe launched in March 2004 to comet 67P / Churyumov-Gerasimenko reached its target in August 2014, after a journey of 7 billion kilometers. The probe detected glycine in the cometary tail (Altwegg

et al. 2016), confirming the Stardust results and the presence of complex carbonaceous matter similar to the insoluble organic matter present in carbonaceous meteorites. The lander, *Philae*, landed on the comet in November 2014, bouncing twice. During the first rebound, the probe was able to analyze the ice splashes. Sixteen organic compounds were identified (Goesmann et al. 2015).

Meteorites

Carbonaceous chondrites delivered organic materials to the early Earth. They contain from 1.5% to 4% of carbon, for the most part as organic materials. One hundred kilograms of the Murchison meteorite, a CM2-type carbonaceous chondrite that fell in Australia in 1969, has been extensively analyzed (Pizzarello 2007; Pizzarello and Shock 2010; Glavin et al. 2021). Murchison organic materials are generally classified according to their solubility in water and organic solvents. Insoluble and soluble components represent, respectively, 70% and 30% of total carbon components. The insoluble organic material is referred as kerogen-like, a poorly identified insoluble macromolecular material of complex composition with average elemental abundances $C_{100}H_{46}N_{10}O_{15}S_{4.5}$. NMR, IR, and pyrolysis analyses suggest the presence of aromatic ring clusters bridged by aliphatic chains, with peripheral branching and functional groups. The insoluble organic material releases a variety of aromatic and heteroatomic hydrocarbons as well as a suite of alkyl dicarboxylic acids up to C_{18} chain length under conditions similar to those of hydrothermal vents (Yabuta et al. 2007).

The soluble organic compounds of the Murchison meteorite represent a diverse and abundant group of organics that vary from small water-soluble compounds such as amino acids and polyols up to 30 carbon-long hydrocarbons. This diversity has been analyzed in considerable detail for the amino acids (Burton et al. 2012). The total number of detected meteoritic amino acid types is now about one hundred. All the possible α -amino alkylamino acids up to seven carbon atoms were identified as well as large abundances of N-substituted, cyclic, β -, γ -, δ -, and ϵ -amino acids. Eight protein-building amino acids

(glycine, alanine, proline, leucine, isoleucine, valine, aspartic acid, and glutamic acid) have been found. Nucleic acid bases, purines and pyrimidines, have also been found in the Murchison meteorite (Stoks and Schwartz 1982). Ribose was recently identified in the soluble organic matter of carbonaceous chondrites (Furukawa et al. 2019). Vesicle-forming fatty acids have been extracted from different carbonaceous meteorites (Yuen and Kvenvolden 1973; Deamer 1985, 1998).

A combination of high-resolution analytical methods, composed of organic structural spectroscopy FTICR/MS, UPLC-QTOF-MS, and NMR, applied to the organic fraction of Murchison extracted under mild conditions allowed to extend its Indigenous chemical diversity to tens of thousands of different molecular compositions and likely millions of diverse structures (Schmitt-Kopplin et al. 2010; Hertkorn et al. 2015).

Most of the amino acids detected in carbonaceous chondrites are chiral but present as racemic, i.e., L- and D-enantiomers are present in equal proportions. However, Cronin and Pizzarello (1997) found L-enantiomer excesses in six α -methyl- α -amino alkanolic acids from the Murchison (2.8–9.2%) and Murray (1.0–6.0%) carbonaceous chondrites. An enantiomeric excess, up to 18%, has been measured for isovaline (2-methyl-2-aminobutyric acid). These amino acids (isovaline, 2-amino-2,3-dimethylpentanoic, α -methyl norvaline, α -methyl valine, and α -methyl norleucine) are either unknown or rare in the terrestrial biosphere and cannot therefore be attributed to terrestrial contamination (Pizzarello 2007). In addition, the indigeneity of D- and L-isovaline enantiomers is supported by carbon and hydrogen isotopic data (Pizzarello et al. 2003; Pizzarello and Huang 2005).

Several organic and inorganic phases of the carbonaceous chondrite matrix were separated and subjected to the Soai reaction, i.e., the addition reaction of i -Pr₂Zn to pyrimidine-5-carbaldehyde. Asymmetric autocatalysis with amplification of chirality gave pyrimidyl alkanol with enantiomeric excesses of detectable level. The asymmetry resides in powders after extraction with water and solvents as well as in the

insoluble organic material obtained after demineralization. Asymmetry is not found any longer in the insoluble organic matter after hydrothermal treatment and in meteorite powders from which all organics had been removed (Kawasaki et al. 2006).

The meteoritic enantiomeric excesses may help to understand the emergence of homochiral (one-handed) life. Each amino acid, with the exception of glycine, exists in at least two enantiomeric forms, L and D, but proteins use only L ones. Proteins adopt asymmetrical rigid geometries, α -helices and β -sheets, which play a key role in their catalytic activity. Homochirality is now believed to be not only a consequence of life, but also a prerequisite for life (Brandenburg 2021), because stereoregular structures such as protein β -sheets, for example, do not form with mixtures of monomers of both handednesses. The use of one-handed biomonomers also sharpens the sequence information of the biopolymers. For a polymer made of n units, the number of sequence combinations is 2^n when the system uses only homochiral monomers. Taking into account the fact that enzyme chains are generally made of hundreds of monomers, the tremendous gain in simplicity offered by the use of monomers restricted to one handedness is self-evident. The enantiomeric excess of amino acids found in the Murchison meteorite may result from the processing of the organic mantles of interstellar grains by circularly polarized synchrotron radiation from a neutron star remnant of a supernova (Bonner 1991).

Strong infrared circular polarization, resulting from dust scattering in reflection nebulae in the Orion OMC-1 star-formation region, has been observed (Bailey et al. 1998). Circular polarization at shorter wavelengths might have been important in inducing chiral asymmetry in interstellar organic molecules that could be subsequently delivered to the early Earth (Bailey 2001).

The discovery of a large number of meteorites since 1969 has provided new opportunities to search for organic compounds in CM type carbonaceous chondrites (Pizzarello et al. 2001; Glavin et al. 2006; Pizzarello and Shock 2010) as well as in Renazzo-type (CR) chondrites found in

Antarctica with enantiomeric excesses of up to 60% (Pizzarello et al. 2012).

Micrometeorites

Interplanetary dust particle collections in Greenland and Antarctic ice sheets (Maurette 1998, 2006) show that the Earth captures interplanetary dust as micrometeorites at a rate of about 20,000 tons per year. Micrometeorites are relevant not only for planetary science and astrophysics as they help understand the composition of the Solar System but also for exobiology. About 99% of this mass is carried by micrometeorites in the 50–500 μm size range. This value is about 2000 times higher than the most reliable estimate of the meteorite flux, i.e., about 10 tons per year. This amazing dominance of micrometeorites already suggests their possible role in delivering organics to the early Earth 4.2 to 3.9 Ga ago when the micrometeorite flux was probably several orders of magnitude higher. Antarctic micrometeorite flux measurements suggest that a huge mass ($\sim 5 \times 10^{24}$ g) of micrometeorites was accreted by the Earth during the first ~ 300 Ma of the postlunar period.

At least ~ 20 wt. % of the micrometeorites survive unmelted after atmospheric entry. As their kerogen fraction represents about 2.5 wt. % of carbon, this amounts to a total mass of kerogen of $\sim 2.5 \times 10^{22}$ g on the early Earth surface equivalent to a ~ 30 -m-thick global layer (Maurette and Brack 2006). This delivery represents more carbon than that present in biomass in the present terrestrial biosphere (10^{18} g). α -Amino isobutyric acid has been identified in Antarctic micrometeorites (Brinton et al. 1998; Matrajt et al. 2004). These grains also contain a high proportion of metallic sulfides, oxides, and clay minerals, a rich variety of inorganic catalysts which could have promoted the reactions of the carbonaceous material which led to the origin of life. Analysis of the dust grains collected by the Cosmic Dust mission supports a cometary origin for the micrometeorites collected in Antarctica.

A collection of CONCORDIA Antarctic micrometeorites recovered from ultraclean snow close to Dome C provided the most unbiased collection of large cosmic dust available. Many

similarities can be found between Antarctic micrometeorites and Wild 2 samples, in terms of chemical, mineralogical, and isotopic compositions, and in the structure and composition of their carbonaceous matter (Dobrica et al. 2013).

Basic Methodology

Laboratory and Space Experiments Supporting Extraterrestrial Delivery

Synthesis

Ultraviolet irradiation of dust grains in the interstellar medium results in the formation of complex organic molecules. The interstellar dust particles are assumed to be composed of silicate grains surrounded by ices of different molecules, including carbon-containing molecules. Ices of H_2O , CO_2 , CO , CH_3OH , and NH_3 were deposited at 12 K under a pressure of 10^{-7} mbar and irradiated with electromagnetic radiation representative of the interstellar medium. The solid layer that developed on the solid surface was analyzed by enantioselective gas chromatography and mass spectrometry GC-MS. After the analytical steps of extraction, hydrolysis, and derivatization, 16 amino acids, including 6 protein amino acids, were identified in the simulated ice mantle of interstellar dust particles (Munoz Caro et al. 2002). These amino acid identifications confirmed the preliminary amino acid formation obtained by Mayo Greenberg (Briggs et al. 1992). The chiral amino acids were identified as being totally racemic. Parallel experiments performed with ^{13}C -containing substitutes definitely exclude contamination by biological amino acids. The results strongly suggest that amino acids are readily formed in interstellar space. Irradiation experiments, run with H_2O , NH_3 , CH_3OH , and HCN , produced only 3 amino acids, glycine, alanine, and serine (Bernstein et al. 2002).

Vacuum UV photo-irradiation of simpler ices containing H_2O , CH_3OH , and NH_3 led to the production of hydantoin, 2,4-imidazolidinedione (De Marcellus et al. 2011), a molecule suspected to play an important role in the formation of oligopeptides. Hydantoin is known to form

under extraterrestrial conditions, since it has been detected in the soluble organic fraction of primitive carbonaceous meteorites (Cooper and Cronin 1995; Shimoyama and Ogasawara 2002). Glycine and alanine were dominantly formed when 5-substituted hydantoins were UV-irradiated and hydrolyzed (Sarker et al. 2013).

Irradiation of ice mixtures of $\text{H}_2\text{O}/^{13}\text{CH}_3\text{OH}/\text{NH}_3$ by circularly polarized light provided 16 distinct amino acids. The L-enantiomeric excesses were measured in five of them: α -alanine, 2,3-diaminopropionic acid, 2-aminobutyric acid, valine, and norvaline, with values ranging from $eeL = -0.20\% \pm 0.14\%$ to $eeL = -2.54\% \pm 0.28\%$. The results support an astrophysical scenario in which the solar system formed in a high-mass star-forming region where icy grains were irradiated during the protoplanetary phase by an external source of circularly polarized light of a given helicity, inducing a stereo-specific photochemistry (Modica et al. 2014).

Key Research Findings

The collection and analysis of micrometeorites suggests their role in delivering complex organics to the early Earth 4.3 to 3.5 Ga ago when life is considered to have emerged.

Applications

Space Travel

To estimate whether different amino acids could survive a trip in space embedded in micrometeorites, a suite of amino acids like those detected in the Murchison meteorite was exposed to space conditions in Earth orbit on board the unmanned Russian satellites FOTON 8 and 11, free and associated with clay minerals. Free exposed aspartic acid and glutamic acid were partially destroyed during exposure to solar UV. However, decomposition was prevented when the amino acids were embedded in clays (Barbier et al. 1998). Amino acids have also been subjected to solar radiation outside the MIR space station for 97 days. The samples were

exposed in free form and associated with different ground mineral supports to mimic micrometeorites, i.e., montmorillonite clay, powdered basalt, and powdered Allende meteorite. In the absence of mineral protection, about half of the amino acids were destroyed by UV radiation. The main photochemical degradation process was the decarboxylation of the carboxylic acid function. Significant protection from solar radiation was observed when the thickness of the added minerals was 4–5 μm or greater (Boillot et al. 2002).

The protective action of meteorite powder was confirmed with the 18-month exposure experiment PROCESS using the EXPOSE-E facility mounted on the European Technology Exposure Facility (EuTEF) platform on board the International Space Station. The amino acids exposed in the free form were degraded by more than 40% while more than 80% of the compounds associated with meteorite powder were preserved (Cottin et al. 2012).

Impact Shock Chemistry

Intense bombardment probably caused some chemical reprocessing of the Earth's primitive atmosphere by impact shock chemistry. An indication of the number and timing of the impacts onto the early Earth can be obtained by comparison with the cratering record of the Moon, which records impacts from the earliest history of the solar system (Ryder 2003). Because of the larger size of the Earth and its greater gravitational pull, about 20 times as many impacts would have occurred on the early Earth as on the Moon. Computer modeling of the impact shock chemistry shows that the nature of the atmosphere strongly influences the shock products (Fegley Jr et al. 1986). A neutral CO_2 -rich atmosphere produces CO , O_2 , H_2 , and NO while a reducing CO -rich atmosphere yields primarily CO_2 , H_2 , CH_4 , HCN , NH_3 , and H_2CO . The last three compounds are particularly interesting for prebiotic chemistry since they can lead to amino acids via the Strecker synthesis. However, it is difficult to know if such an atmosphere really existed. In laboratory experiments, a gas mixture of methane, ammonia, and water subjected to shock heating followed by a rapid thermal quenching yielded the amino acids

glycine, alanine, valine, and leucine (Bar-Nun et al. 1970). Here again, the gas mixture used does not represent a realistic primitive atmosphere, which was dominated by CO₂. Laboratory simulations of shocks were also run with a high-energy laser. CH₄-containing mixtures generated hydrogen cyanide and acetylene, but no organics could be obtained with CO₂-rich mixtures (McKay and Borucki 1997).

Large impacts could also have promoted some fine ejecta particle chemistry. For 10–15 km-sized impactors, modeling (Lyons and Vasavada 1999) has shown that 100 μm fine ejecta particles would have been heated to about 200 °C during reentry in a 0.3 bar CO₂ atmosphere. For impactors larger than 20 km, the heat experienced by the fines would destroy all organics by pyrolysis or combustion.

Furukawa and colleagues (Furukawa et al. 2009) investigated whether, rather than just transporting amino acids, meteorite impacts could themselves synthesize organic compounds. The group subjected a mixture of solid carbon, iron, nickel, water, and nitrogen to high-velocity impacts in a propellant gun. This experiment simulated the chemistry experienced by ordinary chondrites when hitting the Earth's early oceans. They recovered several organic molecules after the impact, including complex molecules such as fatty acids and amines. Glycine, the simplest protein-building amino acid, was formed when the starting material contained ammonia, which is believed to have been formed in prior impacts on the early Earth. To avoid potential contamination by biological materials, the authors used solid carbon composed only of ¹³C. Subsequent analyses of the recovered organic products showed that they were all formed with the ¹³C, ruling out the presence of any naturally formed biological contaminants, which would have been enriched in ¹²C.

The effects of impact shock on amino acids and a peptide in artificial meteorites composed of saponite clay were investigated (Bertrand et al. 2009). The samples were subjected to pressures ranging from 12 to 28.9 GPa, which simulated impact velocities of 2.4–5.8 km/s. Volatilization was determined by weight loss measurement, and

the amino acid and peptide response was analyzed by gas chromatography–mass spectrometry. At the highest shock pressures, amino acids with an alkyl side chain were more resistant than those with functional side chains. Impact shock may therefore act as a selective filter to the delivery of extraterrestrial amino acids via carbonaceous chondrites. The peptide cleaved into its two primary amino acids. Some chiral amino acids experienced partial racemization during the course of the experiment, suggesting that the enantiomeric excesses measured in carbonaceous chondrites are probably underevaluated.

Future Directions

Meteorite and micrometeorite collection and analysis as well as laboratory and space experiments strongly support an extraterrestrial pathway for the delivery of organic molecules at the time that life originated. The building blocks of life or their precursors could have been brought in by small impactors, possibly supplemented by prebiotic molecules formed in the atmosphere and oceans by meteorite impacts.

Cross-References

- [Comet](#)
- [Meteorites](#)

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Extreme Environment

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Keywords

Extremophiles

Synonyms

[Extreme field sites](#)

Definition

An extreme ► [environment](#) is a habitat characterized by harsh environmental conditions, beyond the optimal range for the development of humans, for example, pH 2 or 11, -20°C or 113°C , saturating salt concentrations, high radiation, and 200 bars of pressure, among others. Basically, these are all inhospitable conditions for life. By definition, the organisms that are able to live in extreme environments are known as ► [extremophiles](#). Not so long ago it was thought that life could not occur under extreme conditions. In the 1960s, Professor Thomas D. Brock, from Wisconsin-Madison University, isolated and described the first organisms from Yellowstone National Park, USA. This organism, *Thermus aquaticus*, is capable of growing at temperatures higher than 70°C . Its DNA polymerase has been widely applied in molecular biology as it is the base of the polymerase chain reaction (PCR) based on the thermophilic properties of the micro-organism that produces it. *Sulfolobus acidocaldarius*, growing at temperatures higher than 85°C , was also isolated and characterized

at the same time and was the first characterized hyperthermophilic archaea.

History

In 1974, R. D. MacElroy published “Some comments on the evolution of extremophiles” (Biosystems 6: 74–75); this was the first time the term ► “**extremophile**” was used.

Overview

Depending on the extreme physicochemical conditions that characterize the extreme environments, they are classified as follows:

Extreme temperature. Two types of extreme ecosystems can be described: cold and hot. Extremely cold environments are those with temperatures consistently below 5 °C. They can be found in deep ocean niches, at the peaks of high mountains, or in the polar regions. Organisms living in extreme cold environments are known as psychrophiles. Some of them, such as the organisms found in Vostok Lake are able to live at –20 °C.

Extremely hot environments are characterized by regular temperatures higher than 45 °C. These environments are typically influenced by geothermal activity as geysers and fumaroles of continental volcanic areas or deep-sea vents. Typical extreme hot environments can be found in the geothermal areas of Yellowstone and in some locations of Iceland or Kamchatka. The organisms in these environments are thermophiles. Some microorganisms are able to develop at temperatures higher than 80 °C, and they are called hyperthermophiles. These organisms are associated with hydrothermal activities.

Extreme pH. Extreme environments can be classified as acidic or alkaline according to their pH.

Extreme acidic environments are natural habitats in which the pH is below 5. Some

examples of extreme acidic environments are Río Tinto (Iberian Pyritic Belt, SW Spain), mean pH 2.3, or Iron Mountain in California (USA) where the pH in some areas is below 1. Organisms developing in these acidic environments are known as acidophiles.

Extreme alkaline environments are those with a pH above 9. Examples of this type of environment are the soda lake of Magadi, Mono Lake, or salt pans. Organisms found in these environments are called alkaliphiles.

Extreme ionic strength. Hypersaline environments have an ionic concentration higher than of seawater, >3.5%. Typical hypersaline environments are the Dead Sea (Israel), the Great Salt Lake (USA), or the salterns of Santa Pola (Spain). Organisms able to grow at high ionic strength are known as halophiles. Most alkaliphilic organisms are also halophiles.

Extreme pressure environments are those under extreme hydrostatic or litho pressure, such as aquatic habitats at depths of 2000 m or more or deep-subsurface ecosystems. Organisms living under high pressure can be classified as barotolerant if they can tolerate high pressure or barophilic if they depend on pressure to grow.

High-radiation environments are those habitats exposed to abnormally high radiation doses, including ultraviolet or infrared radiation, like deserts, the top of high mountains, or on the surface of the International Space Station.

Xeric environments are extreme dry habitats with seriously limited water, an extremely important element for life. Cold and hot deserts are some examples of these extreme environments.

Oligotrophic environments are extreme ecosystems that offer low levels of nutrients to sustain life. Oligotrophic environments include deep oceanic sediments, polar ice, or the deep subsurface.

Cross-References

- [Acidophile](#)
- [Alkaliphile](#)
- [Compatible Solute](#)

- [Deep-Sea Microbiology](#)
- [Deep Subsurface Microbiology](#)
- [Desiccation](#)
- [Endolithic](#)
- [Environment](#)
- [Extremophiles](#)
- [Halophile](#)
- [Hyperthermophile](#)
- [Piezophile](#)
- [Psychrophile](#)
- [Radiation Biology](#)
- [Solar UV Radiation, Biological Effects](#)
- [Terrestrial Analog](#)

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Extreme Field Sites

- [Extreme Environment](#)

Extreme Ultraviolet Light

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Synonyms

[EUV](#)

Definition

Extreme ultraviolet light, EUV, corresponds to photons with wavelengths between 100 and 10 nm (12.4–124 eV).

Cross-References

- [Wavelength](#)

Extremophiles

Daniel Prieur
Université de Bretagne Occidentale (University of Western Brittany), Brest, France
Institut Universitaire Européen de la Mer (IUEM),
Technopôle Brest-Iroise, Plouzané, France

Keywords

Acidophile · Alkaliphile · Extremophile ·
Halophile · Hydrostatic pressure · pH ·
Piezophile · Psychrophile · Salt concentration ·
Temperature · Thermophile

Synonyms

[Extremophilic organisms](#); [Life, limits of](#)

Definition

Life is influenced by physical parameters such as temperature, pH, salinity, pressure, etc. Extremophiles are organisms that thrive in ecosystems where at least one physical parameter is close to the known limits of life with respect to this parameter. While some organisms may temporarily survive harsh conditions by forming resistant stages (spores) or through specific mechanisms (heavy metal resistance), true extremophiles require these conditions. For instance, hyperthermophiles successfully complete their life cycle at optimal temperatures above 80 °C and commonly do not grow at all below 60–70 °C.

History

Before 1965, the upper temperature limit known for life was about 73 °C. When Thomas Brock discovered thermophilic bacterium *Thermus aquaticus* in the Octopus Hot Spring in Yellowstone National Park (USA), the research on extremophiles truly began. *Thermus aquaticus* lives in temperatures ranging from 50 °C to 80 °C. Since then, many alkaliphiles, acidophiles, halophiles, and piezophiles have been discovered and studied for their taxonomy, ► [phylogeny](#), physiology, biochemistry, molecular biology, genetics, and applications. According to Gerday and Glansdorff (2007), “For biologists, the realization that many forms of life are actually confined to environments that are severely hostile by human standards will remain one of the most significant achievements of the second half of the twentieth century.” But “the questions raised by the molecular basis and the emergence of different forms of extremophily are not only deep and varied, but, not surprisingly, many remain controversial.” At the beginning of the twenty-first century, research on extremophiles is still an open field.

Overview

Living organisms exposed to severe environmental conditions are frequently named “extremophiles.” However, they belong to different categories. Some organisms resist hostile conditions (elevated temperatures, ► [desiccation](#), etc.) by forming sophisticated resistant and dormant stages such as the spores produced by several Gram-positive ► [bacteria](#). Such forms can survive for very long periods (millions of years in the view of some authors) and then produce growing cells after environmental conditions become favorable. Other organisms can temporarily resist toxic compounds such as heavy metals or ionizing radiation, through specific mechanisms. But these two categories do not require such hostile conditions for growth. A third category truly deserves the name extremophile: These organisms require environmental conditions hostile for most

of the other organisms to complete their whole life cycle: very low temperatures for psychrophiles, very high temperature for thermophiles, very low pH for acidophiles, very high pH for alkaliphiles, elevated salt concentrations for halophiles, or elevated hydrostatic pressure for piezophiles.

Basic Methodology

Since extremophiles thrive in environments hostile for many organisms and particularly human beings, the main difficulty encountered during the study of extremophiles is access to extreme environments. Whereas access to continental hot springs (acidic or alkaline), glaciers, salt mines, or evaporating ponds only requires specific clothing and caution, access to the deep-sea hydrothermal vents, where psychro-piezophiles or hyperthermophiles are found, is much more complex. In this case, sophisticated underwater vehicles (manned submersibles or remotely operated vehicles (ROV)) are needed. The next challenge after sampling is the preservation of samples for further cultivation in the laboratory. Many extremophiles are strictly anaerobic and require anaerobic-reduced conditions during preservation at low temperature. Probably many obligate piezophiles do not survive sampling procedures since it is very difficult (and very expensive) to deploy pressure-retaining samplers. Psychrophiles are very sensitive to moderate temperature (room temperature), and all the glassware and reagents used must be precooled.

Finally, cultivation of extremophiles requires mimicking the main environmental conditions of their environments in the laboratory. The difficulties of growing lithoautotrophic organisms even under non-extreme conditions are great, but the most difficult to grow are probably piezophiles which require high-pressure bioreactors.

Key Research Findings

Thermophiles

Thermophiles are organisms that grow optimally above 60 °C, and hyperthermophiles grow

optimally above 80 °C. The most thermophilic and hyperthermophilic organisms are prokaryotes and belong to the Bacteria, but essentially ► **Archaea** domains. They have been isolated from diverse hot environments such as continental hot springs, oil reservoirs, or deep-sea hydrothermal vents. According to their natural environments, many of them combine thermophily with acidophily or piezophily. They have representatives in various metabolic types: They may be aerobes, microaerophiles or anaerobes, and chemoorganotrophs or chemolithoautotrophs. As a whole, they may use a variety of electron donors and acceptors. Many of them have very short generation times, about 30 min under optimal conditions.

The most thermophilic organism is an Archaea, *Pyrolobus fumarii*, isolated from a deep-sea hydrothermal vent. *P. fumarii* grows in a temperature range of 90–113 °C, with an optimum at 106 °C. It can survive an exposure of 24 h in an autoclave. Growth at 121 °C of an iron reducer organism, also isolated from a deep-sea hydrothermal vent, has been reported. However, the strain has not been published as a novel organism nor deposited in type culture collections, and this result is still to be confirmed. Thermophiles may also harbor viruses that live in the same environmental conditions, but their life cycle and relationships with their hosts are still unknown.

Psychrophiles

Psychrophiles are cold-adapted organisms that grow optimally at temperatures around 15 °C and never grow beyond 20 °C. Their minimum temperature for growth can be below 0 °C. Organisms that can grow at low temperatures but also beyond 20 °C are named psychrotolerant. The lower temperature limit for growth is not easy to determine, since very low temperatures (–80 °C in deep freezer, –196 °C in liquid nitrogen) are used for long-term preservation of both prokaryotic and eukaryotic cells. However, growth of bacterial cells at temperatures as low as –10 to –12 °C, and metabolic activity at –20 °C in concentrated brines have been reported. Psychrophiles not only inhabit the deep cold oceans but also polar

regions, high mountains, glaciers, etc. They almost certainly belong to many phylogenetic lineages, but most of the cultivated species belong to the Bacteria domain, particularly the proteobacteria.

Halophiles

Halophiles are organisms living in salty environments such as the oceans. However, many environments are much more saline and salt concentrations can reach 340 g/l. Typical settings are salt lakes, solar salterns, underground deposits of rock salts, but also salted food products. Organisms living optimally in these highly salted environments are named extreme halophiles. Several salty environments also have a high pH and a rather high temperature, and consequently their inhabitants are polyextremophilic. Extreme halophiles (growing in salt concentrations above 100 g/l) are found in the three domains of life, but most of them are prokaryotes, and the most extreme belong to the Archaea domain. Two lineages of halobacteriales and certain methanogens are included. The halobacteriales are heterotrophic organisms that produce red pigments, some of which (bacteriorhodopsin, halorhodopsin) are involved in light-driven proton and chloride pumps.

Acidophiles

Acidophilic organisms grow optimally at pH below 7, but there is a distinction between moderate acidophiles that grow at pH from 5 to 3 and extreme acidophiles that grow at pH below 3. Acidophiles are found in natural acidic springs in volcanic areas, but also in sulfide ore or coal deposits. Acidophiles exist in the three domains of life, and several yeasts, fungi, and protozoa grow at pH below 2. Among the prokaryotes, acidophiles are very diversified from a metabolic point of view, and both heterotrophs and autotrophs are found. Many acidophiles oxidize sulfides and sulfur, using oxygen as an electron acceptor. Since ferrous iron is stable at low pH under aerobic conditions, many acidophiles are also iron oxidizers. The most acidophilic organism on Earth is the Archaea *Picrophilus*, which has an optimal pH of 0.7 and still grows at pH 0.

Alkaliphiles

Alkaliphiles are commonly divided into two categories: the alkali-tolerant organisms can grow at alkaline pH (8–9), but their optimum is around neutral pH. True alkaliphiles can grow at pH above 10 and/or grow equally well or better (rate, yield) at pH above 9. Some are facultative ► [alkaliphile](#); true alkaliphiles cannot grow at pH below 8. Alkaliphiles occur in natural high-pH environments such as ► [soda lakes](#), underground alkaline waters, and hidden small niches such as insect guts. They are also found in artificial environments such as waste of food-processing industries. They have representatives in the three domains of life, but are most abundant in several lineages of the Bacteria domain, particularly the low G + C Gram-positive bacteria of the genus *Bacillus*. Some alkaliphiles also exhibit slight thermophilic properties.

Piezophiles

Piezophiles were first named barophiles, from the Greek word for weight. Piezophile is more appropriate because it comes from the Greek word for pressure. Piezophiles thrive in environments exposed to elevated hydrostatic pressure. Piezotolerant, piezophilic, and obligate piezophilic exist. The latter requires pressures above 1 bar to grow. They are found in habitats such as deep oceans, deep aquifers, oil fields, and deep sediments. The first obligate piezophile was isolated from a dead crustacean amphipod collected at the Mariana Trench (10,470 m depth). It is an aerobic heterotrophic bacterium that grows optimally at 2 °C (it is also a ► [psychrophile](#)), under 690 bars (or 69 Mpa) with a generation time of 25 h. When exposed to hydrostatic pressure, this organism loses its ability to form colonies and dies. Piezophilic characteristics are also known in some hyperthermophiles isolated from deep-sea hydrothermal vents. *Pyrococcus yayanosii* strain CH1 grows in a temperature range of 80–105 °C, with an optimum at 98 °C, under an optimal hydrostatic pressure of 52 Mpa. Its pressure range extends from 20 to at least 120 Mpa. At all temperatures, no growth was observed for pressures below 20 Mpa.

Applications

Extremophiles are able to grow under extreme conditions of temperature, pH, salt concentration, and pressure. Consequently, the metabolic pathways and enzymes involved in these pathways are also extremophilic and are named extremozymes. Extremozymes have two general properties: they are active under extreme conditions, but are also very stable. For those reasons they represent a powerful tool for industrial biotransformations, carried out under harsh conditions. Most of them come from thermophilic and hyperthermophilic organisms.

Many extremozymes are involved in starch processing: alpha- and beta-amylases, glucoamylases, alpha-glucosidase, pullulanase, CgTases, branching enzymes, and amylomaltases. There are extremozymes that can be used for other transformations such as cellulose, xylan, chitin, pectin-degrading enzymes, proteolytic enzymes, lipases and esterases, alcohol dehydrogenases, glucose and arabinose isomerases, nitrile-degrading enzymes, etc. Modern DNA technology also utilizes extremozymes from thermophiles. The most famous example is the thermostable *Taq* polymerase, from the thermophilic bacterium *Thermus aquaticus*. This polymerase permitted the revolution in DNS technology through the PCR (polymerase chain reaction) technology. Other enzymes such as ligases, nucleases, and topoisomerases are also commonly used.

Extremophiles can also be used as whole-cell biocatalysts for biomining, decontamination or bioremediation, and hydrogen production. Finally, biomolecules extracted from extremophiles such as proteins and peptides, biopolymers, compatible solutes, or lipids have a wide range of applications.

Future Directions

At the beginning of the twenty-first century, the world of extremophiles has revealed a variety of fascinating organisms, most of which are prokaryotes. However, despite the thousands of papers

that have been published on the subject, many questions remain.

Extremophiles thrive at the limits of the life on Earth, but what those limits are precisely is not yet fully understood, particularly for elevated temperatures and pressures. Although it is not possible to imagine an organism more acidophilic than *Picrophilus* (already at the low pH limit), it may be possible to find an organism that combines extreme acidophily with extreme thermophily and piezophily or any other combination. To discover such pluri-extremophiles, exploration of planet Earth for new biotopes must be continued. It was recently reported that living microorganisms exist in very deep (1600 m thickness) and old (110 million years) marine sediments. At this location, temperature was estimated to be only 80–100 °C. But the known temperature limit for life is 113 °C (perhaps more), and because temperature increases by only 30 °C per kilometer, life could occur at even greater depths.

Such organisms may also represent novel lineages and may use novel metabolic pathways or novel enzymes. For each of them, the cellular and molecular mechanisms of adaptation remain to be understood and may open a variety of potential applications.

By pushing the definition of the limits for life to ever greater extremes, biologists engaged in research on extremophiles will help develop novel hypotheses about the origin of life on Earth and its existence elsewhere.

Cross-References

- [Acidophile](#)
- [Alkaliphile](#)
- [Anaerobe](#)
- [Archaea](#)
- [Bacteria](#)
- [Chemolithoautotroph](#)
- [Deep-Sea Microbiology](#)
- [Deep Subsurface Microbiology](#)
- [Desiccation](#)
- [Ecosystem](#)
- [Enzyme](#)

- [Eukarya](#)
- [Extreme Environment](#)
- [Halophile](#)
- [Hot Spring Microbiology](#)
- [Hot Vent Microbiology](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Hyperthermophile](#)
- [Lithotroph](#)
- [PCR](#)
- [Piezophile](#)
- [Prokaryote](#)
- [Psychrophile](#)
- [Soda Lake](#)
- [Thermophile](#)

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Extremophilic Organisms

- [Extremophiles](#)

F

Facula, Faculae

Roland J. Wagner
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

A facula is a bright area on the icy satellites of ► [Jupiter](#), ► [Ganymede](#), ► [Callisto](#), and Amalthea and on ► [Saturn's](#) satellite ► [Titan](#). Faculae on Ganymede and Callisto are circular or elliptical and up to several hundred kilometers in diameter. Faculae are thought to have been created by impacts into the icy ► [crusts](#) of these two Jovian satellites, possibly with plastic or liquid material present in the subsurface. Titan shows two globally abundant surface units characterized by either bright or dark ► [albedo](#). Faculae on this satellite are irregularly shaped, represent slivers or islands of bright terrain, are located within extensive areas of dark terrain, and are possibly of nonimpact origin.

Cross-References

- [Albedo Feature](#)
- [Callisto](#)
- [Crater, Impact](#)

- [Crust](#)
- [Ganymede](#)
- [Impact Basin](#)
- [Jupiter](#)
- [Macula, Maculae](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Titan](#)

Faint Young Sun Paradox

Manuel Güdel
Department of Astrophysics, University of
Vienna, Vienna, Austria

Keywords

Climate · Greenhouse gases · Solar mass loss ·
Young Sun

Synonyms

[Faint young Sun problem](#)

Definition

The apparent contradiction between model calculations that indicate a dimmer young Sun and consequently mean below-freezing temperatures

at the Earth's surface and the geological evidence that early climates on Earth and Mars were mild if not hot and that liquid water was abundantly present on the other hand.

Overview

There is clear evidence for a mild climate on the young Earth and Mars, allowing liquid water – a prerequisite for the formation of life as we know it – to exist on the surface of both planets at ages of a few 100 Myr to 1 Gyr. Liquid water seems to have subsequently disappeared from the surface of Mars. However, detailed stellar evolutionary theory applied to the Sun during its main-sequence life indicates that it was fainter by about 30% when it arrived on the main sequence 4.6 billion years ago, and the radiative output increased only slowly in the next billion years. Both planetary surfaces would thus have been completely frozen. To solve this apparent paradox (Sagan and Mullen 1972), various hypotheses have been proposed although a conclusive answer is still outstanding. The most popular theory assumes higher admixtures of greenhouse gases in the atmospheres of Earth and Mars; such gases include carbon monoxide, ammonia, and methane (CO_2 , NH_3 , and CH_4 , respectively). A radically different hypothesis posits that the young Sun was not faint – it may rather have been brighter because it was more massive by a few percent. Direct evidence for the implied strong mass loss in the younger epochs of solar evolution is still outstanding. Further hypotheses assume a lower albedo due to less efficient cloud formation, for example, as a consequence of more efficient suppression of cosmic rays in the young solar system, or a smaller fractional area of land, or the lack of biologically induced cloud condensation nuclei. For a recent review of the subject and a summary of evidence for a warm early Earth with liquid surface water, see Feulner (2012).

Basic Methodology

The average, effective equilibrium temperature of a planetary surface in the absence of an

atmosphere follows from the energy balance between optical/near-infrared emission irradiating the planet and mid-infrared thermal radiation that is lost to space. The incoming power from the Sun is

$$P_{\text{in}} = \pi R^2 S (1 - A)$$

where $S = L_{\odot}/4\pi d^2 = 1366 \text{ W m}^{-2}$ is the solar constant (solar radiative energy flux at the distance d of the Earth, where $L_{\odot}$ is the solar luminosity), $A \approx 0.29$ is the Earth's Bond albedo (fraction of radiation that is reflected), and $R = 6378 \text{ km}$ is the Earth's radius. The power leaving from the Earth's atmosphere can be approximated as radiation from a blackbody surface with temperature T ,

$$P_{\text{out}} = 4\pi R^2 \varepsilon \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant and ε is the surface mid-infrared emissivity. Equating $P_{\text{in}} = P_{\text{out}}$ leads to

$$T^4 = \frac{S(1 - A)}{4\varepsilon\sigma}$$

With the above numbers and $\varepsilon \approx 0.9$ for solid rock (Sagan and Mullen 1972), $T \approx 260 \text{ K}$. For a planet surrounded by an atmosphere, the effective temperature can be raised owing to the presence of greenhouse gases. The latter are nearly transparent to incident optical and near-infrared light but strongly absorb reemitted thermal radiation in the mid-infrared. The equation for the mean surface temperature of the atmosphere can then be approximated by (e.g., Feulner 2012)

$$T^4 = \frac{S(1 - A)}{4\varepsilon\sigma} \left(1 + \frac{3\tau^*}{4} \right)$$

where τ^* is the column infrared gray opacity responsible for the warming by greenhouse gases.

Heat flow from the interior of the Earth is, in contrast, negligibly small (although it matters for maintaining plate tectonics; Feulner 2012 and references therein). Considering the greenhouse effect for a present-day atmosphere leads to a

somewhat elevated average temperature of 288 K (15 °C), in agreement with measurements (e.g., Sagan and Mullen 1972; Kasting and Catling 2003).

The total radiative output of the young Sun can be assessed from two sources: (1) The theory of stellar evolution indicates that the young Sun at a time when it started core hydrogen burning on the main sequence emitted 30% less electromagnetic radiation than at present (e.g., Sackmann and Boothroyd 2003). (2) The total luminosity of stars with known masses and ages can in principle be derived from observations; stellar masses and ages are, however, difficult to infer accurately.

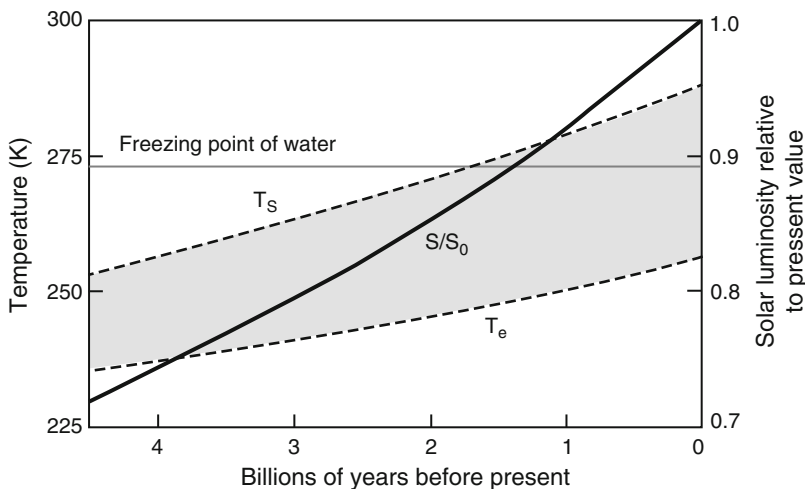
Our knowledge of the early climate history of the Earth and other planets, in particular Mars, relies on geological evidence, such as (1) oxygen isotopes measured in Jack Hills zircons dated at 4.4–4.3 Ga, which suggested that parent rocks interacted with liquid water; (2) 3.8 Ga old sedimentary rocks from Isua (West Greenland) clearly deposited in aquatic environments; and (3) extensive outflow channels and valley networks in the Martian highlands. All of these pieces of evidence indicate mild climates and the presence of liquid

water on both young planets (Valley et al. 2002; Feulner 2012).

Key Research Findings

Assuming the same atmospheric composition for the Earth as today but a solar constant reduced by about 30%, calculations yield average atmospheric temperatures of about 260 K for the young Earth around 4 billion years ago. The temperature would have remained below the freezing point until 2 billion years ago (Sagan and Mullen 1972; Kasting and Catling 2003; Fig. 1). This clearly contradicts geological evidence for a significantly warmer early climate on Earth (e.g., Kasting and Toon 1989) and especially also on Mars. This contradiction is the essence of the faint young Sun paradox (FYSP).

Various hypotheses have been put forward addressing the FYSP but the solution remains inconclusive. We summarize the key points of the proposed solutions below. Considering the above equation for the atmospheric temperature, T , and the determining variables,



Faint Young Sun Paradox, Fig. 1 Illustration of the faint young Sun paradox for the Earth, in the context of the atmospheric greenhouse. The solid line depicts the solar luminosity relative to the present value (right y-axis); the lower dashed curve is the effective temperature of the Earth without atmosphere, and the upper dashed curve shows the calculated, mean global surface temperature affected by the

greenhouse (with fixed CO_2 mixing ratio and relative humidity). (From Kasting and Catling 2003, reprinted, with permission, from the Annual Review of Astronomy and Astrophysics, volume 41 © 2003 by Annual Reviews, www.annualreviews.org. Courtesy of J. Kasting; credit: Scientific American and Princeton University Press)

most potential solutions of the FYSP for the young Earth fall into the following categories: (i) an increased greenhouse effect (τ^*), (ii) a reduced albedo A , and (iii) an increased solar luminosity $L_\odot$. A smaller semimajor axis of the Earth's orbit (resulting in an increased solar flux S at Earth) or a significantly reduced emissivity ε are unlikely (Feulner 2012 and references therein.)

Different Atmospheric Composition: Greenhouses

The composition of the young atmospheres may have been different, allowing for much stronger greenhouses on Earth or Mars. Many authors have favored this hypothesis, although it faces its own problems. Larger amounts of CO_2 would strongly support the greenhouse together with water vapor (Kasting 1993). The required CO_2 level to keep liquid water oceans would be self-regulated by the carbonate-silicate cycle (e.g., Walker et al. 1981; Kasting and Catling 2003). Increased CO_2 levels would at the same time also prevent massive losses of N_2 under the influence of an enhanced early solar wind and enhanced extreme-ultraviolet radiation (Lichtenegger et al. 2010). There are, however, various geochemical and geological evidences against the required very massive CO_2 atmospheres, such as the absence of siderite in paleosols (Rye et al. 1995; Rosing et al. 2010, and references therein); a dense Martian CO_2 atmosphere would significantly enhance the Martian albedo, thus not raising the temperature sufficiently (Kasting 1991). Although these same clouds may also backscatter thermal radiation and therefore support the greenhouse mechanism (Forget and Pierrehumbert 1997), experiments suggest that this effect is too small to raise the temperatures above the freezing point (Glandorf et al. 2002). However, for a period around 2–2.5 Gyr ago, recent calculations indicate that a lower CO_2 content of 2.9 Mb partial pressure would have been sufficient to keep liquid water on the Earth's surface, and this pressure is in agreement with geological findings (von Paris et al. 2008).

Another leading candidate among greenhouse gases is ammonia (NH_3) which would be required

in only relatively small amounts. However, NH_3 dissociates rapidly if subject to solar UV radiation (Kuhn and Atreya 1979), but additional methane (CH_4) may produce a high-altitude haze of organic solids through photolysis, which shields ammonia sufficiently from UV dissociation (Sagan and Chyba 1997). Methane itself is an efficient greenhouse gas (Kasting 1997; Pavlov et al. 2000). But the mixing ratio of $\text{CH}_4:\text{CO}_2$ should stay below unity to avoid increased albedo due to haze formation and therefore an anti-greenhouse effect (McKay et al. 1999; Pavlov et al. 2001; Haqq-Misra et al. 2008), in turn requiring too high levels of CO_2 for a significant greenhouse. Haze is produced at even considerably lower $\text{CH}_4:\text{CO}_2$ mixing ratios (DeWitt et al. 2009). On the other hand, enhanced levels of H_2 suppress haze formation and this limits the anti-greenhouse effect, possibly resulting in a net greenhouse warming by CH_4+CO_2 (DeWitt et al. 2009). The presence of sufficiently high levels of H_2 remains to be demonstrated, however. Ethane (C_2H_6) and carbonyl sulfide (OCS) have been proposed as alternative efficient greenhouse gases in the young terrestrial atmosphere (Haqq-Misra et al. 2008; Ueno et al. 2009) although OCS itself, for example, is rapidly photodissociated (Domagal-Goldman et al. 2011).

Albedo Effects Due to Cloud Formation and Land Coverage

A much lower albedo, A , would allow T to rise. This explanation was initially deemed unlikely because the probably larger surface of the young Earth covered by ice would rather increase A (Sagan and Mullen 1972).

The albedo could, however, have been lower due to a lower cloud coverage in particular in cooler environments (Rossow et al. 1982; Charlson et al. 1987; Rosing et al. 2010). Detailed studies of clouds show two competing effects (Goldblatt and Zahnle 2011a): low-lying clouds reflect solar radiation, thus increasing the albedo; in contrast, high clouds, in particular ice-crystal cirrus clouds, add to atmospheric greenhouse warming, potentially sufficient to solve the FYSP (Rondanelli and Lindzen 2010) although full coverage by an unrealistically thick and cold

cloud cover would be required (Goldblatt and Zahnle 2011a).

There is some evidence that elevated cosmic-ray fluxes have a cooling effect on the Earth's atmosphere because they ionize tropospheric layers, and charged ion clusters lead to condensation nuclei that form reflective clouds (Shaviv 2003). But because the ionized wind of the young Sun is thought to have been much stronger than today, the cosmic-ray flux reaching the inner solar system was more strongly suppressed, therefore suppressing cloud formation in the young Earth's atmosphere and in turn leading to a warmer climate (Shaviv 2003). This model has been observationally refuted, however (e.g., Bailer-Jones 2009 and references therein).

A lower surface albedo may also be the result of the suggested smaller continental area in early epochs although feedback on cloud coverage may result in opposite trends. The absence of cloud condensation nuclei induced biologically (Charlson et al. 1987) also decreases the albedo. Considering these effects and claiming less reflective clouds because of larger cloud droplets (because of fewer biogenically induced condensation nuclei), Rosing et al. (2010) inferred a clement climate for the young Earth without the need for high amounts of greenhouse gases although this solution was again questioned (Goldblatt and Zahnle 2011b).

The amount of ice coverage and thus effects on the energy balance can be influenced by variations in the Earth's axial tilt or its rotation period (slowly increasing with time due to the Moon's tidal forces). Models for these effects are inconclusive (Feulner 2012 and references therein).

A Brighter Young Sun

A radical remedy of the FYSP would be a young Sun that was significantly more massive than at present, losing the excess mass during its main-sequence life in an enhanced ionized wind (Whitmire et al. 1995; Sackmann and Boothroyd 2003). The bolometric luminosity (i.e., the luminosity integrated over the electromagnetic spectrum) of main-sequence stars scales approximately with stellar mass to the third power; further, the radius of the Earth's orbit

would have been smaller for a more massive Sun (the orbital radius scales inversely with the solar mass). Both effects combine to a scaling of the received flux with the fifth power of the solar mass.

Constraints on this model come from the requirement that the young Martian atmosphere was warm enough to maintain water in liquid form, but the Earth's atmospheric temperature was moderate enough to prevent loss of the water oceans in a runaway greenhouse. The appropriate mass range for the young Sun was thus $1.03 M_{\odot}$ to $1.07 M_{\odot}$. Corresponding solar models are in acceptable agreement with helioseismology results (Sackmann and Boothroyd 2003).

The observational evidence is presently unclear. Upper limits to the ionized-wind mass-loss rates deduced from radio observations of young solar analogs are marginally compatible with the "bright young Sun" requirement, indicating a maximum zero-age main-sequence (ZAMS) solar mass of $1.06 M_{\odot}$ (Gaidos et al. 2000). Indirect observations suggest a smaller mass loss. If the solar wind had been constant throughout the Sun's main-sequence life, then, including the losses from conversion of matter to energy in the hydrogen-burning core, a total mass loss of only $0.0004 M_{\odot}$ would have been achieved, which alters the solar radiative output insignificantly. However, observations of "hydrogen walls" in the astrospheres of neighboring solar-like stars support an increased wind-mass loss in younger stars (Wood et al. 2005). A power-law trend extrapolated back to the ZAMS indicates a total mass loss of order $0.01 M_{\odot}$, but some evidence shows that the mass-loss rate was suppressed during the youngest epochs; including this latter effect leads to a total mass loss of only $0.003 M_{\odot}$ (Minton and Malhotra 2007), again too little for a significant luminosity effect. The Wood et al. method has its own limitations, however, and strongly depends on numerical modeling of the complex interaction between magnetic stellar winds and the magnetized interstellar medium (ISM). A possibility is non-isotropic stellar winds that would interact differently with the ISM. The hydrogen wall observations also require

the presence of a neutral ISM component around the astrospheres. The hypothesis of a bright young Sun therefore remains inconclusive.

Cross-References

- [Earth, Formation, and Early Evolution](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Precambrian Oceans, Temperature of](#)
- [Sun \(and Young Sun\)](#)

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Faint Young Sun Problem

► Faint Young Sun Paradox

False Negative

John Lee Grenfell
 Institut für Planetenforschung, Extrasolare
 Planeten und Atmosphären, Deutsches Zentrum
 für Luft- und Raumfahrt (DLR), Berlin, Germany

Definition

In general, a “false negative” refers to the result of an experiment or test which fails to support a particular hypothesis, even though the hypothesis is in fact correct. In an astrobiological context, “false negative” refers to the absence of a detectable life signal even though life is in fact present.

Overview

It is convenient to consider three cases when searching for evidence of life. First is the case where (intelligent) life does not wish to be found and makes efforts to suppress its remote **biosignatures** (e.g., by blocking its

electromagnetic emissions into space or by engineering its atmosphere to suppress the buildup of biosignature gases). Second is the case where physical or/and chemical processes interfere, degrade, or hide (spectral) biosignature(s), e.g., via the presence of an optically thick cloud layer which traps radiation below the cloud base or via photochemical processes which remove biosignature gases in situ in the atmosphere, e.g., via photolytic destruction in high UV environments. Third is the case where our (Earth-based) technology is insufficiently sensitive. For example, the microbial biosignature, nitrous oxide (N₂O) while strongly attributable to life, has rather weak spectral absorption features, which could be overlooked (related to this point, see also the entry on the retrieval of atmospheric properties of exoplanets).

Cross-References

- [Atmospheric Retrieval for Exoplanets](#)
- [Biomarkers \(Atmosphere\)](#)
- [Biosignature](#)
- [False Positive](#)

False Positive

John Lee Grenfell
 Institut für Planetenforschung, Extrasolare
 Planeten und Atmosphären, Deutsches Zentrum
 für Luft- und Raumfahrt (DLR), Berlin, Germany

Definition

A “false positive” refers to evidence which seemingly supports a particular hypothesis or test but which in fact results from unrelated causes. In an astrobiological context, “false positive” refers to evidence which suggests the existence of life but which in reality arises due to abiotic processes which are merely mimicking life.

Overview

Scientific validation of a proposed biosignature requires the assessment and elimination of all known abiotic (nonlife) processes (known as the “false positives”) which could also produce such a signal. There are essentially two issues: first to elucidate whether the *species* associated with the signal (e.g., in the case of atmospheric constituents such as ozone, methane, and oxygen) is being produced by life or by abiotic processes (this point is discussed further in the ► [Biomarker](#) entry), and second, to investigate whether the *signal* itself (e.g., the atmospheric spectral band) is uniquely attributable to a biosignature gas, i.e., one can rule out or subtract the effects of (partially) overlapping spectral bands arising from other gas-phase species, as well as interference from other phenomena, e.g., the presence of clouds, pressure broadening, etc.

Cross-References

- [Atmospheric Retrieval for Exoplanets](#)
- [Biomarkers \(Atmosphere\)](#)
- [False Negative](#)
- [Isotope Biosignatures](#)

Far Infrared (Far IR)

- [Infrared Astronomy](#)

Farbstreifen Sandwatt

- [Microbial Mats](#)

Fatty Acids

- [Carboxylic Acids, Geological Record of](#)

Fatty Acids, Geological Record of

Ross H. Williams

CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology/ University of Maryland, College Park, MD, USA
Solar System Exploration Division, NASA
Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Carboxylic acids · Cellular membranes ·
Lipids · Molecular fossils · Organic acids

Synonyms

[Aliphatic carboxylic acids](#); [Alkanoic acids](#)

Definition

Fatty acids are ► [carboxylic acids](#) with an aliphatic tail (chain) that may be branched, saturated, unsaturated (i.e., contain double bonds), or contain cyclic moieties. Fatty acids typically have C₁₂–C₃₆ chain lengths, though chains of only four carbons are considered “fatty.” Fatty acids are constituents in a variety of biomolecules and are released by the hydrolysis of the ester linkages. Fatty acids are important components of cellular ► [membranes](#) of ► [bacteria](#) and eukaryotes, regulating both fluidity and permeability, and are key energy stores. Fatty acids have also been observed in carbonaceous meteorites (Sephton 2005).

Overview

In sediments and rocks, fatty acids may exist as free fatty acids (i.e., hydrolyzed form) or bound into larger biomolecules or geomolecules (as in

macromolecular ► **kerogen**), or bound to minerals. Fatty acids have varying specificity for particular phylogenetic groups of bacteria and eukaryotes, and also for environmental conditions.

Most natural fatty acids have an even number of carbon atoms because they are biosynthesized by the multiple additions of C₂-acetyl units via the acetyl-CoA coenzyme. Organisms also biosynthesize a limited range of chain lengths and have varying degrees of unsaturation (particularly plants, algae, and bacteria). Biologically produced stereoisomeric configurations of unsaturated fatty acids are all *cis* (the Latin term *cis* describes the orientation of functional groups, on the same side, within a molecule; the opposite term is *trans*, meaning “on the other side” or “across”). All of these features are regarded as general biosignatures and are not observed in abiological fatty acids, such as those observed in meteorites or in synthetics.

Fatty acid abundance diminishes during early diagenesis primarily due to in situ microbial reworking (Meyers et al. 1995; Petsch et al. 2003, 2005). Preferential loss of unsaturated and short-chain moieties is commonly observed. However, in the presence of other refractory materials, fatty acids are incorporated into geomolecules that enhance preservation. Saturated, ω -hydroxyl, and α , ω -diacids are more resistant to diagenesis and have been observed in the ancient geological record. A variety of reactions can lead to the loss of carbon from the alkyl chain, which during later diagenesis leads to molecular patterns having a greater relative abundance of odd-carbon chain lengths. For example, decarboxylation of even-carbon chain length fatty acids leads to odd-carbon alkane chains. Further, thermal maturation and carbon loss of alkanes lead to a diminishing preference for odd or even chain lengths. Thus, in the rock record, molecular distributions of fatty acids and alkanes can indicate biological sources and a relative degree of diagenesis. In some cases, fatty acids from microbes living in rocks or petroleum reservoirs

can complicate molecular interpretations and are important records of recent processes.

Cross-References

- [Acid Hydrolysis](#)
- [Bacteria](#)
- [Biomarkers](#)
- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Carbonyl](#)
- [Carboxylic Acid](#)
- [Carboxylic Acids, Geological Record of](#)
- [Cell Wall](#)
- [Complex Organic Molecules](#)
- [Dicarboxylic Acid](#)
- [Eukarya](#)
- [Hydroxy Acid](#)
- [Kerogen](#)
- [Membrane](#)
- [Molecular Fossils](#)

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Feeding Zone

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

A planet's feeding zone is the region within the ► [protoplanetary disk](#) from where solids can be gravitationally captured by the planet. The planetary feeding zone is schematically a ring in the protoplanetary disk, centered on the central star, the forming planet being located in the middle of the ring. The size of the feeding zone depends on different factors, in particular the planetary mass, its distance to the central star, and the dynamical state of the solids. Typically, the size of the feeding zone is of the order of a few times the Hill Radius of the planet.

The size and location of the feeding zone has an influence on both the formation process of the planet (and therefore the final mass of a planet) and its composition. Large feeding zones, which contain a lot of mass, are required for giant planet formation. Given that radial temperature gradients are thought to translate into compositional variations in the protoplanetary disk, a planet's feeding zone has consequences for its composition. A narrow feeding zone implies that the planet's composition should represent material condensed within a small range in temperatures, and a wide feeding zone implies significant radial mixing during accretion.

Cross-References

- [Planetesimals](#)
- [Protoplanetary Disk](#)

Fennoscandia

Pentti Hölttä¹ and Aleksandr Slabunov²

¹Geological Survey of Finland, Espoo, Finland

²Institute of Geology, Karelian Research Centre, RAS, Petrozavodsk, Russia

Synonyms

[Baltic shield](#); [Fennoscandian shield](#)

Definition

Fennoscandia is the geographic term that covers the Scandinavian countries, Finland, and the northwesternmost part of Russia. The geologic term Fennoscandian Shield (Baltic Shield in some literature) denotes the Precambrian units of this area. The Precambrian of Fennoscandia consists of Archean and Proterozoic rocks, this description dealing with the former.

Overview

Archean rocks comprise much of the eastern and northern parts of the Fennoscandian Shield. They have been divided into five major provinces: Karelia and Norrbotten in the west, Belomorian in the east, and Kola and Murmansk to the north (Slabunov et al. 2006).

Paleoarchean (3.60–3.20 Ga) TTG gneisses have been documented in a few localities in the Norrbotten Province and in the western and south-eastern part of the Karelia Province but in general Mesoarchean and Neoarchean (3.20–2.50 Ga) lithologies dominate, most rocks falling in a relatively restricted age range of 2.84–2.67 Ga (Hölttä et al. 2014, 2019). The Archean provinces comprised the central part of the Kenorland supercontinent that was formed at c. 2.70 Ga (Lubnina and Slabunov 2017). This supercontinent started to break up at the end of the Archean, marked by the intrusion of mafic magmas in the northern and eastern part of the Shield at around 2.5 Ga.

The oldest rock so far reported in the Shield is ca 3.5 Ga trondhjemitic gneiss exposed in the western part of the Finland (Mutanen and Huhma 2003). A tonalitic-trondhjemitic-granodioritic (TTG) association with subordinate ► [greenstone belts](#), paragneisses, granulite complexes, and migmatitic amphibolites dominates the Archean terranes. The TTG magmatism mainly occurred between 2.83 and 2.74 Ga and was followed by a brief period of sanukitoid magmatism between 2.73 and 2.70 Ga. Sanukitoids originate from melting of a metasomatized mantle source (Martin et al. 2010), probably as a result of a slab break-off following continental collision (Halla et al. 2009). The Archean crust was strongly reworked in collisional processes at around 2.71–2.64 Ga, resulting in high-grade metamorphism and partial melting, producing granulites, migmatites and abundant granitic-granodioritic-monzogranitic (GGM) intrusions. The youngest Archean igneous rocks are 2.67–2.61 Ga anorogenic alkaline granitoids that occur in the Keivy terrane in Kola, the 2.61 Ga Siilinjärvi carbonatite close to the western border of the Karelian Province, and 2.68–2.61 Ga mafic dykes in the northeastern part of the Shield (Slabunov et al. 2006).

The oldest (ca. 3.10–2.90 Ga) volcanic rocks are found in greenstone belts in the eastern and northwestern parts of the Karelia Province. Most greenstone complexes are 2.88–2.72 Ga old, often showing an association of plume-related komatiites and tholeiites, island arc-type calc-alkaline volcanic rocks, as well as ► [meta-sediments](#) and ► [banded iron formations](#) (Hölttä et al. 2014). The Sierik and Iringora greenstone belts in the Belomorian Province display ► [ophiolite-like](#) features (Shchipansky et al. 2004; Slabunov et al. 2019). Greenstone belts in the central parts of the Karelia Province are younger (2.75–2.73 Ga) and they have more island arc type lithological and geochemical characteristics than in the western and eastern parts of the Province. Mesoarchean and Nearchean 2.88 Ga and 2.72 Ga eclogites metamorphosed at 14–17 kbars are known in a few areas in the Belomorian Province (Volodichev et al. 2004; Mints and Dokukina 2020), although some recent age determinations

suggest that the eclogitization was a Paleoproterozoic process taking place at 1.9–1.8 Ga (Skublov et al. 2011; Liu et al. 2017).

Two types of microfossils were found in the Mesoarchean (3.00–2.87 Ga) greenstone belts of the eastern part of the Karelia Province: (1) Tubular microstructures, probably fragments of the sheaths of chemolithotrophic filamentous thermophilic microorganisms, being found in the siliceous sedimentary rocks in the basalt-komatiite association (Svetov and Medvedev 2012); (2) Microfossils represented by silicate coccoid forms and pyrite-marcasite spheroids and hollow tubes, being found in sedimentary rocks of an arc-type section (Vysotskiy et al. 2019). In the Belomorian Province, a Nearchean (2.80–2.78 Ga) greenstone belt contains carbonaceous shales, quartz arenites, and tuffaceous-sediments, which themselves hold problematic coccoid micro-organisms and filamentous microstructures (Astafieva and Rozanov 2009).

Cross-References

- [Amphibolite Facies](#)
- [Archean Eon](#)
- [Banded Iron Formation](#)
- [Craton](#)
- [Earth, Formation, and Early Evolution](#)
- [Greenstone Belt](#)
- [Igneous Rock](#)
- [Metamorphic Rock](#)
- [Metasediment](#)
- [Ophiolite](#)
- [Sanukitoid](#)
- [Shield](#)
- [Tonalite-Trondhjemitic-Granodiorite](#)

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Fennoscandian Shield

► [Fennoscandia](#)

Ferment (Obsolete)

► [Enzyme](#)

Fermentation

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Fermentation is an anaerobic ► [catabolism](#) of a reduced carbon source (e.g., glucose) to generate ► [ATP](#) within a strict internal ► [oxidation-reduction](#) balance. In many cases, the same substrate is used both as reductant and oxidant. The hallmark of fermentation is the accumulation of partially oxidized end products. Only a part of the chemical energy stored in the initial substrate is conserved during the synthesis of ATP, usually by a mechanism of substrate-level phosphorylation. Nevertheless, there are some examples of the involvement of an electrochemical ion gradient in the synthesis of ATP (e.g., citrate fermentation).

History

Antoine Laurent Lavoisier (1743–1794) collected the first quantitative data on alcoholic fermentation. Louis Pasteur (1822–1895) studied in depth the fermentation by intact living cells and defined this physiological process as “life without oxygen.” In 1897, Eduard Buchner (1860–1917) showed that fermentation could occur in cell-free extracts, inaugurating the genuine biochemical in vitro approach to living phenomena. Parallel studies on yeast alcoholic fermentation and anaerobic muscle glycolysis during the first half of the twentieth century contributed to the development of biochemistry as a science (Barnett 2003).

Overview

Many microorganisms, obligate or facultative anaerobic, are able to degrade extracellular polymers (e.g., polysaccharides, proteins, nucleic acids) and use the monomers (e.g., hexoses, pentoses, amino acids, purines, pyrimidines) as fermentable substrates. There are other substrates of fermentations such as organic acids (e.g., citrate, succinate, or malonate) or even aromatic hydrocarbons. In this latter case, fermentation appears as a metabolic task of several microbial species working together. Regarding amino acid fermentations, many anaerobic bacteria can catabolize single amino acids but grow better with amino acid mixtures (the Stickland reaction). In this case, some amino acids of the mixture act as reductants, whereas others are the oxidants.

The stoichiometric yield of ATP in a fermentation depends on the particular pathway used and can range from less than one up to 4 mol of ATP per mol of fermentable substrate. Microorganisms are capable of generating a wide array of end products during fermentation, including carbon dioxide, ethanol, lactate, butyrate, acetate, and propionate. In comparison to respiration (i.e., electron transport chain-dependent processes), fermentations are less energetically efficient because a lot of potential chemical energy is still retained in most of the end products. Thus, to compensate this relatively low-energy yield, large

amounts of fermentable substrate are used and most carbons from this can be recovered in the form of end products. Other anaerobic bacteria use the excreted end products of fermentations, building an anaerobic food chain with methanogens at the bottom. From a biotechnological point of view, however, since very ancient times, fermentations are widely used for the processing of food products, such as yogurt, cheese, beer, wine, or bread.

In a few cases, some ATP synthesis during fermentation is associated with the dissipation of an electrochemical potential gradient either of protons or sodium ions. These ion gradients can be generated by electron transport (e.g., fumarate reduction in *Propionibacterium*), membrane decarboxylases (e.g., sodium-pumping succinate decarboxylase of *Propionigenium modestum*), or electrogenic substrate translocation through membranes (e.g., lactic acid bacteria like *Lactococcus cremoris*).

When compared to the other energy-generating systems (such as respiration and photosynthesis), fermentation seems simpler at the structural and enzymatic levels. For this reason, in 1924, Oparin (1924) postulated that fermentation was the earliest metabolic mode.

Cross-References

- ▶ [Anaerobe](#)
- ▶ [ATP](#)
- ▶ [Catabolism](#)
- ▶ [Chemoorganotroph](#)
- ▶ [Embden-Meyerhof-Parnas Pathway](#)
- ▶ [Glycolysis](#)
- ▶ [Origin of Life](#)
- ▶ [Oxidation](#)
- ▶ [Reduction](#)

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Fermi Paradox

Nikos Prantzos
 Institut d'Astrophysique de Paris,
 Paris, France

Keywords

Extraterrestrial civilizations

Definition

The Fermi paradox, attributed to Italian physicist Enrico Fermi, concerns the apparent contradiction between the lack of any evidence for the presence of extraterrestrials on Earth and the view that extraterrestrial civilizations should be rather common in the Galaxy.

History

Fermi formulated his paradox in 1950, during a casual conversation in Los Alamos Laboratory with E. Teller and colleagues, with the famous phrase “where are they?” (or “where is everybody?”). His point was that, if there are many extraterrestrial civilizations, Earth should have been visited by one or more of them, long ago and many times over. The discussion went completely unnoticed for many years. The phrase “where are they?” attributed to Fermi but without comments is first encountered in a paper published in 1963 by American astronomer Carl Sagan. Sagan referred to this problem as “Fermi’s paradox” after American astronomer Michael Hart independently rediscovered Fermi’s arguments in 1975.

Overview

As all paradoxes, the Fermi paradox is better understood if its premises are explicitly stated:

1. There are many extraterrestrial civilizations in the Milky Way.
2. Our civilization is a typical one (not the first to have appeared, neither the most technologically advanced, nor the only one seeking to explore the cosmos and communicate with others).
3. Interstellar travel is not too difficult for civilizations slightly more advanced than ours.
4. Galactic colonization (either by some of those civilizations or their self-replicating robots) can be achieved in less than 10^8 years, i.e., less than 1% of the age of the Galaxy.

If hypotheses (a) to (d) are valid, the conclusion “they should be here” is logically deduced, and the Fermi paradox applies. It ceases to apply if one or more of its premises are refuted. Supporters of ETI (extraterrestrial intelligence) reject one (or more) of the assumptions (b) to (d), in order to save the key hypothesis (a). In contrast, opponents of ETI uphold the plausibility of (c) and (d), while rejecting (b) and even (a). For instance, British astronomer Fred Hoyle thought that interstellar distances make interstellar travel impossible. However, arguments most often discussed refer to the sociological rather than the physical aspects of the problem. Fermi believed that a technological civilization would be too short-lived, destroying itself before mastering interstellar travel. Long before him, the Russian savant and father of astronautics Konstantin Tsiolkovsky preferred the so-called “zoo hypothesis” (reformulated independently in 1973 by American astronomer John Ball), according to which advanced civilizations observe us from afar without interfering, for various reasons (e.g., waiting for us to gain “maturity” before joining the “cosmic club”).

All sociological arguments share a common weak point: It is hard to believe that any one of them applies to every single civilization in the Galaxy. Moreover, in such a case, assumption

(b) would be implicitly violated since we would be the only civilization seeking communication with others. The most “economic” solution to Fermi’s paradox consists in straightforwardly rejecting hypothesis (a): Technologically advanced civilizations are rare in the Galaxy (and, perhaps, we are alone).

Cross-References

- [Drake Equation](#)
- [Fermi, Enrico](#)
- [Galactic Habitable Zone](#)

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Fermi, Enrico

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Enrico Fermi (1901–1954) was an Italian physicist famous by his important contributions to the knowledge and development of the quantum world, mainly on the nuclear and particle physics. In 1926, Fermi discovered, independently of Paul Dirac, the statistical laws, nowadays known as the Fermi-Dirac statistics, governing the particle systems subject to Pauli’s exclusion principle (the fermions).

Between 1934 and 1936, he published two important papers on the artificial radioactivity produced by neutron bombardment and on the absorption and diffusion of slow neutrons (this one led to the discovery of nuclear fission). In

1938, he won the Nobel Prize in Physics for his work on those issues.

In 1939, Fermi and his family, his Jewish wife Laura Capon and their two children, Nella and Giulio, emigrated to the USA, where he worked in the Manhattan Project during World War II. In 1950, while working at the Los Alamos Laboratory, Fermi and some colleagues discussed about the possibility of existence of non-terrestrial intelligent life. Some of them supported the idea that due to the apparent size and age of the Universe, the probability of having been developed alien civilizations would be huge. And if so the aliens have had more than enough time to travel around the Galaxy and visit the Earth. This prompted Fermi to ask, where are they? This significant issue became known as the Fermi paradox. In the 1980s, there is a massive scientific production of writings by scientists in and out of the SETI community to address the Fermi paradox.

The NASA’s Fermi Gamma-ray Space Telescope was launched in 2008 with the scientific mission to study high-energy phenomena and the exotic gamma-ray sources, from ancient black holes, to rapidly rotating neutron stars, or pulsars, in the Milky Way galaxy, to jets powered by supermassive black holes in far-away young galaxies.

Cross-References

- [Fermi Paradox](#)
- [SETI](#)

Fidelity

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Replication accuracy](#)

Definition

In molecular biology and genetics, fidelity is the accuracy of template-dependent nucleic acid copying, in particular DNA or RNA replication. Since accurate genome replication is critical for the viability of cellular organisms, proofreading mechanisms ensure near-perfect fidelity for DNA replication, with average error rates of 10^{-9} – 10^{-12} mutations per nucleotide and round of copy. In turn, the lack of proofreading activity in viral RNA polymerases and reverse transcriptases results in low-fidelity replication, with average error rates of 10^{-3} – 10^{-5} mutations per nucleotide and round of copy.

Cross-References

- [Error rate](#)
- [Mutation](#)
- [Replication \(Genetics\)](#)
- [Template](#)

Fig Tree Group

Christoph Heubeck
Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

Keywords

Archean ocean · Barite · Chert · Banded-iron formation · Early life

Definition

The Fig Tree Group overlies the Onverwacht Group and is overlain by the Moodies Group in the Paleoarchean ► [Barberton Greenstone Belt](#), South Africa and Swaziland. Strata of this group were deposited between approximately 3258 ± 3 and 3225 ± 3 Ma, reach up to 3 km in thickness, and show a wide variety of depositional settings and lithologies.

Overview

The Fig Tree Group consists largely of interbedded siliciclastic and chemically precipitated sedimentary strata, deposited in a range of settings, as well as intermediate to felsic volcanics. In contrast, underlying strata of the ► [Onverwacht Group](#) are dominated by mafic and ultramafic volcanics, with very little terrigenous contribution; strata of the overlying ► [Moodies Group](#) consist largely of shallow-water quartz-rich sandstones. Hofmann (2005) and Lowe and Byerly (2007) provide reviews of the stratigraphy of the Fig Tree Group.

Aside from thick fan-delta conglomerates, turbiditic greywackes, and fine-grained ferruginous and tuffaceous strata (Heinrichs 1980), the Fig Tree Group south of the Inyoka Fault includes thick jaspilitic ► [banded-iron formation](#) (within the Ngwenya Formation of Hofmann 2005), multiple sedimentary barite beds (in the lower Mapepe Formation near the base of the Group), banded carbonaceous ► [cherts](#), and several – in part reworked – impact-derived spherule beds. Fig Tree strata north of the Inyoka Fault largely consist of deeper-water turbiditic siliciclastic rocks. Northern and southern facies are overlain by dacitic volcanic and volcanoclastic rocks of the Schoongezicht Formation (Condie et al. 1970) and the Auber Villiers Formation, respectively (Lowe and Byerly 1999).

Together, these lithologies provide a wealth of unique insights in the chemical and physical setting of the Archean ocean, demonstrating the interplay of organic matter, dissolved Fe, Si, and Ba, and the temporary presence of (photolytically generated?) sulfate (Knauth and Lowe 2003; Bao et al. 2007; Roerdink et al. 2013). The volcanic strata and hypabyssal intrusions in the Fig Tree Group are contemporaneous with TTG plutons adjacent to the BGB, adding another tectonic perspective to our understanding of this unit.

The Fig Tree Group developed in a highly structured paleotopography, including terrestrial alluvial fan deltas, above-wavebase platforms, shelf bank settings, and various deepwater facies. The reasons for the complex paleotopography

may relate to the setting at the margin of the Onverwacht volcanic plateau, syndepositional deformation related to major thrusting (early D2 of Lowe and Byerly, 2007), and the proximity to the Inyoka Fault system. Lowe (2013) suggested that major meteorite impacts (recorded by spherule beds) may have contributed to the change in tectonic setting. Subsequent deformation, however, has overprinted many of the original depositional relationships. Lithology, provenance, depositional environment, volcanism, and style of deformation of the Fig Tree Group are compatible with a tectonic setting analogous to a modern convergent margin, such as a retroarc foreland, interarc, or forearc basin. In that regard, the Fig Tree strata record a transition from the oceanic-plateau setting of the underlying Onverwacht Group to shallow-water continental settings of the overlying Moodies Group.

Cross-References

- [Archean Environmental Conditions](#)
- [Archean Tectonics](#)
- [Banded Iron Formation](#)
- [Barberton Greenstone Belt](#)
- [Barberton Supergroup](#)
- [Barite](#)
- [Moodies Group](#)
- [Onverwacht Group](#)
- [Spherules](#)

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Fischer Projection

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry, a Fischer projection is a two-dimensional representation of a three-dimensional organic molecule devised by Emil Fischer in 1891. Fischer projections depict the stereochemistry of molecules and are thus useful for depicting enantiomers of chiral molecules, especially monosaccharides. The carbon backbone of the molecule is depicted as a vertical line and the bonds of side chains are represented as horizontal lines, with carbon atoms represented by the center of crossing lines. The orientation of the carbon chain is such that the C¹ carbon is at the top of the

molecule diagrammed. Vertical lines lie either in or behind the plane of the paper, while horizontal lines project out from the surface. In a Fischer projection, the plane of symmetry (3D) between two enantiomers becomes a line of symmetry between their 2D representations.

Cross-References

- [Carbohydrate](#)
- [Chirality](#)

Fischer-Tropsch Synthesis

- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)

Fischer-Tropsch-Type Reaction

Natasha M. Johnson¹ and Joseph Andrew Nuth III²

¹NASA Goddard Space Flight Center, Code 691, Greenbelt, MD, USA

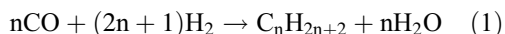
²Solar System Exploration Division, NASA's Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Catalyst · Hydrocarbons · Hydrogenation · Macromolecular organics · Methanation · Organics

Definition

In Fischer-Tropsch-type (FTT) synthesis hydrocarbons are produced through hydrogenating carbon monoxide via surface-mediated reactions, as shown in reaction (1):



The FTT catalytic sequence, as other forms of catalysis, is rather complex and involves several

related reactions on the catalyst surface. A typical FTT experiment involves circulating gases (typically CO and H₂) through and/or over a catalyst at a specific temperature and then measuring the resulting gases (such as water, methane, and carbon dioxide) and residue on the grains as reaction time progresses. As the grains became coated with residue, organics are produced faster and in greater quantities and CO is quickly depleted. The reaction eventually reaches a plateau. Once this point is reached, the gases are removed and the system refilled to be run again.

History

Fischer-Tropsch-type synthesis is a common industrial process developed by coal researchers Franz Fischer (1877–1947) and Hans Tropsch (1889–1935) for obtaining gasoline and other liquid fuels from coal by indirect catalytic hydrogenation of carbon oxides (Hindermann et al. 1993). FTT chemistry was a natural extension of the pioneering work of Sabatier and Senderens (1902), who synthesized ► [methane](#) by passing a mixture of ► [hydrogen](#) and CO/CO₂ over a reduced nickel catalyst. It is important to remember that formation of methane (CH₄) alone is not the Fischer-Tropsch reaction but simply methanation. FTT synthesis was widely used in Germany during World War II to manufacture organic fuels in the form of gasoline, diesel oil, liquefiable gases, and paraffin wax. Early FTT experimentation used nickel and then iron catalysts. However, iron suffered from excessive carbon deposition leading to blockage of the ► [catalyst](#) pores and deactivation (Pearce et al. 1989). As a result, modern FTT plants typically use precious metals, cobalt, or nickel dispersed on substrates (alumina, silica, etc.). In actuality, many of these “fresh” catalytic surfaces are oxides, and it is these metal oxides that have industrial catalytic properties.

Overview

The origins of organics in the early Solar System are complex and still somewhat poorly

understood (Ehrenfreund and Charnley 2000). However, Fischer-Tropsch-type (FTT) catalytic reduction of CO by hydrogen to produce methane and other ► [hydrocarbons](#) has long been recognized as an important potential source of organic material in the ► [Solar Nebula](#), since the “basic ingredients” of this reaction (H_2 , CO, and plausible catalysts) were ubiquitous in this environment (Kress and Tielens 2001). Hayatsu and Anders (1981) compared the results of a wide range of experimental studies of FTT reactions to detailed analyses of the organic residue extracted from ► [carbonaceous chondrites](#). They reported that a significant fraction of the longer-chain hydrocarbons and more complex aromatic compounds in meteorites could be explained by FTT chemistry. However, there are some notable exceptions. In particular, ► [amino acids](#) are not produced efficiently enough or in the proportions and compositional distributions observed in meteorites via FTT reactions. This is in contrast to the Miller-Urey synthesis, which has been successful in generating many of the amino acids associated with living systems and carbonaceous chondrites.

In experimental studies of FTT reactions, pulverized iron-nickel meteorites, powdered carbonaceous chondritic meteorites, and synthetic substrate-supported nickel-iron particles have been used as the active catalyst (Hayatsu and Anders 1981; Llorca and Casanova 2000). In astrochemical experiments designed to measure the efficiency of FTT reactions (Hong and Fegley 1998; Fegley 1999), metallic iron (or iron oxide) was also used as the catalyst. These materials are relevant in that they were surely present in the primitive nebula. However, the bulk form of iron meteorites is not conducive to efficient catalysis, nor is there evidence that iron-nickel particles that might have been found in the nebula would have been analogous to powdered iron meteorites. In addition to the abovementioned materials, preliminary experiments (Ferrante et al. 2000) demonstrated that iron silicate grain analogues – even those containing 10% total iron – are effective FTT catalysts.

Amorphous iron silicates provide reasonably good surfaces to promote the reaction of H_2 , N_2 , and CO to organic materials, resembling those

found in meteorites (Hill and Nuth 2003; Gilmour et al. 2002). Although not as efficient, amorphous magnesium silicates, bronzite, and a range of other natural materials also promote the formation of organic materials from H_2 and CO. Fortunately, the amorphous metal-silicate grains or “smokes” are straightforward to produce in the laboratory and serve as good early Solar Nebula catalyst analogues. In addition to producing volatile organics via the reaction of H_2 and CO on these surfaces, a major reaction product appears to be a macromolecular organic coating on the grain surfaces. However, there is no significant decrease in the reaction rate of volatiles even when this coating comprises up to 10% by mass of the starting material (Gilmour et al. 2002). This implies that the organic coating formed as one of the initial products on any grain surface may also act as an additional effective catalytic surface for the conversion of H_2 , N_2 , and CO into organic materials. These coatings are composed of macromolecular organic phases (Johnson et al. 2004, 2007). These experiments also showed that as the grains became coated, Haber-Bosch-type reactions (catalytic reduction of N_2 by hydrogen to make ammonia) took place, resulting in nitrogen-bearing organics (Hill and Nuth 2003).

These types of FTT reactions are an effective means to produce complex hydrocarbons. Organics generated by this technique could represent the carbonaceous material incorporated in comets and meteorites.

Key Research Findings

Dust grains falling into a protostellar system can provide surfaces that promote the reaction of H_2 , N_2 , and CO into both volatile organics and a macromolecular coating that continues to promote the formation of organic materials. Although the reaction is most efficient in the innermost regions of the nebula, this does not pose significant problems as the reaction products as well as the coated grains can migrate back out to the far reaches of the nebula, thus seeding the entire nebula with the organic building blocks of life (Nuth et al. 2008).

Cross-References

- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)
- [Miller, Stanley](#)
- [Protoplanetary Disk, Chemistry](#)
- [Solar Nebula](#)
- [Urey's Conception of Origins of Life](#)

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Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Biosignatures · Carbon isotopes · Hydrocarbons · Hydrothermal environments · Isotope biological markers · Metal-catalyzed reactions · Serpentinization

Synonyms

[Fischer-Tropsch synthesis](#)

Acronyms

FTT

Definition

The Fischer-Tropsch-Type (FTT) reaction is an industrial process to synthesize hydrocarbons and some aliphatic compounds in the presence of a metal catalyst. The carbon isotope ratios of produced hydrocarbons (methane and short-chain hydrocarbons) and by-products, such as carbon dioxide, show large fractionations relative to the reactants. Abiotic organic products are depleted in ¹³C to a degree like that caused by biological

processes. In specific geological environments, FTT reactions take place sourcing abiotic carbon in rocks and mimicking biosignatures.

History

Franz Fischer and Hans Tropsch developed the original Fischer-Tropsch process at the *Kaiser-Wilhelm-Institut für Kohlenforschung in Mülheim an der Ruhr*, Germany, in 1925. The German firm Brabag (Braunkohle Benzin AG) then commercialized it in 1936. Being petroleum-poor but coal-rich, Germany used the Fischer-Tropsch process during World War II to produce *ersatz* (replacement) fuels.

Overview

Fischer-Tropsch-Type reactions can produce various light and heavy hydrocarbons, oxygen-containing compounds (alcohols, carboxylic acids), and basic N-compounds, including amino acids (Hayatsu and Anders 1981). It is now widely accepted that at temperatures and pressures typical of the continental crust and the mantle, and in presence of natural metal catalysts such as iron, FTT can produce carbonaceous matter. Astrobiologists are particularly interested in FTT reactions in the seafloor hydrothermal environments, since these are the environments where Hadean or Archean life could have originated. It is believed that graphite from sedimentary rocks could have sourced non-biological carbon formed from FTT synthesis during seafloor serpentinization.

The carbon isotopic compositions of the carbonaceous products of FTT reactions display various extents of isotopic fractionation relative to the reactants. The majority of products are depleted in ^{13}C , with $\delta^{13}\text{C}$ values (where $\delta^{13}\text{C} = [(^{13}\text{C}/^{12}\text{C})_{\text{sample}} / (^{13}\text{C}/^{12}\text{C})_{\text{standard}} - 1]$, with the standard being the Pee Dee Belemnite) ranging from 2‰ to 60‰ (‰ = permil) depletion compared to the reactants. Several investigators (e.g., Kerridge et al. 1989; Lancet and Anders 1970) synthesized hydrocarbons from CO and

H_2 at 100–500 °C in the presence of metal catalysts (Fe, Co, Ni, magnetite, etc.) and proposed that such a process could explain the origin of carbonaceous and graphitic matter in meteorites. Their results indicated that short-chain hydrocarbons ($\text{C}_1\text{--C}_4$) were usually more depleted in ^{13}C than the reactant CO. However, the carbon isotopic signature of experimentally produced methane (CH_4) can vary significantly, from very depleted values of –60‰ to values even heavier than the reactant CO (Lancet and Anders 1970).

Horita and Berndt (1999) conducted a series of experiments to investigate isotopic fractionation during hydrothermal production of CH_4 from CO_2 and H_2 in the presence of Ni-Fe alloys. These experiments simulated the production of abiotic methane and other organic compounds during serpentinization. The $\delta^{13}\text{C}$ values of abiotic CH_4 produced from dissolved CO_2 with a mantle-like ^{13}C signature varied from –4‰ to –50‰, overlapping typical $\delta^{13}\text{C}$ values of microbial CH_4 . McCollom and Seewald (2006) produced H_2 , CO_2 , CH_4 , and light hydrocarbons ($\text{C}_2\text{--C}_5$) by heating an aqueous solution of formic acid (HCOOH) in the presence of iron powder at 250 °C and 325 bars in a hydrothermal cell. The $\delta^{13}\text{C}$ of the dissolved CO_2 was –14‰, and values for methane and light hydrocarbons were as low as –49‰. Again, these results show that organic products are depleted in ^{13}C to a degree typically ascribed to biological processes, indicating that the carbon isotopic composition may not be an effective diagnostic means to differentiate between biologic and non-biologic sources (McCollom and Seewald 2006).

Cross-References

- Biomarkers
- Biosignatures, Effect of Metamorphism
- Carbon Isotopes in the Solar System
- Fischer-Tropsch-Type Reaction
- Hydrothermal Environments
- Isotope Biosignatures
- Serpentinization
- Serpentinization (Mars)

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Fitness

Susanna Manrubia

Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Keywords

Environment · Natural selection · Phenotype · Reproduction · Survival

Definition

Fitness is a central concept in evolutionary biology. It usually refers to the average capacity of an organism (as described by its ► [genotype](#)) to produce viable progeny. The genotypes of fitter organisms become more abundant through the action of ► [natural selection](#) along subsequent generations. Fitness is, however, a relative concept since the same genotype, which is the unique heritable material, might express different ► [phenotypes](#) in different environments. In turn, the ability of a phenotype (upon which natural selection acts) to reproduce successfully depends on the ► [environment](#). The quantification of the relationship between genotype and fitness remains an open problem.

Overview

Fitness is commonly defined as the ability of an organism to pass its genes to the next generation. However, many different organismal and environmental traits are involved in the successful completion of this process, and the mathematical form of fitness is therefore difficult to cast. Often, the fitness of a single trait is instead addressed, that is, the advantages conferred by that trait to the individuals carrying it. Actually, the first quantification of fitness measured the relative advantage of an organism with a mutant trait (or genotype) with respect to the non-mutated original type (Haldane 1924). Still, the fitness value of a trait does not depend only on how it performs in comparison to other genotypes, as the case of the mutant allele causing sickle-cell anemia illustrates. In a normal environment, homozygous individuals may experience severe blood disorders. However, the disease confers certain resistance to malaria, enough for heterozygous individuals to be at an advantage in environments where malaria is common, thus enhancing the prevalence of sickle-cell anemia in those regions.

The definition of fitness as the number of offspring of an organism has been challenged since the beginning of evolutionary theory. Already Fisher discussed the case of two individuals having the same number of offspring, the first one breeding only female offspring and the second one breeding half female and half male offspring. Though they are equally fit in terms of the definition above, the progeny of one of them cannot reproduce, and thus that lineage would go extinct if left on its own (Fisher 1930). Hamilton extended the idea of fitness as number of offspring (or number of genes that are passed to the next generation) to include the number of genes an individual can contribute to the next generation by helping kin relatives to reproduce. This is called inclusive fitness (Hamilton 1964).

Several issues have prevented the reaching of a consensus definition for fitness. They include whether fitness is better represented as a short-term or as a long-term quantity; the role played by chance and causality in the fate of populations; whether it should be applied to

species, organisms, or genotypes; and how to consider its dependence on the environment where organisms reproduce and compete with each other (Byerly and Michod 1991; Abrams 2009). As a result, fitness is used with different meanings in different situations, some of them being individual fitness, absolute fitness, and relative fitness (Orr 2009).

Cross-References

- [Adaptation](#)
- [Environment](#)
- [Evolution, Biological](#)
- [Genotype](#)
- [Natural Selection](#)
- [Phenotype](#)
- [Selection](#)
- [Survival](#)

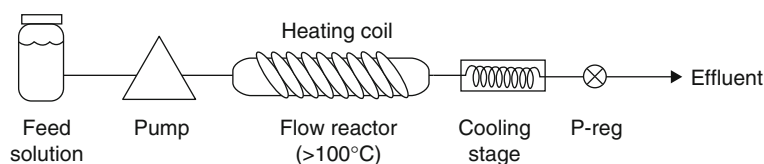
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Flint

- [Chert](#)

Flow Reactor,
Fig. 1 Temperature-controlled flow reactor system schematic



Flood Basalt

- [Trapps](#)

Flow Reactor

Andrew Aubrey
NASA Jet Propulsion Laboratory, Pasadena, CA,
USA

Synonyms

[Plug-flow reactor](#)

Definition

A flow reactor is a temperature- and pressure-controlled reaction vessel with opposite inlet and outlet ends for isothermal exposure of aqueous or gaseous samples under laminar flow conditions. These systems consist of a narrow-bore reactor with an in-line pump and back-pressure regulator and provide an alternative to batch-type reactors. Residence time is equivalent to the ratio of total reactor volume to the volumetric flow rate ($t_r = \frac{V}{v}$), and variable exposures are achieved by adjusting flow rate within the laminar flow regime. Flow reactors are commonly used to investigate aqueous chemical reactivity in high-temperature, high-pressure systems and are commonly utilized in astrobiology for investigation into prebiotic organic synthetic pathways that might be possible at submarine hydrothermal systems (SHSs). High-temperature systems ($\geq 100^\circ\text{C}$) include a rapid cooling stage before ambient sample collection (Fig. 1) to minimize

hysteresis effects. Materials for high-temperature flow reactors include corrosion-resistant metals such as high-nickel steel alloys or gold-plated surfaces.

Cross-References

- [Fischer-Tropsch-Type Reaction](#)
- [Strecker Synthesis](#)

Fluid Inclusions

Pascal Philippot
Equipe Géobiosphère Actuelle et Primitive,
Institut de Physique du Globe de Paris (IPGP),
Paris, France

Keywords

Fluid chemical composition · Fluid-rock interaction · Pressure · Homogenization temperature

Synonyms

[Fluid-bearing micro cavities](#); [Trapped fluids](#)

Definition

A fluid inclusion is a fluid phase present in the rock porosity or filling fractures that is trapped in microscopic cavities during mineral growth or fracture healing. Inclusion fluids can be of sedimentary, metamorphic, or magmatic origin. They can be thought of as time capsules storing information about ancient temperatures, pressures, and fluid compositions relevant at the time of trapping. The composition of most fluids falls in the C-O-H-S-N (H_2O , CO_2 , CH_4 , H_2S , N_2) + NaCl system, with NaCl representing the salt content of the fluid (expressed in weight% NaCl equivalent).

Overview

When crystals grow or recrystallize in a fluid medium of any kind, growth irregularities of many sorts trap microscopic portions of the ambient fluid in the solid crystal. These irregularities are called fluid inclusions. The sealing off of such irregularities may occur during the growth of the surrounding crystal, yielding primary fluid inclusions, or by recrystallization along fractures at some later time, yielding secondary inclusions. Fluid inclusions lining mineral growth zones are the best criteria for a primary origin. Secondary inclusions occur generally along planes cutting across several mineral grains. Fluid inclusions in rock samples are seldom of a unique origin. The presence of fluid inclusions in a rock is the rule rather than the exception. Indeed, the rock sample that contains no inclusions that are visible at high magnification ($>600\times$) is rare, and many minerals such as milky quartz may contain up to 10^9 fluid inclusions per cubic centimeter.

Fluid inclusions are present in all types of rocks, being sedimentary, metamorphic, or igneous in origin. They have been traced down to mantle depths and were found in ultrahigh-pressure minerals such as diamond. They occur in rocks as old as 4000 Ma and have been identified in lunar and meteoric samples. Because fluid inclusions are almost ubiquitous in geological samples, their study is applicable to a variety of geological problems and areas. Fluid inclusions have played a central role in oil and ore exploration research and in evaluating the safety of sites for both nuclear reactors and atomic waste repositories. Gas inclusions in polar ice sheets have permitted reconstruction of CO_2 concentrations of the recent atmosphere, fluid inclusions in speleothems (cave deposits) have provided data on paleotemperatures during the last 350,000 years, and inclusions in samples 3500 Ma old may provide geochemical constraints on the composition of the Earth's primitive atmosphere. In mantle and high-pressure rocks, fluid inclusions have helped clarify the nature and role of volatiles in a variety of geodynamic processes including element

recycling into the deep Earth, explosive volcanism at convergent margins, and the seismic behavior of the subducting plate. In metamorphic and sedimentary terranes, fluid inclusions have proven useful tools for containing the burial and exhumation history of crustal rocks and the pressure and temperature changes attending uplift and erosion of continental masses.

Fluid inclusions can be thought of as time capsules storing information about ancient temperatures, pressures, and fluid compositions relevant at the time of trapping. The basic assumption in all fluid inclusion studies is that the volume (density) and composition of the trapped fluid has not changed since formation of the inclusion or that, if an inclusion did leak, evidence for fluid loss is observable in the sample (decrepitation texture, microfracture, etc.). With the exception of magmatic rocks that can contain glass inclusions, that is, solidified melt inclusions, most rocks contain liquid and/or gas inclusions. At room temperature, a general distinction can be made between liquid and gaseous inclusions. Both types are often found in the same rock. This might indicate immiscibility between two phases at the time of trapping. Miscibility is a function of both the salt content of the aqueous phase and the gas composition. One or more solid phases can also be present. Solid phases can be either accidentally trapped particles that were present in suspension when the mineral grew or represent newly formed mineral that crystallized out of the fluids trapped in inclusions after sealing. In this case, the solid phase is called a daughter mineral.

Under the optical microscope, most fluid inclusions have a rather sharp outer boundary marking the edge of the inclusion cavity. This is because of a significant difference in refractive index between inclusion fluids and their mineral hosts: most aqueous fluids have refractive indices between 1.33 and 1.45, whereas the minerals in which they are included have refractive indices from 1.43 to as high as 3.22. Hydrocarbon liquids have refractive indices that may be similar to their mineral hosts and thus are not all easily visible. Given appropriate fluid inclusions, many aspects

of fluid composition can be determined. The composition of most fluids falls in the C-O-H-S (H_2O , CO_2 , CH_4 , H_2S) + NaCl system, with NaCl representing the salt content of the fluid (expressed in weight% NaCl content) and accounting for KCl, CaCl_2 , and other chlorides. Some fluid inclusions can also contain significant amounts of nitrogen (N_2). Bromine and fluorine can be important volatiles in some systems, but their abundances (as HBr and HF) are generally very low. In sedimentary rocks, oil inclusions can be present. The nature and concentrations of a large variety of major and trace elements can be obtained by crushing and leaching the inclusion fluids out of small samples containing a large number of inclusions or in situ, within a single inclusion. Information on the isotopic composition of light elements (H, C, N, O, S, and some noble gases) of the fluid can also be obtained.

If the composition of the inclusion can be determined and the liquid-vapor curve for that fluid is known, then the density can be determined from the temperature of homogenization of the vapor and liquid phases to one fluid phase. If the P-V-T properties of that fluid are known, then a line of constant density or molar volume is defined in a P-T space. This line, called an isochore, represents the range of P-T conditions over which a fluid of that density was trapped. If one can make an independent estimate of pressure or temperature at the time of trapping of the fluid in an inclusion, then both variables (P and T) can be uniquely determined using the isochore of the fluid. If both aqueous and gaseous inclusions are coexisting in the same healed fracture or fluid inclusion cluster, and the specific criteria for immiscibility between these two phases at the time of trapping can be ascertained precisely, then the intersection point between the two isochores in a P-T space corresponds to the temperature and pressure of trapping of the inclusion fluids.

History and Basic Methodology

The presence of fluids in rocks has been noticed since at least the eleventh century, but the first

fluid inclusion constituents (H₂O, CO₂, petroleum) were identified not before the eighteenth and nineteenth centuries (Dolomieu 1792; Sorby 1858). Sorby (1858) was the first to highlight a relation between metamorphism and filling of fluid inclusions. He suggested that the gas-liquid phases in fluid inclusions reflected thermally contracted fluids. He proposed that reheating inclusions would lead to disappearance of the bubble and that the temperature at which this occurred could serve as an estimate of the temperature of mineral formation. During the twentieth century, fluid inclusions were the subject of intense studies and debates by geologists from Russia, the USA, and Europe. The development and improvement of the equipment for quantitative analysis of fluid inclusions during the late 1960s and early 1970s paved the way to a vast number of geological applications using fluid inclusions as a petrological tool. Especially, a cooling-heating stage was developed (Poty et al. 1976), which expanded to low temperatures the temperature range for easily and accurately measuring phase transition in fluid inclusions. This technique known as “microthermometry” is indispensable for the analysis of single fluid inclusions and opened the possibility for the determination of fluid salinities and densities, and the consequent interpretation on the rock-forming conditions. Numerous analytical methods were developed since then for measuring fluid chemical and isotopic compositions. Among these, the introduction of laser Raman spectroscopy around 1980 (Dubessy et al. 1982; Pasteris et al. 1988) and synchrotron radiation micro-x-ray fluorescence (Frantz et al. 1988; Vanko et al. 1993; Philippot et al. 1998), Laser Ablation Inductively Coupled Plasma Mass Spectrometry (Heinrich et al. 2003), and Laser Microprobe Noble Gas Mass Spectrometry (Bohlke and Irwin 1992) around 1990 allowed quantitative analysis of anhydrous gas species (CO₂, N₂, CH₄, H₂S, and from then on H₂O), major and trace elements, as well as noble gases in individual fluid inclusions. Much of this work has been reviewed in the treatise on fluid inclusions published by Roedder (1984). Some of the important concepts and technical achievements

performed during this period are synthesized in Hollister and Crawford (1981) and Goldstein and Reynolds (1994).

Fluid Inclusions in Meteorites and Early Archean Sediments

The discovery of water-bearing fluid inclusions in 4.5 billion-year-old halite (NaCl) crystals preserved in the matrix of the Monahans and Zag H-► [chondrite](#) regolith ► [breccias](#) (Zolensky et al. 1999) provided important constraints on the fluid composition and P-T conditions in the near-surface environment of the ► [parent bodies](#). Minimum formation temperature of the inclusions has been estimated to be less than 100 °C and could have been as low as about 0.01 °C. The minimum pressure needed to stabilize a NaCl-saturated brine is 0.0754 MPa at 100 °C and 3×10^{-4} MPa at 0.01 °C. These conditions are consistent with the alteration having occurred in the shallow subsurface of the parent bodies. Moreover, the P-T conditions inferred for the formation of these inclusions is within the range of temperatures in which life has been observed to exist and thrive on Earth. Tiny fluid inclusions have also been found in two Martian meteorites (one in ► [Nakhla](#), NSNM 5891–3, and one in ► [ALH 84001](#), 146) (Bodnar 2000) and carbonaceous chondrites (Saylor et al. 2001). Although the fluid inclusions in the Nakhla sample occur as healed fracture and therefore are of secondary origin, the inclusions in the ALH 84001, 146 sample do not occur along fractures and therefore could be of primary origin, that is, trapped during growth of the enclosing pyroxene. The fluid in the inclusions may represent the magmatic fluid that exsolved from the crystallizing melt as the igneous rock formed on Mars. As such, the inclusions can provide valuable information about degassing early in Mars history. Optical behavior of these inclusions suggests that they contain liquid and vapor carbon dioxide.

Insights into the composition of the primitive terrestrial ocean and hydrothermal fluids (Cl/Br ratio, sulfur, and metal components) have been obtained by direct analysis of fluid inclusions preserved in poorly metamorphosed Archean sediments of the Kaapvaal Craton (South Africa) and

Pilbara Craton (Western Australia). Early studies performed in 3.2 Gyr-old (Channer et al. 1997; De Ronde et al. 1997) (but see Lowe and Byerly (2003) for a controversy on the origin of the samples considered) and paleoproterozoic 2.2 Gyr-old (Gutzmer et al. 2003) indicated that the Cl/Br ratio of the fluid trapped in the inclusions was below present-day seawater and resulted from mantle buffering, that is, hydrothermal in origin. However, these studies were based on bulk fluid analyses (i.e., crush-leach), which can result in fluid mixing if several fluid generations occur in a single sample. More recently, chemical analysis of individual fluid inclusions have been performed in 3.5 Gyr-old samples from the Pilbara Craton, Western Australia, by Synchrotron Radiation X-ray micro-Fluorescence (SR-XRF), thus allowing independent analysis of different fluids trapped in the same sample (Fiori et al. 2004). Individual fluid inclusion analysis using SR-XRF revealed the presence of three main fluid populations: a metal-depleted fluid, a Ba-rich and S-depleted fluid, and a Fe-S-rich end-member. The Cl/Br ratio of metal-depleted fluid inclusions (630) is similar to the modern seawater value (649) and was thought to represent a relic testimony of the primitive ocean. By contrast, Ba- and Fe-rich brines have Cl/Br ratios (350 and 390) close to bulk Earth value (420), hence arguing for a mantle buffering and a hydrothermal origin of these fluids. Model composition of “seawater component” has been evaluated to be 1100 mM Na, 2250 mM Cl, and 375 mM Ca, which corresponds to a bulk fluid salinity of 12 wt% salt equivalent. This high Cl concentration (ca. four times the present-day value) together with the occurrence of Cl/Br ratio similar to the modern seawater value (649) indicates that the Archean ocean formed on a typical modern-day seawater evaporation trend.

Cross-References

- [Archean Eon](#)
- [Archean Traces of Life](#)
- [Geothermobarometers](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)

- [Oceans, Chemical Evolution of](#)
- [Syngenecity](#)

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Fluid-Bearing Micro Cavities

► Fluid Inclusions

Fluorescence

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Synonyms

Fluorescent emission

Definition

When an electron in a substance is excited to a higher energy state by a photon, it may return to the lower energy state via a series of two or more intermediate energy states, assuming they exist. The photons which are re-emitted have a lower energy than the exciting photon and are consequently of a lower frequency and longer wavelength. This phenomenon is known as fluorescence. In some instances, two electrons may be adsorbed, allowing for emission of radiation of a shorter wavelength. As in UV spectroscopy, compounds often have unique fluorescence spectra which can be used in determining structure (see ► [Fluorometry](#)). Fluorescence detectors are extremely sensitive, thus this is an excellent analytical technique for trace amounts of substances. The infrared emission bands assigned to ► [polycyclic aromatic hydrocarbons](#) (PAHs) in a variety of astronomical environments have been attributed to fluorescence, with the exciting radiation being in the ultraviolet region of the spectrum.

Cross-References

► [Polycyclic Aromatic Hydrocarbon](#)

Fluorescence Resonance Energy Transfer

► [FRET](#)

Fluorescence Spectroscopy

► [Fluorometry](#)

Fluorescent Emission

► [Fluorescence](#)

Fluorimetry

► Fluorometry

Fluorometry

Michael P. Callahan
Astrochemistry Laboratory, Code 691, NASA
Goddard Space Flight Center, Greenbelt, MD,
USA

Synonyms

Fluorescence spectroscopy; Fluorimetry;
Spectrofluorometry

Definition

Fluorometry is a chemical technique for measuring or monitoring ► [fluorescence](#). In fluorometry, the species is excited from its ground electronic state to an excited electronic state by absorption of a ► [photon](#) (typically from a UV source). The species returns to the ground electronic state by emitting one (resonance fluorescence) or more photons. The amount of fluorescence measured is used to determine the sample concentration by comparison with a standard or by using a calibration curve. Fluorometry is highly sensitive with up to femtomolar detection limits. In addition, fluorometry is considered a more specific technique than ► [absorption spectroscopy](#), since fluorescent molecules (fluorophores) are less common.

Cross-References

- [Absorption Spectroscopy](#)
- [Fluorescence](#)
- [Fluorophore](#)
- [Photon](#)

Fluorophore

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Keywords

Chromophore

Definition

A fluorophore is a molecule or a portion of a molecule that has fluorescent properties. While many compounds are inherently fluorescent as they contain fluorophores, there are many compounds that are not. For the sake of analyzing these latter types of molecules, a fluorophore is often introduced via chemical derivatization with a fluorescent reagent, for example, fluorescein isothiocyanate (FITC) or fluorescamine. Many widely used DNA stains and cell stains such as 4', 6-diamidino-2-phenylindole (DAPI) are fluorophore-containing molecules.

In the interstellar medium, infrared emission attributed to ► [polycyclic aromatic hydrocarbon](#) molecules (PAHs) is thought to result from fluorescence following the absorption of ultraviolet photons.

Cross-References

- [Fluorometry](#)
- [Polycyclic Aromatic Hydrocarbon](#)

Fluvial or River Delta

- [Mars, Delta](#)

Flux, Radiative

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The radiative flux is the amount of electromagnetic power crossing one surface unit. In astronomy, it corresponds to the part of the power emitted by a celestial object received per area unit at the Earth. If the contributions at all the wavelengths are summed, one speaks of bolometric flux and the unit is W m^{-2} . If only a small interval in frequency (or wavelength) is considered, one speaks of spectral flux (unit: $\text{W m}^{-2} \text{Hz}^{-1}$). In the radio domain, the unit currently used is the Jansky ($10^{-26} \text{W m}^{-2} \text{Hz}^{-1}$).

Cross-References

- [Electromagnetic Radiation](#)
- [Magnitude](#)

Fomalhaut b,

Fig. 1 False-color, unsmoothed image of the 2012 STIS data. The box inset is 1° . on a side and magnifies the image of Fomalhaut b. North is *up*, east is *left*. (Image from Kalas et al. 2013)

Fomalhaut b

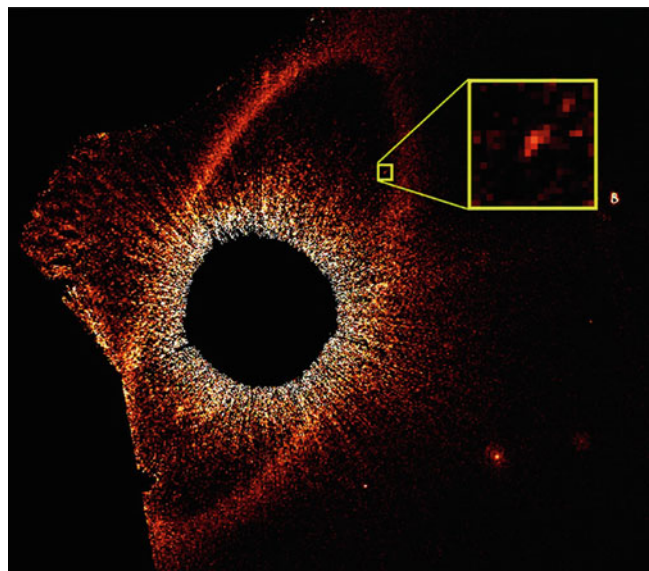
Marc Kuchner¹ and Nader Haghighipour²
¹NASA Goddard Space Flight Center, Exoplanets
and Stellar Astrophysics Laboratory, Greenbelt,
MD, USA
²Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

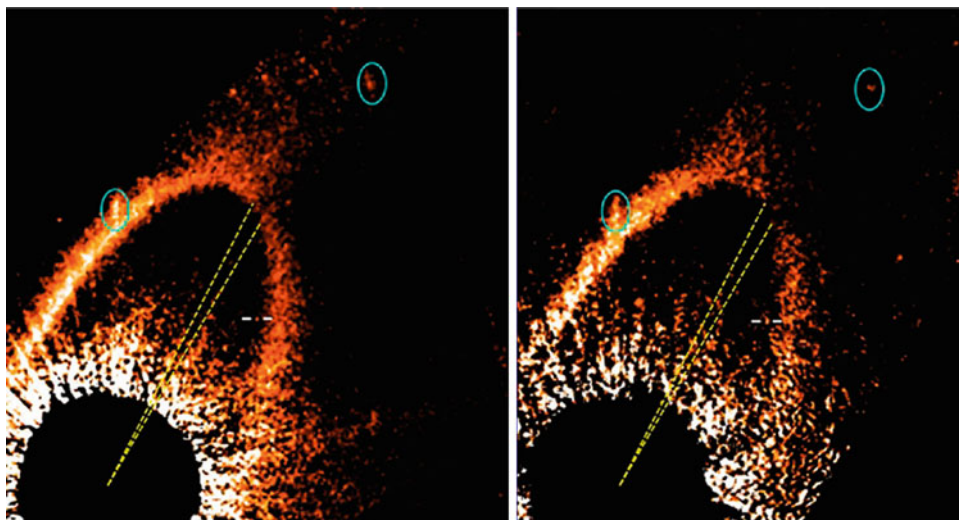
Synonyms

[α Piscis Austrinus b](#)

Definition

Fomalhaut b is a massive planet orbiting roughly 115 AU (► [AU = astronomical units](#)) from the main sequence A-type star Fomalhaut, 25 light years from Earth. Paul Kalas, James Graham, and Mark Clampin discovered the planet in 2008 in a series of images of the star made by the ► [Hubble Space Telescope](#) (HST), showing the object to orbit the star just inside a narrow ring of dust. The planet's mass is constrained to the range





F

Fomalhaut b, Fig. 2 Northwest portions of the 2012 data (left) and 2010 data (right) with 5×5 median binning and a hard *grayscale* stretch to emphasize the northwest gap. The dotted lines are at P.A. = 329.8° and 332.8° in both

data sets. *Ovals* indicate background galaxies and Fomalhaut b is marked between *white line* segments. (Image from Kalas et al. 2013)

0.05–3 Jupiter masses based on the shape of the dust ring, which the planet stirs gravitationally. The ring of dust around Fomalhaut tipped off observers in the 1980s that this star might host a planetary system. Images of this narrow ring with the *HST* showed that the ring is not centered on the star; its center is offset from the star by 15 AU. This offset suggested the presence of a planet perturbing the ring, and led to the planet's discovery in 2008. The planet remains mysterious; it is several times brighter than expected for a body with this mass, and it has so far escaped observers who have tried to image it using other instruments. Fomalhaut b is considered the first extrasolar planet directly imaged by the *HST*; it is roughly a billion times fainter than the star it orbits (Figs. 1 and 2).

Cross-References

- [Beta Pictoris b](#)
- [Direct-Imaging, Planets](#)
- [Exoplanets, Discovery](#)

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Fool's Gold

- [Pyrite](#)

Footballene

- [Fullerene](#)

Formaldehyde

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Keywords

Formose · Prebiotic chemistry · Strecker
synthesis

Synonyms

Methanal; Methyl aldehyde; Methylene oxide;
Paraformaldehyde

Definition

Formaldehyde (methanal, HCHO), the simplest ► **aldehyde**, is a one-carbon molecule intermediary along the redox continuum between CO₂ and CH₄, at the same oxidation state (0) as ► **graphite**. Formaldehyde was first reported by the Russian chemist Butlerow in 1860 and was conclusively identified by von Hofmann. It exists transiently but prominently in the abiological carbon cycle (Cleaves 2008). It is an abundant interstellar molecule and is a constituent of cometary ices (Biver et al. 2002, Schutte et al. 1993). It is readily produced in prebiotic simulation experiments from a variety of gas mixtures and energy sources.

HCHO may have played an important role in the synthesis of organic molecules relevant to the origin of life. HCHO is likely a significant precursor for the prebiotic synthesis of ► **glycine** and other amino acids (Miller 1957). HCHO can react to form sugars under basic conditions (Butlerow 1861) via the so-called ► **formose reaction**, a reaction of potential importance for the origin of an ► **“RNA World”** or early nucleic acids based on alternative sugars in a potential “pre-RNA

World” (Joyce et al. 1987). It has been argued that HCHO may in fact be the *only* one carbon C-, H-, and O-containing molecule capable of generating complex organic compounds for the origin of life (Weber 2002).

Overview

Basic Methodology

The geochemical behavior of formaldehyde is studied by a variety of techniques, including routine chemical analysis and laboratory simulation, spectroscopy, and various computational modeling approaches.

Key Research Findings

Prebiotic Sources of HCHO

One important source of HCHO on the primitive Earth is atmospheric photochemical synthesis by the photoreduction of CO₂ with H₂O:

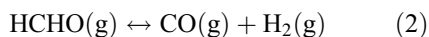


Pinto et al. (1980) estimated that HCHO could be produced in yields of up to 10¹¹ moles/year, reaching a steady-state oceanic concentration of 10^{−3} M in 10⁷ years. Electric discharges acting on a variety of gas mixtures also produce HCHO in good yield (Stribling and Miller 1987); however, photochemistry may have been more significant simply due to the greater energy flux. Photochemical production from atmospheric CH₄ and/or CO could also have been a significant source of HCHO, though the production and rainout rates of HCHO are highly sensitive to energy source and atmospheric composition (Chang 1993).

HCHO could also potentially be produced in hydrothermal vents (Ferris 1994), for example, by the reduction of aqueous formate, CO or CO₂, or by the oxidation of methanol or CH₄, although HCHO does not appear to be a stable redox state of carbon under hydrothermal conditions. HCHO may be an intermediate in the redox equilibration of other more stable compounds (Seewald et al. 2006).

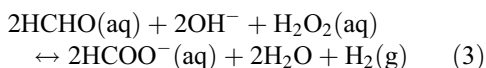
Prebiotic Sinks for HCHO

HCHO decomposes thermally in the gas phase above 300 °C to give CO and H₂ (Bone and Smith 1905) (Eq. 2):



Long-wavelength photochemical destruction was also likely a significant sink for HCHO (see below) (Calvert and Steacie 1951). Sekine (2002) found that MnO₂ catalyzes the oxidation of HCHO at room temperature to CO₂ under atmospheric conditions. Löb (1906) found that electric discharges acting on HCHO in the presence of water vapor give CO, CO₂, H₂, and CH₄ as products, which is essentially the reverse of the reaction demonstrated by Miller (1953).

There is reason to believe that there was a considerable flux of atmospherically synthesized and rained out H₂O₂ to the primitive oceans, particularly if the atmosphere was nonreducing (Kasting and Brown 1998). Reaction of HCHO with aqueous hydrogen peroxide gives formate and H₂ (Walker 1964) (Reaction 3):



Prebiotic Solution Chemistry of HCHO

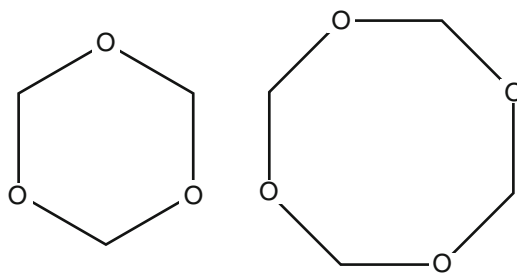
An excellent monograph has been written on the chemistry of HCHO (Walker 1964). In an aqueous solution, HCHO is mostly present as the monohydrate, methylene glycol (Eq. 4):



HCHO absorbs UV radiation strongly in the range of 250–350 nm, resulting in photolysis. The hydrate does not absorb light at these wavelengths, thus dissolution in water could be an important photoprotection mechanism for HCHO.

Oligomerization Chemistry: Polyoxymethylene

Low-molecular weight polymers, ► **polyoxymethylene** (POMs) (of formula HO(CH₂O)_nH), form readily in neutral concentrated aqueous HCHO solution. The cyclic oligomers,



Formaldehyde, Fig. 1 Cyclic oligomers of HCHO, trioxane, and tetraoxane

trioxane, and tetraoxane (Fig. 1) may also form where acid catalysis is available.

Oligomerization Chemistry: The Formose Reaction HCHO can be oligomerized under basic conditions into sugars via the so-called formose reaction (Butlerow 1861) (see ► **Formose Reaction**). The equilibrium constant for the dimerization of HCHO to give ► **glycolaldehyde** is not well known, but is of considerable interest, since, while HCHO is volatile, glycolaldehyde is not and could thus be concentrated by evaporation.

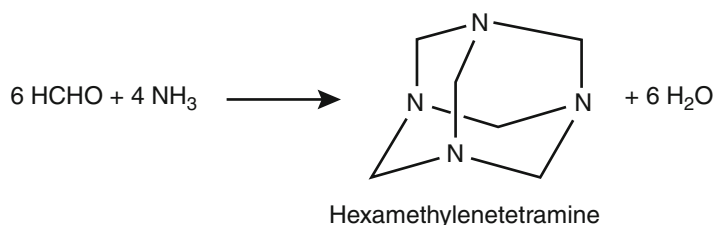
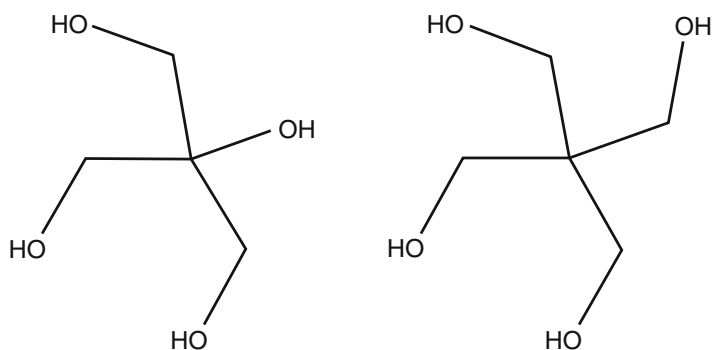
HCHO reacts with ► **acetaldehyde** at much lower concentrations to give acrolein, among other products (Cleaves 2003).

The reaction of HCHO into formose is one limiting reaction pathway for the accumulation of HCHO in primitive waters, which would depend on the rate of HCHO production and delivery to the primitive oceans (Pinto et al. 1980). If HCHO became sufficiently concentrated, side reactions may have established the steady-state concentration regardless of the production rate. Given the observed photochemical synthesis of pentaerythritol (Fig. 2, left-hand side) (Schwartz and De Graaf 1993), and its likely mechanism of synthesis, it seems possible that HCHO is converted to CH₃CHO by UV light, and thus it appears unlikely that bulk oceanic concentrations of HCHO could have been much higher than 10^{−3} M.

HCHO is prone to photoreaction in the primitive oceans. For example, HCHO photochemically reacts to give mostly pentaerythritol

Formaldehyde, Fig. 2

2-Hydroxymethylglycerol and pentaerythritol: major products of photochemical reactions of HCHO

**Formaldehyde, Fig. 3** Hexamethylenetetramine (HMT) forms readily from NH_3 and HCHO

(Schwartz and De Graaf 1993), among other non-sugar products (Fig. 2) (Shigemasa et al. 1977).

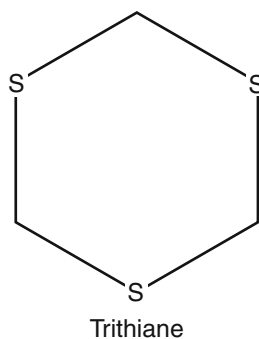
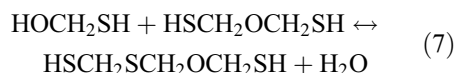
Reactions with Amines

HCHO is converted to ► **hexamethylenetetramine** (HMT or 1, 3, 5, 7-tetraazatricyclo [3.3.1.1^{3,7}] decane) (Fig. 3) by reaction with ammonia (NH_3).

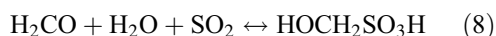
The reaction of fairly dilute ($\sim 0.003 \text{ M}$) aqueous HCHO and NH_3 between 100°C and 250°C produces amino acids, amines, and amino alcohols (Aubrey et al. 2009), and the reaction of somewhat more concentrated HCHO (0.02 M) with NH_3 (0.04 M) has been shown to produce traces of amino acids at lower temperatures (40°C) (Weber 1998). Thus, for at least several simple amino acids, NH_3 and HCHO may be sufficient for synthesis to occur.

Reactions with Sulfur Species

HCHO and H_2S react rapidly to produce trithiane and other oligomers (Fig. 4), which have been detected in hydrothermal vent effluent (Simoneit 1992), as well as in hydrothermal vent simulations (Cole et al. 1994) (Eqs. 5, 6, and 7):

**Formaldehyde, Fig. 4** Trithiane is formed from H_2S and HCHO

Aqueous HCHO reacts with SO_2 to give methylolsulfonic acid (Walker 1964) (Eq. 8):



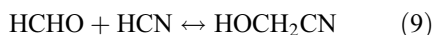
The salts of this compound are nonvolatile, but decompose in dilute acid, liberating HCHO.

Mineral Interactions

There have been few studies of the adsorption of HCHO to minerals, though the ones that do exist suggest that HCHO clay adsorption equilibria are not especially high. This is generally also true for low molecular weight POMs (Parfitt and Greenland 1970). The adsorption equilibria may be more significant for clays such as illite and ► [kaolinite](#) (Chandra and De 1983). Clay adsorption may have led to significant concentration effects which may have facilitated reactions of HCHO such as oligomerization to formose products and redox reactions to ► [methanol](#), formate, and CO₂.

Reaction with HCN

Aqueous HCHO reacts readily with HCN to give glycolonitrile (Henry 1890) (Eq. 9):



The K_{eq} for the reaction is exceptionally high (Schlesinger and Miller 1973); thus, any atmospheric composition which results in the production of the two compounds essentially results in the production of ► [glycolic acid](#), after hydrolysis of the ► [nitrile](#).

Schwartz and Goverde (1982) found that the addition of HCHO or glycolonitrile to HCN actually accelerates the formation of HCN tetramer diaminomaleonitrile (DAMN). HCHO reacts readily with DAMN to form a crystallizable product (Koch et al. 2007).

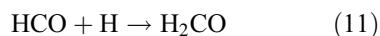
Reaction of HCN, HCHO, and NH₃ produces the amino acid glycine via the Strecker synthesis.

Cannizzaro reactions may also be important loss channels for HCHO. If HCHO concentrations are high enough, HCHO disproportionates to form formate and methanol (Walker 1964), which reduces the concentration of HCHO available to form sugars. These reactions are acid-, base-, and metal- catalyzed (Walker 1964). As the reaction is apparently a third order, it is unclear whether it would occur significantly in dilute solution.

Interstellar Formaldehyde

Formaldehyde was the first polyatomic organic molecule detected in the interstellar medium by

Zuckerman et al. (1970). Since its initial detection, it has been observed in many regions of the galaxy. As the gas-phase reaction that produces formaldehyde is too inefficient to produce the abundance of formaldehyde that has been observed, it has been proposed that HCHO is formed via the hydrogenation of CO in ice (Eqs. 10 and 11):



There are several side reactions that take place with each step of the reaction that depends on the nature of the ice on the grain (Woon 2002). The isotopic ratio of [¹²C]/[¹³C] in HCHO in the galactic disk has been determined to be ~50:1 (Henkel et al. 1985), while the terrestrial ratio is ~100:1.

Formaldehyde in Biology

Free formaldehyde is rarely found in living metabolism, as formaldehyde is mutagenic due to its reactivity with proteins and nucleic acids. The main biological HCHO carrier is tetrahydrofolate; however, in methanogenesis, HCHO is masked as a methylene group in methanopterin.

Future Directions

A great deal remains to be discovered and quantified about the reactivity of formaldehyde in geochemical settings, and how this reactivity may have contributed to the complexification of organic materials for the origins of life.

Cross-References

- [Aldehyde](#)
- [Formose Reaction](#)
- [Strecker Synthesis](#)

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Formamide (NH₂CHO)

Didier Despois

Laboratoire d'Astrophysique de Bordeaux,
CNRS-Université de Bordeaux, Bordeaux,
France

Synonyms

[Methanamide](#); [NH₂CHO](#)

Definition

Formamide (IUPAC name, methanamide) is the ► [amide](#) with the simplest structure (other amides have one, two, or three hydrogen atoms replaced by radicals). Formamide is the smallest molecule with a peptide bond. At room temperature and standard pressure, it is a colorless liquid. It remains liquid between 3 and 210 °C: this large range is one of the reasons for which formamide was proposed as an alternative to water as the “ideal” solvent for life. Above 90 °C, it decomposes to HCN and water. Ammonium formate, itself a product of the reaction of the two simple species, formic acid and ammonia, produces formamide when heated. Formamide is a potential starting material to create the RNA bases (Barks et al. 2010). Formamide has been found in the ► [interstellar medium](#) and in comets.

History

Formamide was detected for the first time in 1971 in the interstellar medium by Rubin et al. and in 1997 in the bright comet C/1995 O1 (Hale-Bopp) by Mehringer et al.

Cross-References

- [Comet](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)
- [Peptide](#)

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Formamido Pyrimidines

Raffaele Saladino

Department of Ecological and Biological
Sciences, University of Tuscia, Viterbo, Italy

Keywords

Formamide · Pyrimidines · Nucleobases
chemical synthesis

Synonyms

[N-\(pyrimidinyl\)formamide](#)

Definition

(1) Pyrimidine derivatives bearing one or more formylated amino moieties. (2) Formamide derivatives bearing one or two pyrimidinyl substituents on the amino group.

History

Formamido pyrimidines are key intermediates in the synthesis of purine and pyrimidine

nucleobases and analogues. They are produced during single electrophoretic line DNA sequencing procedures (Negri et al. 1991) by nucleophilic addition of formamide to C-8 position of purine nucleosides (Saladino et al. 1996). This reaction is one of the main DNA repair pathways under radiation and oxidative stress (Ober et al. 2003), and it catalyzed by the presence of mineral oxides (Saladino et al. 2003). Under prolonged sequencing procedures, formamido pyrimidines are further degraded to *N*-ribosyl urea and urea (Saladino et al. 1997). Examples of the synthesis of formamido pyrimidines under prebiotic conditions and their conversion into nucleobases and nucleosides are reported, including thermal condensation of formamide in the presence of montmorillonites (Saladino et al. 2004), multi-component reaction between malononitrile, amidinium salts and formic acid and metals (Becker et al. 2018), and condensation between formic acid and preformed aminopyrimidines (Becker et al. 2016). These procedures are characterized by high regioselectivity, simple one-carbon containing compounds, such as formamide and HCN oligomers, playing the role of both reagent and reaction medium (Yodav et al. 2020).

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Formamine

► [Hexamethylenetetramine](#)

Formation of Planetesimals: The Building Blocks of Planets

Anders Johansen

Lund University, Lund, Sweden

Keywords

Dust · Particle concentration · Pebbles · Planet formation · Planetesimals · Protoplanetary disks · Streaming instability · Turbulence

Definition

Planetesimals are traditionally defined as solid objects (rocky or icy or a combination of both) whose internal strength is dominated by self-gravity rather than material strength. This corresponds to bodies of approximately 100 m to 1 km in size (Benz 2000). However, this definition does not take into account the role of the body in the planet-building process. Planetesimals of km in size are vulnerable to erosion and fragmentation in collisions with other planetesimals at the speeds relevant in protoplanetary disks (Ida et al. 2008). One can instead define the *planetesimal formation stage* as the growth of bodies to sufficient sizes to be insensitive to disruption in collisions with equal-sized bodies. This stage of planet formation may extend to as large as 1000 km in size, depending on the strength of the gas turbulence which is responsible for inducing high planetesimal-planetesimal speeds.

Overview

Planet formation takes place in ► [protoplanetary disks](#) of gas and dust which surround young stars. The embedded dust and ice particles represent only approximately 1% of the mass of the protoplanetary disk, but their structure formation

through collisions and sticking is responsible for the growth of planetary bodies.

The formation of *planetesimals* is an important step in the growth of planetary systems. Planetesimals are the building blocks of the rocky terrestrial planets (Mercury, Venus, Earth, and Mars) as well as the cores of the gas giants (Jupiter and Saturn) and the ice giants (Uranus and Neptune). The ultimate outcome of the planetesimal formation stage is the production of planetesimals of sufficient sizes to obtain gravitational cross sections much larger than their physical cross sections, hence accelerating the growth toward fully fledged planets. The gravitational cross section can here refer to either the ability to accrete other planetesimals (Levison et al. 2010) or to accrete mm–cm-sized pebbles facilitated by the strong gas drag felt by such small particles (Lambrechts and Johansen 2012).

The lack of ► [gravitational focusing](#) in the planetesimal formation stage means that direct sticking is key to particle growth. However, dust particles encounter many barriers and bottlenecks in their growth toward planetesimals, as bouncing and fragmentation become increasingly likely with increased size (Zsom et al. 2010). Particles of sizes from mm to several m are nevertheless concentrated in the turbulent flow of the gas, and the overdensities can become high enough for the collective gravity to be dominant (Johansen et al. 2007). This leads to the formation of large planetesimals (100–1000 km radii) by gravitational collapse of particle filaments and clumps.

Basic Methodology

Planetesimal formation can be studied observationally, experimentally, or theoretically. Important constraints on the planetesimal formation process are obtained from studying the structure and dynamics of minor bodies in the solar system – asteroids, Kuiper belt objects, and comets – or from studying debris disks around other stars. In the latter, the observed dust is produced through collisions within an (unseen) planetesimal population. In the Solar System measurements of size distributions, spectral classes and binarity have

proven useful for developing planetesimal formation models.

The outcome of collisions between particles of different sizes can be measured in the laboratory. Particle aggregates are typically built from micrometer-sized silicate monomers. These aggregates can then collide with each other and the outcome is measured in terms of sticking, bouncing, or fragmentation (Güttler et al. 2010), depending on the collision speed.

Knowing the collision outcome for a wide range of input parameters, the growth of populations of dust particles can be modeled on a computer. The collision speed depends on the sizes of the colliding particles. For small particles, the Brownian motion dominates, while larger particles have increasing contributions from the turbulent gas, peaking at approximately 5–50 m/s for m-sized particles under typical turbulent conditions.

Hydrodynamical simulations are used to investigate the concentration of particles in the turbulent gas flow of the ► [protoplanetary disk](#). Particle concentration mechanisms can be divided into two categories. *Passive concentration* occurs as particles pile up in regions of high gas pressure. On small scales of the turbulent flow, these regions reside between swiftly rotating turbulent eddies (which are themselves low pressures). Small particles, under some conditions similar in sizes to those stuck at the bouncing barrier (Zsom et al. 2010), concentrate between the eddies (Cuzzi et al. 2001). On large scales where Coriolis forces from the rotating disks are dominant, large-scale vortices and axisymmetric pressure bumps arise spontaneously in the turbulent flow (Johansen et al. 2009) or near transitions in the turbulent viscosity (Lyra et al. 2008). These geostrophic high-pressure structures concentrate large particles, of typical sizes from 10 cm to 1 m.

Active concentration occurs through the streaming instability (Youdin and Goodman 2005). This hydrodynamical instability arises in the coupled motion of particles and gas, from the free energy present between the inward-flowing particles and the outward-flowing gas in the midplane. The gas in the protoplanetary disk is slightly pressure supported in the radial direction,

since the gas is denser and hotter close to the star. The pressure support acts like a reduced gravity on the gas and causes the gas to orbit a bit more slowly than the Keplerian speed, by approximately 50 m/s. Solid particles do not sense the pressure gradient force from the gas and would orbit at the Keplerian speed in absence of friction, but the headwind of the slower moving gas drains angular momentum from the particles and causes them to drift toward the star. The drift speed peaks for typical particle sizes of 10 cm to 1 m, in the inner few AU of the protoplanetary disk, with a drift timescale as low as a few hundred years. Regions of slightly increased particle density drift more slowly toward the star as the gas there is accelerated toward the Keplerian speed by the drag force from the particles. The streaming instability causes an exponential increase of the density of the filament as isolated, fast-drifting particles continue to pile up in the overdense region.

Key Research Findings

Dust growth models have identified a number of bottlenecks in the planetesimal formation process. The *electrostatic barrier* describes the inability for dust grains to grow beyond a few 10 μm , as negatively charged aggregates repel each other (Okuzumi 2009). The *bouncing barrier* sets in at sizes from 0.1 to 1 mm, as compactified dust aggregates of these sizes will bounce rather than stick if collision speeds are higher than a few mm per second (Zsom et al. 2009). The *fragmentation barrier* sets in at collision speeds higher than 1 m/s, although growth can still be obtained if small impactors hit much larger targets at speeds up to 25 m/s (Wurm et al. 2005). Finally the formidable *radial drift barrier* requires that growth must be faster than the radial drift of particles (Weidenschilling 1977). Even if the radial drift barrier could be somehow overcome, the fragmentation barrier has second branch for km-scale planetesimals whose collision speed can be excited to super-escape values by the turbulent gas (Ida et al. 2008).

While ideas exist for circumventing the many growth barriers, e.g., by invoking sticky organics

(Kouchi et al. 2002) or dust rims to enhance sticking between the mm-sized chondrules which are found in meteorites (Ormel et al. 2008), any growth must compete with the radial drift of the particles. Global models of particle coagulation have only managed to produce planetesimals by sticking either in the innermost part of the disk (within 1 AU) or by assuming high sticking threshold speeds and invoking pressure bumps to stop the radial drift (Brauer et al. 2008).

Another path to planetesimal formation is through the concentration of particles in the turbulent gas flow, followed by a brief phase of gravitational contraction and collapse. Large-scale axisymmetric pressure bumps were identified already by Whipple (1972) as traps of drifting particles. Barge and Sommeria (1995) explored dust trapping in anticyclonic vortices – structures which could arise in protoplanetary disks around at transitions from weak to strong turbulence (Lyra et al. 2008) or at the edge of gaps produced by giant planets. Turbulence in protoplanetary disks may be driven by the magnetorotational instability (Balbus and Hawley 1991). Computer simulations of magnetorotational turbulence in accretion disks show the emergence of large-scale pressure bumps which trap dm–m-sized dust particles (Johansen et al. 2009). The streaming instability was discovered by linear stability analysis by Youdin and Goodman (2005). The process of piling up isolated particles into overdense filaments leads to very high particle densities, as high as 10,000 times the local gas density (Johansen et al. 2012).

The growth of particles by sticking and collapse of overdense particle filaments into planetesimals are not mutually exclusive. Particles must grow to sizes of at least mm in order to be able to concentrate in the turbulent gas, and some mechanisms like vortices and pressure bumps seem to require particles as large as 10 cm to begin with. Particle growth also does not stop at the collapse phase. Particle densities reach very high values during the contraction to solid densities and hence collision rates are high. The outcomes of these collisions determine the sizes of the planetesimals which emerge from the contracting clouds. Nesvorný et al. (2010) investigated the outcome of collapsing pebble clouds

and found that an initial mean rotation of the cloud (which could be inherited from the overall rotation of the disk) leads typically to the formation of a binary planetesimal surrounded by particles clumps which can be interpreted as a swarm of smaller planetesimals. This model agrees with the observation that the classical cold component of the Kuiper belt – the most pristine planetesimals in the Solar System which have undergone very little collisional and dynamical evolution – have a very high binary fraction.

Applications

Results from planetesimal formation models can be used as input for understanding the formation of planetary systems. The birth sizes of planetesimals can be applied to the asteroid belt to understand the origin of the current size distribution of asteroids as well as the emergence of the major asteroid classes. Water delivery to Earth is thought to have happened via collisions with icy planetesimals, so the origin of life on Earth is deeply connected to the formation of planetesimals.

Future Directions

An important priority for planetesimal formation studies in the future is to develop models of the growth of dust particles by sticking which take into account the concentration and gravitational collapse into planetesimals of a wide range of sizes. While many aspects of particle growth and concentration are well understood, the single most important parameter in determining which processes are dominant is the strength of the turbulence in the gas. Strong background turbulence suppresses the streaming instability so that particles must grow to sizes of at least 10 cm in order to concentrate in large-scale pressure bumps and vortices. The streaming instability can concentrate particles down to cm sizes if the turbulence is moderate or weak. Thus, an increased comprehension of the presence and strength of turbulence in protoplanetary disks will be crucial for understanding how planetesimals form in protoplanetary disks.

Cross-References

- ▶ [Asteroid](#)
- ▶ [Coagulation in Planetary Disks](#)
- ▶ [Core Accretion, Model for Giant Planet Formation](#)
- ▶ [Gas drag](#)
- ▶ [Kuiper Belt](#)
- ▶ [Meter-Size Catastrophe](#)
- ▶ [Planet](#)
- ▶ [Planet Formation](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Runaway Growth](#)
- ▶ [Small Solar System Body](#)
- ▶ [Solar Nebula](#)
- ▶ [Turbulence \(Planetary Disks\)](#)
- ▶ [Vortex, Vortices](#)

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Formic Acid

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

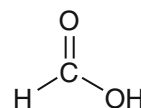
Synonyms

[Methanoic acid](#)

Definition

Formic acid is a carboxylic acid, whose chemical formula is HCOOH (Fig. 1). It has a dissociation constant in water ($\text{p}K_{\text{a}}$) of 3.74. It dissolves readily in water and is slightly soluble in hydrocarbons. It is mostly present as dimers in hydrocarbon solvents and in the gas phase. It can react as a reducing agent. It dissociates to carbon monoxide and water upon heating or by the addition of sulfuric acid. In an early report on the abiotic

Formic Acid,
Fig. 1 Formic acid



synthesis of organic compounds, Garrison et al. (1951) reported that formic acid was produced by helium ion irradiation of an aqueous solution containing CO_2 and Fe^{2+} . Formate is also produced by the hydrolysis of HCN or formamide. Melting point, $-8.4\text{ }^{\circ}\text{C}$; boiling point, $101\text{ }^{\circ}\text{C}$; density, 1.22 g cm^{-3} .

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Formic Acid Methyl Ester

► [Methyl Formate \(\$\text{HCOOCH}_3\$ \)](#)

Formonitrile

► [Hydrogen Cyanide](#)

Formose Reaction

Henderson James Jim Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Keywords

Autocatalysis · Carbohydrate · Formaldehyde · Formose · Ribose · RNA World · Prebiotic chemistry · Sugars

Synonyms

Butlerow reaction

Definition

The formose reaction, discovered by Butlerow in 1861, is a complex autocatalytic set of condensation reactions of formaldehyde to yield sugars and other small sugar-like molecules. The reaction is particularly noteworthy in the context of astrobiology and prebiotic chemistry in that it could serve as a potential abiotic source of carbohydrates, in particular ribose, which could be important for the origin of an RNA World.

Overview

The formose reaction is an autocatalytic reaction discovered by Butlerow (1861). It involves the formation of sugars, polyols, and hydroxy acids from ► [formaldehyde](#) in a series of carbon-to-carbon condensations, as opposed to carbon-to-oxygen condensations of HCHO to form ► [polyoxymethylene](#). Formose is a contraction of formaldehyde and the suffix -ose, denoting a sugar. In fact, many biological sugars have empirical formulas of the form $(\text{CH}_2\text{O})_n$, for example, glucose, $(\text{CH}_2\text{O})_6$, and ► [ribose](#), $(\text{CH}_2\text{O})_5$. The formose reaction may be a mechanism for the prebiotic synthesis of sugars from formaldehyde, of relevance to the origin of an ► [RNA World](#) (Gesteland and Atkins 1993), early nucleic acids based on alternative sugars in a potential “pre-RNA World” (Joyce et al. 1987), as well as other sugar-based models for the origin of life (Weber 1997, 2001). The formose reaction is one of the few chemical systems proposed to be close to an autocatalytic proto-metabolic cycle (Orgel 2000).

Both formaldehyde and ► [glycolaldehyde](#) have been observed spectroscopically in outer space in both the ► [interstellar medium](#) and in comets (Hollis et al. 2000). Formaldehyde and sugar-related compounds, such as ► [glycerol](#), which could be derived from this reaction, are abundant in some carbonaceous chondrites (Cooper et al. 2001); thus, the formose reaction

could be a cosmically common abiotic mechanism for sugar synthesis.

Basic Methodology

The formose reaction has been studied as a chemical reaction traditionally, and thus approached using various analytical chemistry techniques. It has also been studied in various computational simulations.

Key Research Findings

Reaction Mechanism

The mechanism of the reaction has been studied intensively, and the complexity of the product mixture is notorious (Breslow 1959). The reaction is typically carried out from concentrated HCHO under alkaline conditions in the presence of divalent metal ions, such as calcium, magnesium, or lead, and is preceded by an induction period which can be shortened by the addition of glycolaldehyde or other aldehydes as initiators. Reaction does not proceed at an appreciable rate under neutral conditions at room temperature. At high pH, it is sluggish in the absence of catalysts such as divalent metal ions (Orgel 2000). It has been difficult to decipher whether the reaction *requires* divalent cations or higher aldehydes to initiate. It has been reported that carbohydrates and other trace impurities in commercial formaldehyde solutions or paraformaldehyde present in ppm quantities may be the cause of the autocatalysis observed in some of the formose reactions studied to date (Socha et al. 1980). For example, paraformaldehyde sublimed into $\text{Ca}(\text{OH})_2$ suspension was not transformed to sugars via the formose reaction, but only to methanol and formate by the base-catalyzed Cannizzaro reaction, and a 3 ppm trace of glycolaldehyde was sufficient to initiate conventional autocatalysis (Socha et al. 1980). However, at neutral or slightly basic conditions, redistilled formaldehyde solutions undergo the classical reaction (at 80°) in the presence of several minerals, while no reaction is observed in their absence (Schwartz and de Graaf 1993a; see below).

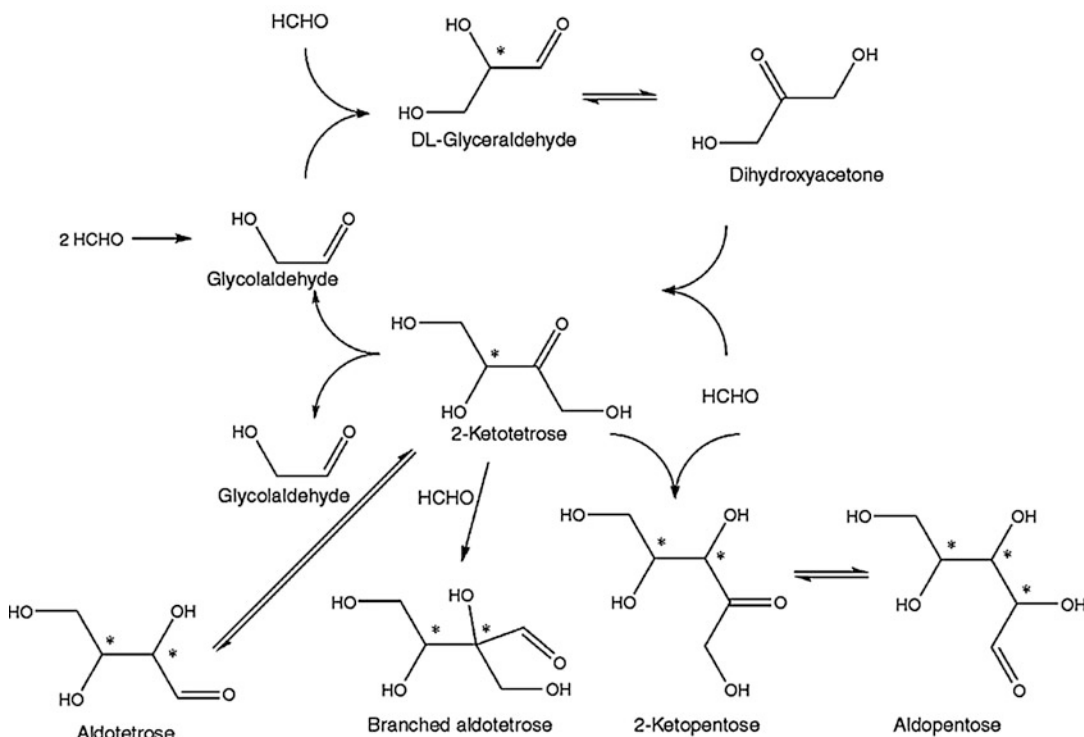
The reaction involves a series of intermediate steps including aldol reactions, reverse aldol reactions, and isomerization reactions. A number of intermediates have been identified including glycolaldehyde, glyceraldehyde, dihydroxyacetone, and tetroses. Figure 1 shows a simplified proposed mechanism for the reaction (Breslow 1959).

The reaction is proposed to begin with the apparently kinetically slow reaction of two formaldehyde molecules to make glycolaldehyde. Glycolaldehyde then reacts via an aldol condensation with another formaldehyde molecule to yield DL-glyceraldehyde. Isomerization of glyceraldehyde forms dihydroxyacetone (DHA), which can react with glycolaldehyde to form a 2-ketopentose. This 2-ketopentose may then isomerize to yield various isomeric pentoses. DHA can also react with formaldehyde to produce a 2-ketotetrose which can isomerize to give an aldotetrose. At this

step, the aldotetrose can react via a retro-aldol reaction to give two molecules of glycolaldehyde. Due to the generation of two molecules of glycolaldehyde from the input of one, the reaction becomes autocatalytic.

Mineral Interactions

Mineral adsorption may have been an important sink or concentration mechanism for HCHO and sugars. Mineral surfaces and other inorganic species can also have significant effects on the course of the reaction, as both general and selective catalysts for synthesis and degradation for the reaction products. There have been relatively few studies of the adsorption of HCHO to minerals, though the ones that do exist suggest that HCHO-clay adsorption equilibria are not especially high, which is also true for low molecular weight POMs (Parfitt and Greenland 1970). Adsorption equilibria may be higher for clays such as illite and kaolinite (Chandra and De 1983).



Formose Reaction, Fig. 1 A simplified scheme for the formose reaction. The stereochemistry of the asymmetric carbon atoms (marked with an *asterisk* in the diagram) is

not specified, but in general all isomers are formed. Side reactions leading to branched-chain molecules complicate the cycle and divert molecules from it

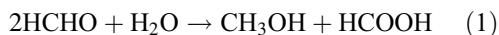
Many minerals appear to catalyze the formose reaction, for example, various clays, apatite, and calcite were found to be catalysts (Gabel and Ponnampertuma 1967; Reid and Orgel 1967; Cairns-Smith et al. 1972; Schwartz and de Graaf 1993b). The reaction can be carried out at lower pH and in the absence of glycolaldehyde initiator in the presence of some minerals (Schwartz and de Graaf 1993a). Certain mineral types, in particular ► borates and silicates, stabilize intermediates in the reaction pathway at high pH and might significantly alter the product mixture under these conditions (Ricardo et al. 2004; Lambert et al. 2010). This may be particularly significant given the wide distribution of silicates in the solar system. Double-layer hydroxide minerals have been shown to be catalysts for aldol condensations under very dilute conditions (Arrhenius et al. 1994).

Mineral effects have generally been studied using high concentrations of HCHO (0.01 M or higher) or other aldehydes; it remains unknown whether minerals affect the reaction of more diluted HCHO (see below).

Competing Chemistry

Cannizzaro Reactions

At high concentrations, HCHO undergoes a disproportionation reaction to form formate and methanol (Eq. 1) (Walker 1964), which reduces the amount of HCHO available to form sugars. These reactions are acid, base, and metal catalyzed (Walker 1964). The reaction reportedly shows third-order kinetics. It is not clear whether it would occur significantly in dilute solution.



Oligomerization to Polyoxymethylene

A series of low-molecular weight polymers, polyoxymethylenes (POMs) (of formula $\text{HO}(\text{CH}_2\text{O})_n\text{H}$) as well as small six- and eight-membered cyclic oligomers, form readily in neutral concentrated aqueous HCHO solutions. This polymerization is highly concentration dependant. A 5 wt% (~1.3 M) aqueous HCHO solution contains only ~14% POM dimer, 3% trimer, and

0.5% tetramer. Polymerization equilibria would be much lower for the prebiotic oceanic concentrations of HCHO which have been estimated.

Sugar Degradation

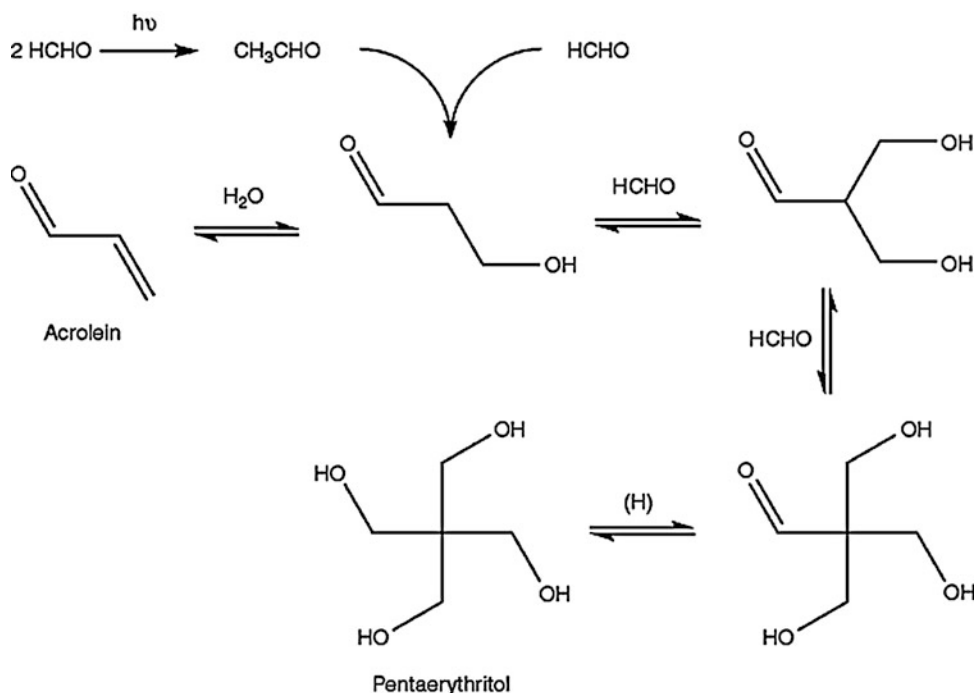
Under the basic reaction conditions which allow the formose reaction to occur, sugar decomposition into tars (Reid and Orgel 1967; Shapiro 1988), furans, and other low molecular weight degradation products (De Bruijn et al. 1986; Cooper et al. 2001) is also facilitated (Larralde et al. 1995). This has been shown to be less significant depending on the presence of high concentrations of inorganic species which may act as stabilizers (Ricardo et al. 2004; Lambert et al. 2010).

Photocatalysis and Reaction with CH_3CHO

The photochemical synthesis of formaldehyde from ultraviolet irradiation of CO_2 and water is quite robust (Pinto et al. 1980). Although its hydrate has a low-UV cross section, HCHO may have been prone to photoreaction in primitive surface waters. Schwartz and De Graaf found that UV irradiation of dilute solutions of formaldehyde-produced acetaldehyde (CH_3CHO) in significant yield, as well as very high yields of pentaerythritol (Fig. 2) (Schwartz and de Graaf 1993a). Other nonsugar products have been observed from photochemical formose reactions by others (Shigemasa et al. 1977).

Significant quantities of acrolein ($\text{CH}_2 = \text{CHCHO}$) have also been detected in spark discharge experiments (van Trump and Miller 1972). The ΔG for the condensation of CH_3CHO and HCHO in the gas phase was estimated at $-4.44 \text{ kcal mol}^{-1}$ and the K_{eq} as 1640 (Malinowski et al. 1963). Thus, the overall reaction is thermodynamically favorable.

Acrolein is an intermediate in the industrial synthesis of pentaerythritol from concentrated HCHO and CH_3CHO in aqueous alkaline solution (Berlow et al. 1958). HCHO reacts with CH_3CHO at much lower concentrations, to give acrolein among other products, than the formose reaction has been observed to occur (Cleaves 2003). The synthesis of acrolein from equimolar HCHO and CH_3CHO was found to be fairly independent of



Formose Reaction, Fig. 2 Scheme for the photochemical synthesis of CH_3CHO , acrolein, and pentaerythritol from UV irradiation of HCHO

pH between pH 7 and 11 and relatively independent of concentration between of 10^{-4} and 1 M. In contrast, glycolaldehyde and glyceraldehyde syntheses were found to be extremely concentration dependent. At 10^{-3} M concentration of equimolar HCHO and CH_3CHO and below, neither glycolaldehyde nor glyceraldehyde was detected. The same is presumably true of the higher sugars.

It has been demonstrated that acrolein is one of the few compounds with which the nucleobases of RNA/DNA will readily react (Nelsestuen 1980). Thus, acrolein could have been an important sink for the nucleobases in the prebiotic environment and a significant hindrance to the start of an RNA World.

Environmental Limitations

The efficiency of the formose reaction in a prebiotic environment is highly dependent on the rate of HCHO production and delivery to the primitive

oceans (Pinto et al. 1980). The reaction has been observed to occur with HCHO as dilute as 0.01 M (Reid and Orgel 1967; Schwartz and De Graaf 1993a), although there are accounts of its reaction as dilute as 10^{-3} M (Gabel and Ponnamperna 1967). These concentrations may have been difficult to achieve in the bulk early oceans. As HCHO became concentrated, side reactions may have established a low steady-state concentration regardless of the production rate. Given the observed photochemical synthesis of pentaerythritol described above, it may be unlikely that bulk oceanic concentrations of HCHO could have been much higher than $\sim 10^{-3}$ M.

If the concentration and reaction of HCHO on the primitive Earth were difficult because of all of the potential competing geochemical sinks, sugars may have been derived from meteoritic input. Polyols such as glycerol and ribitol have been identified in the Murchison meteorite, although the only actual sugar identified was DHA

(Cooper et al. 2001). This can potentially be explained by the instability of sugars over the ~4 billion years since the Murchison parent body formed and the observed organic synthesis presumably occurred. The initial synthesis to form sugars may have occurred relatively rapidly on the parent body, while only those compounds stable enough to survive until the present day are still detectable. The detection of these compounds does however present an interesting paradox for prebiotic chemistry. If the polyols and their precursors were generated by the same aqueous phase chemistry which produced the amino and hydroxy acids, as well as the purines and pyrimidines which have been detected in the Murchison meteorite (Pizzarello 2004), apparently the suggested inhibition of HCHO chemistry by HCN and vice versa (Schlesinger and Miller 1973) is not a genuine problem. The ratio of glycolic acid to glycine in Murchison suggests that NH_3 concentrations were fairly high in the parent body (Peltzer et al. 1984). These quantities also suggest that the reactions which form HMT and glycolonitrile are not limiting to either purine or sugar synthesis and that slow kinetic effects may be more important than the initial rapid equilibrium obtained.

The prebiotic oceanic concentrations of most precursor organic compounds such as HCHO and NH_3 were also likely quite low (Stribling and Miller 1987). It is necessary to consider the geochemical processes which might have concentrated HCHO sufficiently to allow the formose reaction to occur. It is worth considering what happens to dilute solutions of more complex mixtures of HCN, HCHO, and other aldehydes, NH_3 , urea, nitrate, nitrite, sulfides, ferrous iron, salts, etc., as they are evaporated in the presence of UV and visible light over mineral surfaces, or as they are frozen from dilute solution under visible and/or UV irradiation.

Possible Geological Settings for the Formose Reaction

Sugars are easily made by the reaction of HCHO under certain conditions (fairly high concentrations and slightly basic to basic pH). Such

conditions of pH and concentration are likely only attainable in certain geological environments such as in eutectics and in evaporative environments after HCHO is rendered nonvolatile by reaction with other aqueous species, for example, NH_3 , SO_3^- , or H_2S .

Eutectic Freezing

Eutectic freezing can effectively concentrate dilute prebiotic reactants to form purines, pyrimidines, and ► amino acids (Sanchez et al. 1966; Levy et al. 2000; Miyakawa et al. 2002). Whether HCHO can also be concentrated via eutectic freezing to form sugars is unknown, but plausible. One significant advantage of this process is that sugars are generally much more stable at low temperatures (Larralde et al. 1995). The eutectic freezing and thawing of precursor ice-grain organics such as HCHO in carbonaceous chondrites may have allowed for the synthesis of sugars on these bodies (Cooper et al. 2001). The frozen clay model proposed by Lahav and Chang (1976) may warrant careful reconsideration.

Concentration by Evaporation

Evaporative concentration is a plausible geochemical mechanism for concentrating nonvolatile species. The equilibrium constant for the dimerization of HCHO to give glycolaldehyde is not known, but is of considerable interest, since while HCHO is volatile, glycolaldehyde is not and could thus be concentrated by evaporation. A rough calculation using the free energy of the aldol reaction of HCHO given by Weber (2002) suggests the equilibrium constant is 40, but this does not take into account various kinetic factors which may limit the reaction. This simple reaction is worthy of further investigation from the standpoint of prebiotic chemistry, especially given the presence of glycolaldehyde in interstellar space (Hollis et al. 2000).

Hydrothermal Vents

Although some hydrothermal vent environments are characterized by rather alkaline conditions which would be ideal for formose chemistry, most modern vent systems are generally

characterized by low organic concentrations and moderate to very high temperatures and thus may not be optimal sites for formose chemistry. In addition to the thermal instability of sugars, HCHO does not appear to be a stable one-carbon species under hydrothermal conditions (Osada et al. 2004; Seewald et al. 2006).

Given the uncertainties regarding primitive Earth conditions, the existence of specialized conditions which would allow the formose reaction to occur cannot be ruled out. The synthesis of sugars in such environments from low initial HCHO concentrations under mild conditions might be extremely facile and warrants further investigation, as does formose synthesis in the presence of congeners such as HCN, NH₃, and inorganic compounds such as borate, sulfide, and sulfite, and the impact of UV and visible radiation on this chemistry.

As mentioned above, the perceived importance of the formose reaction rests mainly on its role in sugar synthesis, which is important in the context of abiotic nucleic acid synthesis. Sugar synthesis, of course, is merely one step on the way to nucleoside, nucleotide, and nucleic acid synthesis, which also may require certain specialized environmental conditions (Fuller et al. 1972), although there are proposed mechanisms for nucleotide formation which do not necessarily depend on direct condensation of the nucleic acid base with a sugar (Powner et al. 2009).

Future Directions

The possible prebiotic importance of formose chemistry has launched a great deal of experimental study of its kinetics, products and robustness in geochemical settings. It is likely there remains a good deal of chemical complexity to yet be revealed in this fascinating reaction.

Cross-References

- Carbohydrate
- Formaldehyde
- Ribose
- RNA World

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Formyl Cation (HCO^+)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

HCO^+

Definition

The triatomic ion HCO^+ is one of the most abundant molecular ions in dense interstellar clouds. It is a key intermediary in the production of ► **carbon monoxide**, CO , which is in turn the most abundant constituent of these regions after molecular hydrogen (H_2). The abundance ratio of HCO^+ to its deuterated counterpart, DCO^+ , can provide a measure of the electron density in molecular clouds. HCO^+ is a linear, closed-shell molecule, so that its pure rotational spectrum consists of a series of harmonically related lines, with the lowest transition in the 3 mm wavelength band.

History

In 1970, L. Snyder and D. Buhl reported the detection of an unidentified emission line in the spectra of several interstellar ► **molecular clouds** and referred to the unknown carrier as “X-ogen.”

Laboratory measurements subsequently confirmed that X-ogen was HCO^+ , in agreement with the theoretical predictions of ion-molecule chemistry by W. Klemperer and E. Herbst that this ion should be abundant in such clouds.

Cross-References

- Carbon Monoxide
- Deuterium
- Molecular Cloud
- Molecules in Space

References and Further Reading

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Förster Resonance Energy Transfer

- FRET

Fortescue Group

Martin J. Van Kranendonk
School of Biological, Earth and Environmental
Sciences, University of New South Wales,
Sydney, NSW, Australia

Definition

The 2.77–2.63 Ga Fortescue Group is a well-preserved, thick (0.5–6 km) succession of continental flood ► **basalts** and interbedded sedimentary rocks deposited unconformably on basement granite-greenstone crust of the ► **Pilbara Craton**, Western Australia. Together with the contemporaneous Ventersdorp basalts in South Africa, the volcanic rocks are the oldest

known continental flood basalts (trapps). The 2.63–2.45 Ga Hamersley Group, containing thick deposits of ► **banded iron formation**, conformably overlies the group. Sedimentary rocks of the Fortescue Group contain several horizons of stromatolitic carbonates, deposited in freshwater lacustrine environments. Controversial filaments showing septa have also been observed and related to septate microbial microfossils.

Cross-References

- Archaean Traces of Life
- Banded Iron Formation
- Basalt
- Pilbara Craton
- Stromatolites
- Trapps

Fossa, Fossae

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

Fossae are long, narrow depressions, often occurring in arrays (definition by the International Astronomical Union; <http://planetarynames.wr.usgs.gov/jsp/append5.jsp>). This is a descriptor term for naming surface features on the ► **terrestrial planets**, the Moon, and on icy satellites.

Cross-References

- Moon, The
- Satellite or Moon
- Terrestrial Planet

Fossil

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

A fossil is the preserved remnant of an organism after its death. A fossil may be morphological or chemical. A fossil can have various sizes (microscopic to macroscopic) and composition (organic or mineral) and may represent a whole organism, part of an organism, colonial organisms, or the morphological or chemical imprint of an organism or of its activity. The processes of fossilization are complex, and they may lead to the preservation of organisms in their original composition or partially or be completely replaced by another (organic or mineral) material or preserved as a mold or cast or as traces of activity such as footprints, trails, or burrows (“ichnofossil”).

Cross-References

- [Biomarkers, Morphological](#)
- [Biomineralization](#)
- [Dubiofossil](#)
- [Fossilization, Process of](#)
- [Microfossils](#)
- [Molecular Fossils](#)
- [Pseudofossil](#)

Fossilization Processes

- [Biosignatures, Effect of Metamorphism](#)

Fossilization, Process of

Karim Benzerara
Institut de Minéralogie et de Physique des Milieux
Condensés, UMR 7590, CNRS, Sorbonne
Université & Muséum National d’Histoire
Naturelle, Paris, France

Keywords

Biomineralization · Diagenesis · Taphonomy

Definition

Fossilization refers to the processes leading to the preservation of traces of life in the geological record. While metazoans and single-cell eukaryotes leave undisputed traces in the geological record in the form of hard mineral parts, the fossilization of microorganisms such as *Bacteria* or *Archaea* or of viruses has long been debated due in particular to the difficulty to recognize unambiguously such fossils in old rocks. ► [Biomineralization](#) controlled or induced by microorganisms themselves seems to be a major process allowing preservation of cell structures and/or of organic molecules.

Overview

The three domains of life can, in principle, be preserved as ► [microfossils](#), depending on the conditions of preservation and their original composition. Most fossils in the Phanerozoic are made of hard mineral parts or imprints of hard mineral parts of metazoans or eukaryote unicellular organisms (e.g., diatoms, foraminifers). Some prokaryotes can also form biominerals that might be preferentially preserved in the geological record (Benzerara et al. 2019). However, we focus here on processes of fossilization of soft tissues and mostly of microorganisms that are more relevant to astrobiology than macroorganisms.

Interestingly, it has been widely suggested that microorganisms were often involved in the fossilization of metazoan soft tissues (e.g., Raff et al. 2006; Iniesto et al. 2015).

There are undisputed fossils of prokaryotes in the geological record, and some have been assigned taxonomic names such as *Girvanella* (Riding 2002). The abundance of these microfossils has varied through geological time. The absence of microfossils has sometimes been interpreted as evidence for abiotic conditions prevailing during the formation of a rock. For example, the absence of microfossils in Archean stromatolites has been used to question their biogenicity (e.g., Grotzinger and Rothman 1996; Brasier et al. 2006). Alternatively, the varying abundance of microfossils has been related to variations of environmental conditions triggering or hindering fossilization (e.g., Arp et al. 2001). It is thus important to understand processes of fossilization in order to identify the main factors controlling the formation of microfossils and better read the paleontological record.

When a microorganism dies, organic molecules and cellular structures can be degraded very rapidly. It is usually thought that enzymes released by dying cells and/or other cells catalyze this process (lysis) and that this results in a rapid cycling of organic matter. However, in some cases, the development of microbial biofilms somehow retards the degradation of organic tissues and may therefore allow more time for mineral precipitation to occur, favoring subsequent fossilization (Iniesto et al. 2016). The molecular mechanisms and determinants of such a microbially mediated protection remain to be understood. Moreover, some organic molecules might be selectively preserved because they are more resistant to this chemical degradation such as polymers forming the cell wall of spores (e.g., sporopollenin, Bernard et al. 2015) or molecules transformed secondarily by chemical reactions such as sulfurization of organic carbon (e.g., Lepot et al. 2009a; Damste et al. 1998) or formation of geopolymers (Vandenbroucke and Largeau 2007). Precipitation of minerals on cells, that is, biomineralization, is another major process that favors fossilization of prokaryotes by armoring

cellular structures against the lytic action of enzymes (Li et al. 2013). A broad diversity of mineral phases can fossilize microbial ultrastructures exquisitely, including phosphates (Cosmidis et al. 2015), carbonates (e.g., Couradeau et al. 2013), or silicates (Zeyen et al. 2015). Several mechanisms can favor mineral precipitation within and/or at the surface of cells and usually involve specific metabolic activities and environmental conditions. For example, it has been proposed that anoxic conditions are necessary for fossilization. The absence of O₂ might indeed limit aerobic respiration, hence degradation or organic matter but is not a sufficient parameter (Allison 1988). In addition to this, anoxic environments are usually rich in metals (e.g., Fe, Mn) and/or sulfides that can precipitate on cells.

Experimental taphonomy refers to fossilization experiments conducted in the laboratory or in the field. Although these studies may not all reflect the full complexity of natural environmental conditions, they may reveal biotic patterns and fossilizable properties that have been overlooked and eventually allow a better understanding of the molecular mechanisms operating during fossilization. First, such studies have shown that fossilization of microorganisms can be achieved in few days or few weeks. For example, exposing bacterial cells to a solution rich in Ca, Fe, or Si can lead to their encrustation in few hours (Toporski et al. 2002; Benzerara et al. 2004a; Ferris and Magalhaes 2008; Miot et al. 2009). Moreover, these experiments help decipher what can be preserved in microfossils, regarding their chemistry as well as their ultrastructure. Cyanobacteria have received particular attention. Intra- and extracellular silicification has been observed. It has been shown that sheaths are preferentially preserved as compared to walls and cytoplasm (e.g., Bartley 1996). Some transformations could be observed including cell collapse, shrinkage and disappearance, trichome disarticulation, varying terminal cell morphology, and rupture of sheath (e.g., Toporski et al. 2002). If precipitation occurs in close connection with the microbial structures and if the minerals are small enough, very fine cellular details can be preserved. For example, a 40-nm-thick cell wall of Gram-negative bacteria can be

fossilized by calcium phosphates (e.g., Benzerara et al. 2004a) or by iron minerals (e.g., Miot et al. 2009). Such a preservation of the 40-nm-thick cell wall of Gram-negative bacteria has also been evidenced recently in phosphorite samples from Morocco dating from the Paleocene (Cosmidis et al. 2013). Embryos of eukaryotes could be preserved as well in the laboratory at different development stages by phosphatization, simulating what likely occurred during the fossilization of the famous ~630 Ma old Doushantuo embryos (e.g., Yin et al. 2007). While some organic carbon might be degraded during these processes, it has been shown that most of it can be preserved within resulting mineralized microfossils (e.g., Benzerara et al. 2004b). The diversity of organic moieties that can be preserved in fossils still seems poorly assessed. Biomarkers, that is, highly resistant organic molecules comprising cell walls, are obvious examples (e.g., Derenne et al. 2008). Some organic geochemistry studies have however shown that additional molecules such as proteins could be preserved more than a 100 million years (Riboulleau et al. 2002). Although they remain difficult to recognize in the geological record, viruses, which have been major players in life evolution (e.g., Forterre 2006), seem to be prone to fossilization under some conditions through permineralization (Perri et al. 2018; De Wit et al. 2015). Interestingly, some taphonomy experiments have been performed on these “organisms.” Biomineralization experiments on viruses show that dissolved iron can penetrate virus capsids and bind to internal sites (Daughney et al. 2004). As a result, virus capsids can serve as nuclei for the growth of iron oxide particles. The resulting morphology differs from abiotic iron oxides and organic molecules, which originally composed the capsids, can be efficiently preserved by the iron minerals that armor them, increasing the possibility of accurately identifying them (e.g., Kaiser and Guggenberger 2000).

After the precipitation of minerals on organic structures, further degradation of morphology and organic molecules can take place. This stage is influenced by mechanical stresses, interactions with fluids of varying chemistries, and metamorphism, for example, an increase in temperature

and pressure. Formation of carbonate nodules has been inferred as an efficient mechanism for fossil preservation (e.g., Muller 1985). Observations of natural samples have shown that fossils can sometimes be preserved even after high-grade metamorphism (e.g., Bernard et al. 2007; Galvez et al. 2012), suggesting that T and P might not be prominent factors in the disruption of microfossils. In contrast, mineral growth/transformation has been shown to be highly damaging (e.g., Oehler 1976). Metamorphic processes take place over much longer timescales, so it is more difficult to simulate them in the laboratory. Some studies have suggested that time and temperature are inherently linked and that aging at low temperature over long timescales can be simulated by shorter aging at a higher temperature (Skrzypczak-Bonduelle et al. 2008). This principle has inspired additional studies aiming at simulating natural fossilization processes in the laboratory (e.g., Picard et al. 2016; Alleon et al. 2017; Cousins et al. 2020). However, while Li et al. (2014) clearly showed with such laboratory experiments, that microbial cell encrustation by minerals may favor preservation of chemical and morphological features upon heating, they also stress on the difficulties to relate experimental conditions directly to geological conditions.

Last, one key problem encountered in the study of microfossils is that relatively complex morphologies can be produced by purely abiotic processes (e.g., Garcia-Ruiz et al. 2003) and can thus make their identification difficult. Laboratory experiments can be of value to identify possible specific features that might be used to discriminate abiotic from biological objects. In addition to morphology, the composition of the organic matter produced by reactions such Fischer-Tropsch has been carefully scrutinized and compared with mature kerogens (e.g., McCollom and Seewald 2007). For example, a combination of infrared spectroscopy (providing an aliphaticity index of the organic matter) and microscale measurements of the carbon isotopic compositions was used by Sangely et al. (2007) to distinguish between biology and Fischer-Tropsch-type reactions as genetic processes for the bitumen found in the Cretaceous uranium deposits of Athabasca. Known abiotic

products that can mimic life morphologies or chemistries include vesicles made in the laboratory from meteoritic kerogen or in other prebiotic chemistry experiments (e.g., Deamer et al. 2006), fluid inclusions, carbonaceous filamentous shapes resulting from migrating organic matter (with carbon isotopic fractionation resembling life patterns) around minerals casts in hydrothermal environments (Brasier 2005; Brasier et al. 2006), aggregates of silica spheres and rods in silica-rich waters of hydrothermal springs, migration of carbonaceous materials along microfractures (Van Zuilen et al. 2007), within or around silica (e.g., Jones and Renaut 2007; Lepot et al. 2009b). Finally, mineralized pseudo-fossils have been produced using a mixture of barium carbonate and silica in laboratory experiments (Garcia-Ruiz et al. 2003) or by reacting sulfides with dissolved organics (Cosmidis and Templeton 2016). In both cases, the resulting auto-assembling, sometimes segmented, filaments contain organic matter and are very comparable morphologically with some geological occurrences.

Basic Methodology

Characterization of field samples using analytical tools at multiscale, including scanning electron microscopy, transmission electron microscopy, Raman spectromicroscopy, confocal laser scanning microscopy, NanoSIMS. Laboratory experiments simulating fossilization, biomineralization, diagenesis, and metamorphism.

Key Research Findings

Fossilization is a very fast process. Fossilization can preserve very fine details and chemical heterogeneities down to the nanometer-scale.

Applications

Search for ancient traces of life on Earth and elsewhere.

Future Directions

Several directions remain widely open: first, an improved characterization of microfossils in ancient rocks which will allow in particular discriminating between genuine microfossils and microfossil-like abiotic features. Most of the oldest traces of life are indeed still debated. The advance of cutting-edge technologies, such as Raman spectromicroscopy (Bernard et al. 2008; Schopf and Kudryavtsev 2009), transmission electron microscopy (e.g., Lepot et al. 2008), focused ion beam milling (Wirth 2009; Wacey et al. 2012), synchrotron-based X-ray microscopy (e.g., Lepot et al. 2009a; Obst et al. 2009), and NanoSIMS (e.g., Oehler et al. 2009), provides analyses of mineral and organic matter down to the nanoscale; this should help in achieving that goal. Second, experimental taphonomy can be developed further, inspired by studies of metazoans (e.g., Briggs and Kear 1993). A wide diversity of biomineralizing microbial systems is now available and can provide pre-fossils. Their extensive characterization down to the nanoscale will offer new insight into what can be potentially preserved in the geological record. In addition, a significant improvement in the design of protocols to simulate diagenesis (in particular, the use of fluids with an appropriate chemical composition), aging, and possibly metamorphism would complement this approach. An ultimate and exciting challenge for this field may take place in several years: assessing the presence of potential fossils of microorganisms in rocks recovered at the surface of Mars and brought back to Earth by the Mars sample return mission.

Cross-References

- [Biomarkers, Morphological](#)
- [Biomineralization](#)
- [Bioprecipitation](#)
- [Microfossils](#)

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Fossilized Microbial Mats

► [Stromatolites](#)

Fossils (from Antiquity to the Eighteenth Century)

Otto Hermelin

Department of Geological Sciences, Stockholm University, Stockholm, Sweden

Keywords

History of geology · Paleontology ·
Petrifaction · Stratigraphy

Synonyms

[Petrifaction](#)

Definition

Fossils, Preserved remains, Impressions, Trace of once-living organism.

History

Herodotus (484–424 BC) studied, among other things, how the Nile slammed again, and obviously he understood the concept of time – something that is very central in geology. More speculative claims, however, were the interpretation of the tertiary nummulites (foraminiferal shells) that he found in the limestone from which the pyramids of Giza were built. He interpreted those who petrified the remains of the lentils that were part of the pyramid builders' meals.

Aristotle (384–322 BC) and his philosophy came to make their mark on geological research throughout the Middle Ages until a time shortly after the Renaissance. He observed fossil fish but did not understand the origin but believed that the

fish migrated along underground streams and became petrified.

In 1027, the Persian physician, astronomer, thinker, and writer Avicenna (c. 980–1037) explained fossils' stoniness in *The Book of Healing*: “If what is said concerning the petrification of animals and plants is true, the cause of this (phenomenon) is a powerful mineralizing and petrifying virtue which arises in certain stony spots, or emanates suddenly from the earth during earthquake and subsidies, and petrifies whatever comes into contact with it. As a matter of fact, the petrification of the bodies of plants and animals is not more extraordinary than the transformation of waters.”

In Europe, however, there was a standstill in the field of geology. Albertus Magno (1205–1280) considered, e.g., that mountain ranges formed when water boiled and the water bubbles petrified. Fossil was explained as “*vis plastica*,” i.e., incomplete attempts to create life from inorganic material.

It was only in connection with the Renaissance that direct observations and experiments came into the picture. Leonardo da Vinci (1452–1519) explained the fossilization and conservation of mussels from northern Italy, which for the most part would still stand today. He also understood that the water surface had a different location than in modern times. However, he did not believe in mountain range folds but considered that the mountains were formed solely by erosion. However, it would take a long time before such theories would be recognized. Fossils were still produced as “*vis plastica*” or simply as “*lusu naturae*” – the waste of nature.

During the seventeenth and eighteenth centuries, it became difficult to maintain Aristotle's teaching about the origin of the stones. However, an attempt was still made to find an explanation in accordance with the Old Testament. It was generally thought that the fossils originated from the biblical flood. The Swiss scholar Johan Jakob Scheuchzer (1672–1733) considered fossils as “*tricks of nature*” or just as leftovers from the flood. He depicted a giant fossil salamander which was found in a quarry as “*Homo diluvii testis*,” i.e., one of those abominable people

whose sins brought the calamity of The Flood upon the earth. Ideas like this were accepted for a long time since it seemed to verify the claims of Christian scripture.

The Danish scientist Nicolaus Steno (1638–1686) although questioned the common “knowledge” at the time, that fossils must have grown in the ground, this since the Bible stated God had created the solid Earth during the first week. He realized that fossils were the remains of once living organisms that had been deposited over time. This contribution to geology has led subsequent scholars to rank him as one of the founders of stratigraphy.

Voltaire tried to explain the fossil animal remains that came to light as remains after picnic meals. However, it was not until the Würzburg professor Johann Bartholomeus Adam Beringer (1667–1740) that the “*vis plastica*” doctrine suffered shipwreck. For many years, Beringer collected a fossil material that became increasingly rare and more sensational; animals, plants, spider webs, planets, comets, and God’s own name in Hebrew, all this was published in a scientific publication *Lithographiae Wirceburgensis* (1726). When he finally saw his own name on one of the stones, he realized that he was affected by the students’ sense of humor. He spent the rest of his life trying to buy back the books he had published, here by the concept of Beringer’s lying stones (*Lügensteine*).

The Englishman William Smith (1769–1839) was an engineer and actually engaged in canal construction, but during his work he discovered that fossils could be used to identify sedimentary layers in different areas. He saw that the fossil-bearing layers formed on the seabed and represented the animal world that lived white for the time being. In 1799, he established a table for the stratigraphy (carbon-chalk) stratigraphy of the sedimentary sequences and the most important fossils in each layer. This was something completely new and Smith’s principle is the basis of modern stratigraphy. Gradually, during this time that followed, one systematically examined sediments and fossils from most places on earth.

Detailed descriptions of fossils already appeared in the late eighteenth century, but it was not really until the nineteenth century that modern paleontology developed. The pioneer in this area was Georges Cuvier (1769–1832), a contemporary of William Smith. He was a comparative anatomist and treated the material as if it were a “living” zoological material and not just as petrifying fossils. Among other things, he studied tertiary vertebrates from the Paris Basin. He explained that successive layers could contain such different fossils that each period in the Earth’s history ended with a catastrophe – this was the basis of the catastrophe theory.

Cuvier found support for his disaster theory in the presence of large moving blocks that were thought to have been moved by large rivers (here the idea of The Flood comes back). He did not believe in evolution, but in innovation after every disaster. He argued that the species had not changed since the Creation. The argument was that each species was so well coordinated, functionally and structurally, that it could not survive significant change. In the last great “catastrophe,” which was paralleled with the flood, one could include everything that is today attributed to the last ice age. It was not Cuvier himself who drew the parallels with the Bible.

Overview

The findings of fossils, remains of earlier life, have through history resulted in a wide variety of explanations: everything from meal leftovers, “nature’s waste,” remains from The Flood of the Bible, to more sensible explanations.

Cross-References

- ▶ [Cuvier’s Conception of Origins of Life](#)
- ▶ [Fossil](#)
- ▶ [Fossilization, Process of](#)
- ▶ [Life, Concept of \(from Antiquity to the Eighteenth Century\)](#)

Further Reading

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Foton Capsule, Spacecraft

René Demets

ESTEC (HSF-USL), Noordwijk, The Netherlands

Definition

Foton is an unmanned recoverable spacecraft, designed and manufactured by TsSKB-Progress in Samara (Russia). Fifteen Fotons were launched between 1985 and 2007, initially from Plesetsk, later from Baikonur. The launch vehicle is a Soyuz-U. The reentry capsule is spherically shaped with a diameter of 2.3 m. Touchdown in the border zone of Russia and Kazakhstan. Payload consisting of scientific and technological experiments with often significant contributions from Western Europe. Power provided by batteries, flight duration therefore limited to 10–16 days. Orbital parameters: inclination 63°, period 90 min, orbital shape: near-circular, cruising altitude around 300 km. Foton has frequently been used for space exposure studies in astrobiology and astrochemistry (► [Biopan](#)) as well as reentry experiments (► [Stone](#)). Spacecrafts Modified Foton have been launched since the failure of Foton M1 in 2002 at launch. Since Foton M4, which was successfully launched and retrieved in 2014, the spacecraft is equipped with solar panels replacing former batteries.

Cross-References

- [Biopan](#)
- [Stone](#)

Fractional Abundances

- [Abundances](#)

Fractionation

Jennifer C. Stern

Planetary Environments Laboratory, NASA

Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Differentiation](#); [Disproportionation](#); [Partitioning](#); [Separation](#)

Definition

Fractionation is the partitioning of a chemical species into two or more phases based on its chemical or physical properties. The chemical or isotopic composition of each phase may reflect an enrichment or depletion in one element or isotope with respect to the others, which can yield information about the mechanism of formation. Fractionation can be caused by differences in mass and binding energy and by biochemical reactions, which alter the ratio of one element or isotope to another. For example, fractionation of stable carbon isotopes can provide information on the biotic or abiotic origin of some organic compounds, as photosynthetic reactions process the lighter isotope, ^{12}C , more rapidly than ^{13}C , resulting in enrichment in ^{12}C of its products.

Cross-References

- [Deuterium/Hydrogen Ratio](#)
- [Differentiation, Planetary](#)
- [Distillation, Rayleigh](#)
- [Fractionation, Mass Independent and Dependent](#)

- [Isotope](#)
- [Isotopic Exchange Reaction](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Nitrogen Isotopes](#)

Fractionation, Mass Independent and Dependent

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Keywords

Isotope · Mass fractionation

Definition

Isotope fractionation is referred to as mass dependent when observed isotopic abundances deviate smoothly and monotonically with the masses of the isotopes from those in the reference material. Both kinetic and equilibrium processes are known to account for this most common form of isotope fractionation. Alternate patterns are referred to as mass independent and are known for O and S in some specific environments and are often related to photochemistry in the solar nebula and in planetary atmospheres.

Overview

Isotope fractionation varies approximately with the difference of the isotopic masses. Using ► [oxygen isotopes](#) as an example, the mass difference $^{18}\text{O} - ^{16}\text{O}$ is +2 and $\delta^{18}\text{O}$ will therefore be twice the $\delta^{17}\text{O}$ (where, e. g., $\delta^{18}\text{O}$ is $[(^{18}\text{O}/^{16}\text{O})_{\text{sample}} / (^{18}\text{O}/^{16}\text{O})_{\text{std.}} - 1]$).

In a $\delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ diagram, all terrestrial samples plot on the same fractionation line with a slope of 0.5. Different planets plot on parallel

fractionation lines, except the Earth and the Moon, which plot on the same line, a strong argument in favor of a common origin for the two planetary objects (the Moon giant impact). Small variations of the slope reflect different conditions of fractionation, notably kinetic and distillation effects. Solar oxygen measured in the solar wind implanted in lunar metallic particles or in the particles collected by the Genesis spacecraft contains a mass-independent ^{16}O excess of 5%.

Mass-independent isotope fractionation (MIF) in the solar system is observed for some elements, and the most noticeable effects occur for O and S. The deviation from the mass-dependent isotope fractionation regime is noted $\Delta^{17}\text{O}$ for oxygen and $\Delta^{33}\text{S}$ for sulfur. The $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ of calcium-aluminum-rich refractory inclusions (► [CAIs](#)) and chondrules in chondrites tend to plot on a line with a slope of 1.0, instead of the normal slope of 0.5 expected from mass-dependent fractionation. Likewise, the oxygen of some trace atmospheric compounds, notably ozone, nitrate, and sulfate, also plot on a line with a slope of 1. Pre-2.3 Ga sulfur also shows MIF of $\delta^{33}\text{S}$ with respect to $\delta^{34}\text{S}$.

Causes for solar system MIF are not agreed upon, at least not for all the elements. Self-shielding calls for isotope-dependent shifts of absorption wavelengths in the UV range: Dissociation in the gas phase is proportional to the abundance of a particular isotope and not to its mass. Self-shielding upon dissociation of a CO-rich gas was well into the 2010s a popular interpretation of mass-independent oxygen isotope anomalies in the solar nebula. The correlation found between $\Delta^{17}\text{O}$ and excess of neutron rich isotopes ^{54}Cr and ^{50}Ti demonstrated that the deviation of oxygen isotopes from the mass-dependent fractionation regime in the solar nebula can only be explained by nucleosynthetic anomalies. In other words, the different parts of the solar system involve at least three unrelated molecular cloud progenitors: the Sun, which is endowed with a huge ^{16}O excess of about 5%, the inner solar system from Mercury to Mars, and the outer

solar system beyond the asteroid belt. The correlation between $\Delta^{17}\text{O}$ and ^{54}Cr excesses, by showing the heterogeneous nature of the solar nebula, made the classic Laplace theory of the origin of the solar system fall out of favor.

Ozone present in the modern stratosphere blocks solar UV radiation. Prior to the “► [Great Oxygenation Event](#)” at 2.3 Ga, the abundance of O_2 in the atmosphere was low and the ozone layer absent: Photolysis of the tropospheric SO_2 released by volcanic activity by solar UV is thought to have been the cause of the MIF recorded in the $\Delta^{33}\text{S}$ of Archean sulfates and sulfides.

Finally, the finite volume of heavy nuclei and spin-orbit coupling may be additional minor causes of deviation of isotope fractionation patterns from the purely mass-dependent trends.

Cross-References

- [Isotopic Fractionation \(Planetary Process\)](#)
- [Oxygen Isotopes](#)
- [Sulfur Isotopes](#)

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Fragmentation of Interstellar Clouds

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Star formation

Definition

The dense cores that form stars through gravitational collapse are embedded in much larger and more rarefied expanses of gas. How the parent ► [molecular cloud](#) produces its substructure of dense cores is the problem of fragmentation. The traditional view is that the parent cloud breaks apart as it collapses in on itself. In numerical simulations, objects resembling dense cores are created in turbulent, collapsing clouds. However, there is little evidence that large clouds are indeed collapsing. If they are not, but are at least temporarily stable, then dense cores must be produced in another fashion, perhaps by the slow accretion of background gas.

Overview

The interstellar clouds that contain young stars are relatively small structures embedded within more diffuse background gas. These dense cores have sizes of about 0.1 pc and masses comparable to that of the Sun. The diffuse parent bodies, known as dark clouds or clumps, have sizes larger by two orders of magnitude and masses of at least 1000 times solar.

It is the gravitational collapse of dense cores that creates the new stars we observe in them. But how are dense cores themselves created? The general, and as yet unsolved, issue of how these substructures arise within relatively large molecular clouds is the problem of fragmentation.

A starting point for many theories is the observed fact that the parent cloud has far too much mass, and is far too cold, to be supported by internal pressure. In the absence of other forces, the object must collapse on itself. The traditional view of fragmentation is that this collapse generates substructure. As the cloud contracts, it breaks apart, producing several daughter clouds. Each daughter, in turn, collapses and breaks up. After a number of generations, fragments with stellar-type mass are produced – the observed dense cores.

Within the last few decades, many theorists have performed numerical simulations of collapsing clouds. The fragmentation hierarchy is not seen. However, if the parent cloud is also turbulent, it may directly create substructures resembling dense cores. Intriguingly, the simulated objects even exhibit the range of three-dimensional shapes of real cores.

Unfortunately, there is little evidence that the larger bodies are undergoing collapse. Observations indicate that the typical age of dark clouds and clumps is 10 million years, an order of magnitude longer than the time for them to collapse. It thus appears that these entities are indeed supported, probably by their internal magnetic fields and turbulent motion.

If the parent bodies are not collapsing, then dense cores must arise in another way. Rather than breaking off from the parent (the top-down view), they may accrete gas from their surroundings (the bottom-up view). The mass of the ► [dense core](#) increases until the object becomes unstable and undergoes collapse. This picture is in better accord with the observation that dense cores themselves appear to be in force balance, at least before they form stars.

Cross-References

- [Dense Core](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Star Formation, Observations](#)
- [Star Formation, Theory](#)
- [Stellar Cluster](#)

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Free Amino Acid

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In chemistry, a free amino acid is an amino acid which is not covalently bound in a peptide or in another sort of linkage, for example, in a melanoidin polymer, an ► [HCN polymer](#), or chelated to an inorganic ion.

Cross-References

- [Amino Acid](#)
- [Amino Acid Precursors](#)
- [HCN Polymer](#)
- [Oligopeptide](#)
- [Protein](#)

Free Energy

Jacques Reisse

Université Libre de Bruxelles, Brussels, Belgium

Definition

Free energy refers to the amount of energy in a system that can be converted to work when the reaction takes place at constant pressure. This amount of energy is necessarily less than the available enthalpy. For chemical reactions taking place at constant pressure (which is frequently the case), free energy refers to the Gibbs free energy. The thermodynamic definition of the Gibbs energy (G) leads to the familiar relation $G = H - TS$, where H stands for enthalpy, T for temperature, and S for entropy.

Cross-References

- ▶ [Bioenergetics](#)

Free Radical

- ▶ [Radical](#)

Free Water

- ▶ [Water Activity](#)

Freefall

- ▶ [Microgravity](#)

Free-Fall Time

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

The time required for an astronomical object to collapse under the influence of self-gravity is called the free-fall time. A hypothetical gas sphere of uniform density and zero temperature collapses to a point at its center in a finite time. This time is inversely proportional to the square root of the initial density. The free-fall time of real objects can still be approximated from the idealized result. For stars, this time is roughly 1 h. Such objects are normally supported by internal pressure and do not collapse. In this case, the free-fall time is approximately equal to the sound-crossing time and to the period of global oscillations.

Cross-References

- ▶ [Gravitational Collapse, Stellar](#)
- ▶ [Fragmentation of Interstellar Clouds](#)
- ▶ [Protostars](#)

Free-Free Emission

- ▶ [Bremsstrahlung Radiation](#)

French Astrobiology Society

- ▶ [SFE, France](#)

French Space Agency

- ▶ [CNES, France](#)

Freon-40

- ▶ [Chloromethane \(CH₃Cl\)](#)

FRET

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Fluorescence resonance energy transfer](#); [Förster resonance energy transfer](#)

Definition

FRET is a technique used to measure the proximity of chemical groups in macromolecules or

between host and guest molecules. It involves the use of a donor (in an excited electronic state) and an acceptor ► [chromophore](#). When they are in close proximity (usually <10 nm), the donor may transfer its energy to the acceptor through nonradiative dipole-dipole coupling. This is known as “Förster resonance energy transfer.” When both chromophores are fluorescent, the term “► [fluorescence](#) resonance energy transfer” is used instead, although the energy is not actually transferred by fluorescence but by nonradiative transfer.

Cross-References

- [Chromophore](#)
- [Fluorescence](#)

FRIPON

Michel Viso
Innovaxiom, Paris, CX, France

Acronyms

Fireball Recovery and Interplanetary Observation Network

Definition

FRIPON is an international ground-based network of dedicated video cameras observing the sky to record tracks of light left by fireballs. The data are gathered in a laboratory in Marseille and then processed to infer the trajectory of the falling object and to determine the possible landing area. The network is designed to initiate field searches in less than 24 hours of ► [Meteorites](#) or other fallen objects. The consortium, beginning as of 2022, gathers 105 video cameras and the contribution of 25 military radars of the GRAVES network (Grand Réseau Adapté à la VÉille Spatiale) spread over 15 countries. Most of the cameras are

in Europe and a vast majority in France. The distribution of cameras on French territory constitutes a network with a mesh of 50–60 km.

History

The project was initiated in 2013 at the initiative of a team of French researchers and supported by a grant from the Agence Nationale pour la Recherche (ANR). This first grant was used to design and standardize the hardware, to set up the network and data processing in France. In 2016, neighbouring countries joined the project which is operational and seeks expansion.

Cross-References

- [Meteorites](#)

Reference and Further Reading

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Frost Line

- [Snow Line](#)

FU Orionis (Object)

Lee Hartmann
University of Michigan, Ann Arbor, MI, USA

Acronyms

FUor FU Orionis (Object)
AU astronomical unit, Earth-Sun distance

Synonyms

[FUor](#)

Definition

FU Orionis objects are very young stars that become extremely bright as a result of sudden accretion of large amounts of gas and dust from a circumstellar disk (Herbig 1977; Hartmann and Kenyon 1996; Hartmann et al. 2016). The main members of this class brighten by factors of 100 or more over timescales of months to years and can take decades to a century or more to fade. During the accretion outburst, the disk itself becomes so luminous that it outshines the central star, and so the visual (and near-infrared) spectrum is dominated by disk emission.

Pre-outburst, the FU Orionis systems are thought to consist of young (ages <one million years), 0.7–0.2 solar mass stars surrounded by a circumstellar disk like those thought to be the sites of planet formation. During the accretion outbursts, as much as 0.01 solar masses (10 Jupiter masses) can be transferred onto the central star. The disk becomes very hot, with maximum surface temperatures ~6000 K at small radii; models indicate that the internal temperatures at the inner edge of the disk are very much higher, 50,000 K or more, due to radiative trapping of the intense release of accretion energy.

The radial extent of the rapidly accreting region is not very well-determined, but it probably extends out to 0.3 AU or so (Zhu et al. 2008), roughly corresponding to the region where the internal temperatures during outburst are thought to reach ~1000 K. These temperatures are high enough to provide the melting of calcium-aluminum-rich inclusions (CAIs) seen in the most primitive chondritic meteorites, and models of marginally gravitationally unstable disks suggest that such particles could be transported outward as far as 10 au (Boss et al. 2012, 2020).

What produces the outbursts is not clear. The large amounts of mass accreted suggest that gravitational instabilities in the disk are responsible, perhaps either by accreting self-gravitating blobs (Vorobyov and Basu 2005) or by heating which triggers magnetic turbulence (Armitage et al. 2001; Zhu et al. 2010; Bae et al. 2013). Continuing infall from remnant protostellar clouds may help keep the disks massive. It seems increasingly

likely that more than one mechanism can be responsible for outbursts, as advances in monitoring broad areas of the sky have turned up many new variables that exhibit considerably smaller accretion events (e.g., Hillenbrand et al. 2018).

Event statistics are uncertain; the FUors, especially the ones with the biggest outbursts, are rare, because the low-mass stars can't spend a lot of time accreting at 10^{-5} – 10^{-4} solar masses per year. Nevertheless, current estimates suggest that at least some stars must undergo perhaps 10 bursts or more (Herbig 1977; Hartmann and Kenyon 1996), with a higher frequency for the more numerous small events. Statistics should improve with increased all-sky monitoring projects, which should help understand the role of accretion outbursts in star formation and thermal processing in protoplanetary disks.

Cross-References

- [Accretion](#)
- [Accretion, Stellar](#)
- [Protoplanetary Disk](#)
- [Protoplanetary Disk Instability](#)

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Fullerane

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

[Hydrogenated fullerene](#)

Definition

Fulleranes are hydrogenated derivatives of fullerenes. It has been speculated that they may be present in the interstellar medium and in the envelopes of certain types of stars.

Cross-References

► [Fullerene](#)

Fullerene

Franco Cataldo^{1,2} and Susana Iglesias-Groth³

¹Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania, Catania, Italy

²Actinium Chemical Research, Rome, Italy

³Instituto de Astrofisica de Canarias, La Laguna, Tenerife, Spain

Keywords

Carbon molecules · Hydrogenation · Spectroscopy · Interstellar molecules

Synonyms

[Buckminsterfullerene](#); [Buckyball](#); [Footballene](#)

Definition

A fullerene is a carbon molecule arranged in the form of a hollow sphere. Any graphene sheet can be closed into a fullerene cage provided that 12 pentagons are inserted into the sheet of condensed hexagonal rings. Only fullerenes having the 12 pentagonal sites fully annealed by hexagonal rings are stable and have been isolated in macroscopic quantity. This is an important rule regulating the fullerene stability known as “isolated pentagons rule” or IPR. The fullerenes isolated in macroscopic quantity are those following strictly the isolated pentagons rule: C_{60} , C_{70} , C_{76} , C_{84} , C_{90} , C_{94} ... Each fullerene contains $2(10 + \zeta)$ carbon atoms corresponding to 12 pentagonal sites and ζ hexagons. This building principle is a consequence of Euler’s theorem (e.g., Kirk 2007; see also Cataldo et al. 2011). Fullerenes can have elements (metals, noble gases) trapped inside the cages, and these molecules are known as endohedral fullerenes (Kroto et al. 1991; Yang and Wang 2014; Popov 2017).

History

The structure of the most common fullerene, C_{60} , was first hypothesized in 1970 by Eiji Osawa in Japan and was the object of topological and theoretical calculations by the Russians I. V. Stankevich, D. A. Bochvar, and E. G. Gal’pern in 1973. Only in 1984–1985, using mass spectrometry, was it possible to observe a series of carbon clusters that were recognized as fullerenes. H. Kroto, R. Curl, and R. Smalley were awarded the 1996 Nobel Prize in Chemistry for their role in the discovery of this new class of molecules. The production of fullerenes in microscopic quantities at first by W. Kraetschmer and D. Huffman in 1990 created a major breakthrough in fullerene science. The fullerenes are named after Buckminster Fuller, an architect who designed polyhedral domes based on hexagonal and pentagonal faces.

Overview

Fullerene C₆₀ is the most studied fullerene. It is composed of 60 sp²-hybridized carbon atoms arranged in a truncated icosahedron geometry resembling a soccer ball. The molecule contains 30 weakly conjugated double bonds located between the hexagons. The diameter of C₆₀ is 700 pm (picometers). All carbon atoms in C₆₀ are equivalent, giving a sharp single signal in the ¹³C-NMR spectrum located at a chemical shift of 143.2 ppm (parts per million by frequency). The mean C-C distance is 141 pm, which is almost same as in graphite (Kroto et al. 1991).

Basic Methodology

Fullerenes are produced by quenching carbon vapor in a helium atmosphere. Carbon vapor can be generated by resistive heating of graphite or in a 40–60-ampere carbon arc. The best yields of fullerenes are obtained at a helium gas pressure between 100 and 200 mbar. Under these conditions, a carbon soot is collected which, when extracted with benzene or toluene, releases 5–10% of its weight under the form of extractable colored matter consisting of a mixture of C₆₀ and C₇₀ fullerenes. C₆₀ is by far more abundant than C₇₀ in the mixture. The two fullerenes can be separated by common chromatographic procedures on an alumina column using hexane/toluene as eluents. Small amounts of higher fullerenes (C₇₆, C₈₄, C₉₀, C₉₄) can be further separated by high-performance liquid chromatography on reversed phase using acetonitrile/toluene as mobile phase. In the extracted soot, fullerenes > C₁₀₀ remain, which can be further extracted with 1,2,4-trichlorobenzene (Taylor 1999). Fullerenes can be produced in relatively small yield also under controlled combustion conditions in sooting flames and extracted with solvents from the recovered soot (Howard et al. 1992). This method has achieved industrial applications (Murayama et al. 2004).

Key Research Findings

Fullerenes were predicted to be present in space (Hare and Kroto 1992) and have indeed been

found. The main sources of carbon dust and molecules in the interstellar medium are the late-type carbon-rich stars (Ehrenfreund and Charnley 2000; Millar 2004), but there is a class of stars, which lies in the transition between the asymptotic giant branch (AGB) and the ► [planetary nebula](#) stage, that was thought as a very promising source of fullerenes. The stars in this class are rather rare, are helium rich, and are extremely depleted in the hydrogen content of their gaseous shells, so that as the carbon vapor is ejected from the star, it cools and forms an ideal environment for fullerene formation (Kroto 2006). In fact, the presence of hydrogen is known to have negative effects on the formation of the fullerene cage and to favor the production of ► [polycyclic aromatic hydrocarbons](#) (PAHs) and other products (Goeres and Sedlmayr 1992, 1993). The prototype of such stars where fullerenes may be present is *R Coronae Borealis* and the corresponding class of RCrB stars (Unsold and Baschek 2002; Kaler 2006). Indeed, C₆₀ fullerene has been found in RCrB stars, but its detection was not easy and its abundance low or negligible, in contrast with the expectations (Garcia-Hernandez et al. 2011).

On July 2010 the fullerenes C₆₀ and C₇₀ were found for the first time around a young ► [planetary nebula](#) of our Galaxy known as Tc1 (Cami et al. 2010). The discovery was made possible through Spitzer infrared space telescope measurements. The detection of fullerenes in that astrophysical object came as a surprise, since it is known that fullerenes are formed only in environments completely free from hydrogen. The fullerenes were detected in the inner core region of Tc1, which turned out to be carbon rich, hydrogen poor, and dusty (Cami et al. 2010). Furthermore, from the spectral signature, it was evident that C₆₀ and C₇₀ were embedded into the carbon dust and not in the vapor phase (Cami et al. 2010). Since the discovery of Cami et al., especially fullerene C₆₀ and sometimes also C₇₀ have been found in many other astrophysical objects, for example, in planetary nebulae belonging to the Magellanic Clouds (Garcia-Hernandez et al. 2010), in proto-planetary nebulae (Zhang and Kwok 2011), and subsequently in a number of planetary nebulae in our Galaxy and in the Large and Small Magellanic Clouds (Garcia-Hernandez et al. 2012). C₆₀

fullerene was detected even in the IC308 star cluster of the Perseus molecular cloud (Iglesias-Groth 2019).

Fullerene C_{60} has been also detected in the interstellar medium and more precisely in the reflection nebulae NGC 7023 and NGC 2023 (Sellgren et al. 2009, 2010).

In the interstellar medium, C_{60} fullerene should be present as a neutral molecule or may undergo ionization to C_{60}^+ . This cation may be responsible for some spectral features in the diffuse interstellar bands (DIBs), absorption bands detected in the spectra of stars in our Galaxy, and beyond (Foing and Ehrenfreund 1994). Further claims for the detection of C_{60}^+ in the ISM seem to confirm once again that this molecule is ubiquitous in space (Berné et al. 2013). Fullerene cations may undergo multiple addition of atomic hydrogen, forming hydrogenated derivatives (Petrie et al. 1995). In 2013 Iglesias-Groth and Esposito reported the detection of C_{60} cation in the protoplanetary nebula IRAS 01005 + 7910 (Iglesias-Groth and Esposito 2013).

In 2016 the C_{60}^+ was unambiguously detected in diffuse clouds through the reddened star HD 183143 through an excellent and high level laboratory research work combined with astrophysical observational data (Campbell et al. 2016; Maier and Campbell 2017). It was firmly confirmed that fullerene cation is the carrier of the DIBs at 957.7 nm and at 963.2 nm (Maier and Campbell 2017).

Neutral fullerenes also add atomic hydrogen easily at very low temperatures (Howard 1993), so that it is reasonable to think that fulleranes, the hydrogenated fullerene derivatives, should be present in the interstellar medium (Petrie and Bohme 2000; Cataldo and Iglesias-Groth 2010).

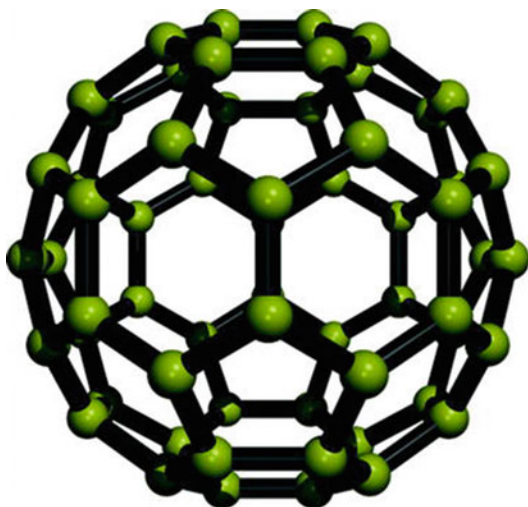
Fulleranes can be produced in the laboratory under a variety of conditions (Cataldo and Iglesias-Groth 2010). Deuterated fulleranes have also been synthesized. Significant isotope effects both in the photolysis and in the thermal decomposition of fulleranes and perdeuterofulleranes have been observed (Cataldo et al. 2009a; Cataldo and Iglesias-Groth 2010). An enrichment in the deuterium content in fulleranes is hence expected in the space environment. Additionally, fulleranes

release molecular hydrogen under certain circumstances and are thought to play a role in molecular hydrogen formation in space, starting from atomic hydrogen (Cataldo and Iglesias-Groth 2010).

Calculated infrared spectra for hydrogenated fullerenes have been published in comparison with the ► [unidentified infrared emission bands](#) (Webster 1991; Cataldo and Iglesias-Groth 2010). The infrared spectrum of $C_{60}H_{36}$ has also been compared with the infrared features of astrophysical objects like the protoplanetary nebulae (Cataldo 2003). An inventory about fullerenes and hydrogenated derivatives in the interstellar medium and their theoretical spectral properties can be found in the recent works of Iglesias-Groth (2004, 2005, 2006). A connection between fulleranes and the strongest ► [diffuse interstellar band](#) (DIB) known in the optical has also been proposed (Iglesias-Groth 2007, 2008).

The reference infrared spectra of fullerenes and fulleranes (the hydrogenated fullerenes) are now available in a wide range of temperatures useful for searching and recognizing such molecules (Iglesias-Groth et al. 2011, 2012). Furthermore, the molar extinction coefficients and integrated molar absorptivity of these molecules are now available for the estimation of the abundance of fullerenes and fulleranes (Iglesias-Groth et al. 2011, 2012). For an updated view on fulleranes and hydrogen addition to the fullerene cage, it is highly recommended the work of Tanuma et al. (2021).

An important property of molecules of astrochemical interest regards their stability to UV photons. A plethora of organic molecules are today known in different space environments (Ehrenfreund and Charnley 2000; McGuire 2021), some of them known to be the precursors of life. Photochemical processing may lead to the production in space of other interesting molecules from common precursors or may lock certain molecules into dust or dust-forming nanoparticles. In this context, the photophysical and photochemical properties of fullerenes and their hydrogenated counterparts, the fulleranes, are of interest, both for the detection of these species and to estimate their survival and their fate in the harsh space environment. The photophysical properties



Fullerene, Fig. 1 Stick and ball model of C_{60} fullerene

of fullerenes are well known, the photochemistry and the radiation chemistry of these molecules having been explored, revealing a very high stability of fullerenes to both high-energy photons and corpuscular radiation (Cataldo et al. 2009b) (Fig. 1).

Future Directions

The search for fullerenes in various natural environments has been the object of a monograph (Rietmeijer 2006). Fullerenes have been found in the Cretaceous-Tertiary boundary layer, in meteorites, and in organic deposits. The search for fullerenes in space will be intensified (Sellgren et al. 2009; Iglesias-Groth 2007, 2008; Lambert et al. 2001; Clayton et al. 1995; Goeres and Sedlmayr 1993). It will be necessary to record the laboratory spectra in the infrared, the ultraviolet, and the visible of fullerenes and fulleranes, especially at low temperatures, in order to have available reference spectra useful for the research of this class of molecules in space. Moreover, future research in the laboratory will be directed toward higher fullerenes, which until now have been scarcely studied simply because they are not easily accessible.

Fullerenes have been found mixed with PAHs in certain astrophysical environments, and it is

completely reasonable that both fullerenes and PAHs share the same destiny when ejected into the interstellar medium. One interesting aspect of future research regards the reactivity of fullerenes with PAHs. We know already that fullerenes easily merge with linear PAHs to form Diels-Alder adducts known as acenes (Cataldo et al. 2013). The spectra of adducts of fullerenes and PAHs prepared in the lab could be used as reference when searching for evidence of the reactivity of fullerenes with PAHs in space.

Another intriguing aspect regards the fact that fullerenes can be a source of carbon for prebiotic synthesis on icy grains or under other conditions. Fullerene C_{60} is insoluble in water, but if radiolyzed in a water medium or in water-ammonia medium, it yields a polyhydroxylated fullerene, which is completely soluble in water and which can be considered a source of organic carbon for the synthesis of simple molecules precursors of biochemistry (Iglesias-Groth et al. 2013). A mass spectrometric analysis of the radiolysis products of C_{60} fullerene in interstellar ices analogs has revealed the formation of polyynes, ene-yne, and polyenes derivatives (Ursini et al. 2019).

Cross-References

- Diffuse Interstellar Bands
- Fullerane
- Planetary Nebula
- Polycyclic Aromatic Hydrocarbon

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Fulminic Acid

► [HCNO Isomers](#)

Fumarole

Jörn Helbert

DLR, Institut für Planetenforschung, Berlin, Germany

Definition

Fumaroles (Latin fumus, smoke) are vents from which volcanic gas escapes into the atmosphere. Fumaroles may occur along tiny cracks or long fissures, in chaotic clusters or fields, and on the surfaces of lava flows and thick deposits of pyroclastic (explosive ash) flows. They may persist for decades or centuries if they are above a persistent heat source or disappear within weeks to months if they occur atop a fresh volcanic deposit that quickly cools.

Fumaroles are common on ► [Earth](#); for example, there are an estimated four thousand fumaroles within the boundaries of Yellowstone National Park. The Mars Exploration Rover Spirit has identified possible fumarolic deposits in Gusev crater.

Cross-References

- [Crater, Impact](#)
- [Cryovolcanism](#)
- [Earth](#)
- [Mars](#)

Fullness of Being

► [Principle of Plenitude](#)

Functional Inhibitor

► [Antibiotic](#)

Fungal Weathering

Saskia Bindschedler¹ and Eric P. Verrecchia²

¹Laboratory of Microbiology, University of Neuchâtel, Neuchâtel, Switzerland

²IDYST, Faculty of Geosciences and the Environment, University of Lausanne, Lausanne, Switzerland

Keywords

Biochemical weathering · Biomechanical weathering · Biominerals · Geomycology · Symbioses · Mycelial network

Synonyms

[Biotic mineral alteration](#); [Biotic mineral dissolution and complexation](#)

Definition

Fungi are essential drivers of biogeochemical cycles at the Earth surface. They are involved in both rock weathering and neogenesis of minerals, the latter as by-products of their impact during alteration. During biomechanical weathering, fungi can penetrate into minerals forming tunnels and channels. During biochemical weathering, fungi mobilize elements contained in minerals using acidolysis, complexolysis, redoxolysis, and metal accumulation in their biomass. Secondary minerals, such as metal-oxalates, -carbonates, -phosphates, and clays, are also generated by fungi as a result of mineral weathering. Moreover, symbiotic associations involving fungi (mycorrhizae and lichens) play a major role in mineral weathering and soil biogeochemical cycles.

Overview

Fungi are eukaryotic organisms that first appear in the fossil record 1 billion years ago (Loron et al. 2019) in agreement with molecular clocks

(Berbee and Taylor 2010). They are heterotrophic and, as such, are well-known for their role in the decay of organic materials (OM). This ability had made them essential in the biogeochemical cycling of the main elements found in OM, i.e., C, N, S, and P. However, they also play a fundamental role in the cycling of other elements crucial for life, such as Ca, K, Mg, Na, and Fe, and trace elements. Recent research has demonstrated their numerous implications in both mineral weathering and neogenesis (Gadd 2017a, b). Most fungi grow as a filamentous network called the mycelium, which exhibits fractal and three-dimensional properties. For example, filamentous fungi have the ability to extensively colonize mineral substrata and actively modify the mineral-fungal interface. They do this not only to physically expand but also to access macro- and micronutrients. Indeed, they are key players in macronutrients translocation (e.g., Ca, K, Mg, Na, and Fe) from minerals to organisms. In addition, they are involved in the mobility of trace elements in numerous ecosystems, e.g., in boreal forests. Consequently, fungal presence and activity directly alter mineral substrates and contribute to continent weathering on a large scale (Hoffland et al. 2004).

The processes at work during fungal weathering can be divided into two main types of action: biomechanical and biochemical. Biomechanical fungal weathering results from direct and indirect physical attacks. Direct biomechanical attack arises mainly as a consequence of the turgor pressure that is exerted at the tip of the fungal hyphae (Money 2008). This mechanism allows fungal mycelia to penetrate into pores and cracks that are already present in rocks, as well as to dig into minerals leading to the formation of fungal tunnels or channels. By this means, mineral surfaces to be weathered increase, leading to higher surface to volume ratios. Indirect biomechanical attacks result from the attachment of fungal hyphae to solid surfaces. Filamentous fungi produce soluble exopolymeric substances (EPS) in order to adhere to a surface. EPS contains water as well as acidic mucopolysaccharides and some other associated chelating agents. These coupled mechanical and chemical processes

efficiently contribute to the weakening of mineral surfaces, accelerating mineral weathering.

Biochemical fungal weathering is due to the interaction of fungi with mineral surfaces, in order to either access nutrients or colonize new niches that are present in rocks. Fungi use four main mechanisms to mobilize the elements contained in minerals: acidolysis, complexolysis, redoxolysis, and metal accumulation in their biomass. Acidolysis refers to the action of (i) low-molecular weight organic acid (LMWOA) secretion (e.g., citric and oxalic acids; Gadd 1999); (ii) the release of CO₂ through catabolic respiration; (iii) nutrient uptake (e.g., ammonium conversion to nitrate during N uptake); and (iv) thigmotropism, which corresponds to proton excretion at the hyphal tip to survey the topography of the hyphal microenvironment (Bowen et al. 2007). Complexolysis is also associated with LMWOA, as well as to other chelating compounds such as siderophores. Siderophores are organic ligands involved in iron bioavailability enhancement and are extremely diverse in terms of molecular structure (Renshaw et al. 2002). All these compounds facilitate mineral dissolution by sequestering metals mobilized from mineral lattices. Redoxolysis is present in fungi, although it is less common than in bacteria. For example, reduction of Fe(III), Mn (IV), Au(III), and Hg(II) in association with fungi has been reported in several studies (Gadd 2007). The main reason for such reactions is either nutrient uptake or metal detoxification. Finally, fungi are able to immobilize metals within their biomass, either externally (biominerals or metal-chelates) or internally (adsorption to the cell wall, complexed onto cytoplasmic proteins, or intraorganelle accumulations). Similar to complexolysis, this process leads to the displacement of the reaction equilibrium in favor of mineral dissolution (Harms et al. 2011).

Fungal weathering is evidenced by dissolution traces on the mineral surface, which appear as large areas with a different aspect than the original mineral surface (Hoffland et al. 2004). They result from the alteration of the mineral surface after selective ion uptake (destruction of the crystal lattice). Other common traces associated with

fungal weathering consist of marks and imprints of fungal hyphae on the mineral surface (Li et al. 2016), as well as tunneling within mineral substrates (Smits 2006).

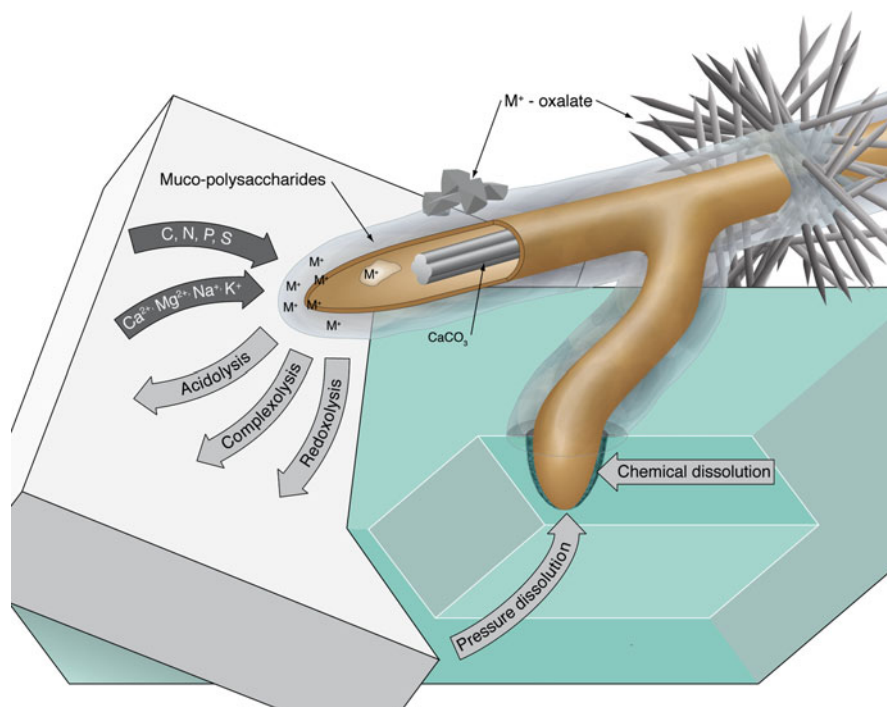
Another way by which fungal weathering can be detected is the presence of secondary minerals. Metal oxalates, -carbonates, -phosphates, and clays have been observed in controlled experiments examining mineral weathering as a result of fungal activity. Moreover, metal oxalates and carbonates of fungal origin are regularly documented in natural settings (Gadd 2017a, b). Although many metal oxalates are considered as by-products of fungal weathering, they are mostly observed in laboratory experiments and in specific settings, such as polluted sites. Regarding calcium oxalates (whewellite and weddellite), they represent the most widespread forms of fungal oxalate crystals observed in natural environments. They are associated with litter and wood degradation and also form during the weathering of calcium-rich rocks (Gadd 2006). Carbonate minerals are another form of secondary minerals biomediated by fungi. They have been documented in microcosm experiments as a result of fungal weathering. They are also extremely common in the vadose zone environment (caves and soils) where they appear as needle-fiber calcite and calcitic nanofibers (Bindschedler et al. 2016). Metal-phosphates formation has also been described as a by-product of fungal weathering of minerals containing toxic metals. Phosphate salts with uranium (Fomina et al. 2008), lead (Liang et al. 2015), and copper (Crusberg 2004) have all been observed in fungal microcosm experiments. Finally, clays have also been reported as secondary minerals during soil formation in association with fungal activity. Such secondary layered silicates result from nucleation on chelate complexes that are used as templates for crystal structures (Jackson 2015).

At a global scale, symbiotic associations involving fungi, such as mycorrhizae and lichens, have a major role in mineral substrate weathering and consequently in biogeochemical cycles. Mycorrhizae consist of the association of fungal hyphae and plant roots in soils. They are widespread on land surfaces, and it is considered that

approximately 90% of plants are mycorrhized. Ectomycorrhizae, in particular, have extended mycelial networks actively colonizing mineral substrates at great distances from plant roots in order to transfer nutrients such as P and Ca to their symbiotic plant. This is assumed to significantly contribute to rock weathering and soil formation (Quirk et al. 2012). Lichens are fungi living in symbiosis with photosynthetic organisms (cyanobacteria and eukaryotic microalgae) and are also of major biogeochemical relevance since they colonize about 6% of the continental surface. For example, areas at high altitudes and high latitudes exhibit high densities of lichens. Similarly, all mineral surfaces in urban areas (e.g., buildings) are prone to colonization by lichens.

In addition to this, early stages of biological soil crusts (SBCs) consist in fungal-cyanobacterial associations that are functionally similar to lichens (Belnap et al. 2016). The fungal partners of lichens and SBCs mechanically alter mineral surfaces to adhere to their substrate along with the secretion of large quantities of LMWOA and chelating compounds for nutrient uptake (Chen et al. 2000). Finally, both lichens and SBCs are considered as efficient agents affecting the biogeochemical cycles of nutrients, as they contribute to the formation of podzols in boreal forests (Finlay et al. 2009) and initial soil formation at glacier forefields (Schulz et al. 2013).

In conclusion, fungi are prominent agents of mineral weathering due to their filamentous



Fungal Weathering, Fig. 1 Sketch showing the different mechanisms involved in fungal weathering and their outcomes. (Modified and redrawn from Fomina et al. 2007). Biomechanical weathering results directly from pressure dissolution at hyphal tips and indirectly from chemical dissolution related to hyphal adhesion to mineral substrates through exopolymeric substances (EPS). Biochemical weathering results from acidolysis (e.g., H^+ and LMWOA excretion), complexolysis (e.g., LMWOA and siderophores), redoxolysis, and metal (M^+) accumulation

linked to fungal biomass (either in the EPS layer, adsorbed to cell wall polymers, or stored in vacuoles). Biominerals are also evidence of fungal weathering impact. They may be intracellular, such as $CaCO_3$ in the form of needle fiber calcite, or extracellular in the form of various metal oxalates (the most common being whewellite and weddellite). Nutrient uptake (macro- and micronutrients) is the main driver of mineral weathering, as well as colonization of new physical niches and resistance to toxic metals

nature, ubiquity, and diversity of biochemical and biophysical mechanisms involved in mineral alteration (Fig. 1). Their role in the biogeochemical cycles must not be underestimated.

Cross-References

- [Biogeochemical Cycles](#)
- [Biomining](#)
- [Carbon Cycle, Biological](#)
- [Endolithic](#)
- [Exopolymers](#)
- [Fungi](#)
- [Heterotroph](#)
- [Lichens](#)
- [Ligand](#)
- [Spore](#)
- [Weathering](#)

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Fungi

Aldo González

Centro de Biología Molecular, CBMSO Consejo Superior de Investigaciones Científicas
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Aspergillus · Carpophores · Filamentous fungi · Hyphae · Mushrooms · *Penicillium* · Yeasts

Definition

Fungi are nonphototrophic, heterotrophic eukaryotic microorganisms that contain rigid cell walls and produce spores. Fungi form a tight phylogenetic cluster.

Overview

Defining fungi within the group of eukaryotes is a complex and difficult task and it is preferable to construct a definition based on their common properties rather than on the differences that separate them from the rest of the eukaryotic species. Their peculiar method of reproduction is perhaps one of the main axis on which it is possible to construct a phylogenetic classification, reflecting, in some way, the mechanisms of evolution of each of the groups of fungi represented on Earth.

Many species behave according to Mayr's species definition, presenting a sexual life cycle where two mycelia having sexually compatible cells join to produce a panmictic population that mates randomly after meiotic division generating a fertile population, while others are parasexual

(i.e., involving nuclear fusion followed by gradual de-diploidization).

In a high percentage of species, this mechanism implies an asexual reproduction system that gives rise to specialized cells known as conidiphores that produce dikaryotic cells by mitosis (only nuclear division) which are able to generate a new organism. When they are isolated in pure culture, the asexual strain, known as anamorphous (i.e., *Aspergillus nidulans*), is obtained by the mating of two anamorphous, while the sexual strain is known as teleomorphous (i.e., *Emericella nidulans*). One species has these two reproductive states (asexual and sexual). These two ways of representation in the world of living beings make it necessary to create two systems of classification, one for each type of reproductive state, knowing beforehand that the one for the sexual cycle is close to a phylogenetic proposal and that the other, based on the forms of conidia production, is rather artificial.

About 120,000 species of fungi have been described to date, although the total estimated number of species is around 1.5 million. The versatility of their “soma,” also named mycelia, which in the case of filamentous fungi are made up of a group of septate hyphae, allow them to be present in all possible ecosystems on Earth. Where they are a minority, it is because this environment has, in fact, been little studied yet. Recent studies of metagenomics report their presence in ecosystems under environmental pressure or in the sea. In recent studies of classification of all described species, six kingdoms have been established. Fungi have been included in the kingdom Mycota, in which seven monophyletic “true fungi” are included: Chytridiomycota, Zygomycota, Endomycota (Yeasts), Ustomycota, Ascomycota, Basidiomycota, and Deuteromycota, all grouped as Eumycota. The organisms known as “pseudo-fungi” are phylogenetically close to Protists and contain the Oomycota and Hyphochytridio-Labrynthulomycota groups.

According to their special way of life, all fungi can be defined by the following characteristics: (1) They are heterotrophs and their nutrition is by absorption. (2) In the vegetative stage, they grow

on or inside the substrate as hyphae forming a mycelium showing internal protoplasmic streaming. Reproductive stages with mobility may occur. (3) Cell wall is generally formed by glucans and chitin and, in some cases, glucans and cellulose. (4) Nuclear status, Eucariota, uni- or multinucleate, the thallus may be homo- or heterokaryotic, dikaryotic or diploid, the last usually of short duration with exceptions in some groups. (5) Their life cycle is simple although in some cases complex. (6) Propagules are typical little spores produced in high amounts. (7) Sporocarps or carpophores can be microscopic or macroscopic, with characteristic shapes. In some groups they are known as mushroom and are limited to differentiation tissues. (8) Habitat, ubiquitous in terrestrial, freshwater habitats and in lower numbers in marine waters, although fungal species have been less studied in this environment. (9) In ecology, they play important roles as saprotrophs, mutualistic symbionts, parasites, or hyperparasites. (10) In pathology, they are the cause of serious pathologies to animals and plants. (11) They have a cosmopolitan distribution. (12) Degradation, they are important degraders of plant eliminate macro-polymers (i.e., cellulose, lignin); of fossil combustibles; “sequesters” of heavy metals and radioactive elements at high concentrations.

In general they are responsible for 75% of the turnover of carbon (► [Carbon Cycle](#)), contributing to the degradation of biomass and facilitating its reincorporation into the vital cycle of terrestrial and aquatic plants. At present, the objective is to promote a new taxonomy based directly on comparisons of selected DNA sequences that encode genes with a conserved biological function, instead of or in addition to phenotypic characteristics. These gene sequences should allow the construction of phylogenetic trees integrating microscopic, ultrastructural, and biochemical data leading to a fuller understanding of fungal taxonomy with monophyletic criteria. Nevertheless, the most reliable current criterion to define a given species continues to be the cross-linking of two sexually compatible monokaryon mycelia to form dikaryotic mycelia able, in turn, to produce carpophores.

Cross-References

- [Carbon Cycle, Biological](#)
- [Eukarya](#)
- [Eukaryote](#)
- [Heterotroph](#)
- [Phylogeny](#)
- [Yeast](#)

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FUor

- [FU Orionis \(Object\)](#)

Furanose

Ramanarayanan Krishnamurthy, Tammy Campbell and Eun-Kyong Kim
The Scripps Research Institute, La Jolla, CA, USA

Keywords

Alpha- versus beta-configuration · Carbohydrates · Monosaccharide · Five-membered ring · D- or L-chirality · Anomeric carbon · Conformation · Aldehyde · Alcohol

Definition

The term furanose denotes a five-component cyclic structure containing four carbon atoms and one oxygen atom and is generally reserved for the description of the molecular framework in monosaccharides. The furanose ring can be a cyclic hemiacetal of an aldopentose (e.g., ribose in RNA and deoxyribose in DNA) or a cyclic hemiketal of a ketohexose (e.g., fructose).

Overview

Furanose denotes a five-membered cyclic structure, belonging to a class of compounds termed carbohydrates, which are molecules composed

of carbon, oxygen, and hydrogen with the empirical formula $C_n(H_2O)_n$. Furanoses are differentiated by various means, including the carbon framework from which hydroxyl groups are attached, the stereochemistry of the hydroxyl groups at each carbon (R or S), and the conformation of the overall structure (envelope or twist). Furanoses are either assigned a D- or L-configuration depending on the ► [chirality](#) of the stereocenter at the carbon farthest away from the aldehyde.

Furanose form can exist in an equilibrium distribution between a cyclic hemiacetal or cyclic hemiketal and an uncyclized free ► [aldehyde](#) or ketone, respectively. Entropy effects favor the intramolecular reaction of the aldehyde (or ketone) and hydroxyl group leading to the distribution of forms as: hemiacetal >99.99%, free aldehyde ~0.01%, and the hydrate in trace amounts (Drew et al. 1998). The two predominant hemiacetals formed are furanose and ► [pyranose](#). In general, furanoses are kinetically preferred, but thermodynamically less stable than pyranoses. The anomeric carbon produced during cyclic hemiacetal formation is bonded to two oxygens. One oxygen is located inside the ring and the other as a hydroxyl substituent in either endo (beta)- or exo (alpha)-position relative to the ring. These are diastereomers or anomers of furanose and generally have altered ratios due to epimerization in solution.

The variations between the aldehydes, pyranoses, and furanoses are biologically important since nature favors one structure over the other. In the case of aldopentoses, four monosaccharides exist: arabinose, ► [ribose](#), xylose, and lyxose. The equilibrium formation of furanose from each aldopentose varies in solution according to their stereogenic centers. Important keto-furanoses in biology include ribulose and xylulose. Ribulose is converted to ribose in the pentose phosphate pathway which is then used by cells in the synthesis of nucleoside triphosphates and ► [nucleic acids](#).

The molecular basis of why ► [RNA](#) is founded on a ribo-furanose and not a ribo-pyranose

structure (Eschenmoser 1999) is a key question that has been addressed extensively in the field concerning the origins of life. One study revealed limitations of the conformational diversity of canonical nucleic acids by systematically synthesizing alternative nucleic acid structures. Markedly lower level of helicity was exhibited by pentopyranosyl nucleic acids in comparison to ribonucleic acid, lending support to the idea that the pentofuranose structure is responsible for the helical shape of the duplex in RNA and ► [DNA](#) (Eschenmoser and Dobler 1992; Pitsch et al. 2003). Another study explored the assemblage and accumulation of pentofuranoses through a borate-mediated stabilization of cis-diols in furanose form (Prieur 2001; Ricardo et al. 2004). Interestingly, among the four aldopentoses, ribose has the highest percentage of furanose form (Drew et al. 1998). Furthermore, model protocellular membranes exhibit a diastereoselective advantage for ribose in the uptake of carbohydrates from solution (Sacerdote and Szostak 2005). And, more recently, by studying the base-pairing properties of oligonucleotides constructed from ribulofuranose and xylulofuranose and comparing them with those of corresponding RNA sequences, the importance of the role of the furanose-ring structure in controlling the anti-conformation of the nucleobases was demonstrated (Stoop et al. 2013; Krishnamurthy 2014). It was shown that the ribo-furanose structure orients the Watson-Crick hydrogen-bonding face of the nucleobases away from the phosphodiester backbone, while the ribulo- and xylulo-furanose rings reverse this orientation resulting in compromised base-pairing properties.

Together, these findings suggest additional functional reasons for why ribose (in its furanosyl form) may have been selected as the structural basis upon which modern biology is based.

Cross-References

- [Monosaccharide](#)
- [Ribose](#)

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Fusion Crust

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

A fusion crust is a feature of the external appearance of ► [meteorites](#). It describes a glassy coating of the meteorite. The crust forms as a consequence of the frictional heating and melting of the most external layer of the meteorite as it passes through the atmosphere and descends to the ► [Earth's](#) surface. Most of the melt is lost due to ► [ablation](#). Thus, the fusion crust is mostly about 1 mm thick.

Cross-References

- [Ablation](#)
- [Earth](#)
- [Meteorites](#)

G

Ga

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Synonyms

[Giga-annum](#); [Gigayear](#)

Acronyms

Ga, Gyr

Definition

Ga is a common scientific abbreviation for the derived Latin word giga-annum or 10^9 years. Note that the Latin accusative, annum, expresses an absolute age, while the English accusative, years (giga-years), expresses a period of time. It is widely used in fields such as astronomy and geology. For example, the current best estimate for the age of the universe, from the Wilkinson Microwave Anisotropy Probe (spacecraft) data on the cosmic microwave background radiation, is 13.7 Ga, and the ► [age of the Earth](#), commonly taken as the time of the completion of accretion, is 4.56 Ga. In geology, the term is often used to signify time before the present; for example, the

time of the Moon-forming impact is 4.51 Ga, and the age of the oldest rocks at the Earth's surface (► [Acasta Gneiss](#)) is about 4.03 Ga.

Cross-References

- [Acasta Gneiss](#)
- [Earth, Age of](#)
- [Geochronology](#)
- [Geological Timescale](#)
- [Geological Time Scale, History of](#)

Gabbro

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Gabbro is a common mafic intrusive igneous rock, chemically equivalent to the effusive basalt or occasionally to a basaltic cumulate. A medium- to coarse-grained, dark-coloured rock, gabbro is composed of Ca-plagioclase and clinopyroxene, with or without ► [olivine](#), orthopyroxene, or amphibole. Earth's oceanic crust is composed of 3–5 km-thick layered gabbro, produced by

crystallization of basaltic magma erupting at the ► [mid-ocean ridges](#), covered by pillow basalts and sediments. Gabbro, and its extrusive equivalent basalt, is common on the Moon Highlands (anorthositic gabbro), Mars, Mercury, many large asteroids, and probably Venus.

Cross-References

- [Basalt](#)
- [Mars](#)
- [Mercury](#)
- [Mid-Ocean Ridge](#)
- [Moon, The](#)
- [Olivine](#)

Gaia

- [Biosphere](#)

Gaia Hypothesis

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

According to the Gaia Hypothesis, the biosphere and the physical components of the Earth form a complex interacting system that maintains the climatic and biogeochemical Earth conditions in homeorhesis. It was originally proposed by James Lovelock who called it the Earth feedback hypothesis, and it is frequently described as a way of seeing the Earth as a single organism.

Overview

James Lovelock first formulated the Gaia Hypothesis in the 1960s, as a result of his work for NASA on developing methods of detecting life on Mars.

At first, the theory was a way to explain the stable concentrations of chemicals such as oxygen and methane that persisted in Earth's atmosphere. Lovelock suggested that detecting such unstable combinations in other planets' atmospheres was a relatively reliable and cheap way to detect life.

Lovelock tried to explain the existence of a global control system over surface temperature, the salinity of the oceans, and the atmospheric composition suggesting that life on Earth functions as a homeostatic feedback system. He called this self-regulating living system Gaia, after the Greek goddess. Since 1971, the distinguished biologist Lynn Margulis collaborated closely with Lovelock in developing the Gaia Hypothesis, and scientific experiments have provided a number of useful predictions to support the hypothesis, although it has always had highly scientifically respected detractors. After long debate and much criticism, a modified Gaia Hypothesis has found acceptance in the field of ecology. Ecologists generally consider the biosphere an ecosystem, and the Gaia Hypothesis is consistent with today's vision of global ecology, which takes into consideration the interactions between biota, the oceans, the geosphere, and the atmosphere.

Cross-References

- [Autopoiesis](#)
- [Homeostasis](#)

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Gaia Mission

Alessandro Sozzetti

Istituto Nazionale di Astrofisica (INAF) –
Osservatorio Astrofisico di Torino, Pino Torinese,
Italy

Keywords

Astrometry · Exoplanet · Extrasolar planet ·
Planetary systems

Definition

Gaia is the ► European Space Agency's flagship all-sky astrometric survey. Successfully launched in December 2013, Gaia monitors astrometrically all point sources (► stars, ► asteroids, quasars, extragalactic supernovae, etc.) in the visual ► magnitude range $V = 3\text{--}21$ mag, a huge database encompassing almost 2×10^9 objects. Gaia completed its 5-year nominal mission lifetime in summer 2019 and is now progressing in its extended mission. Using the continuous scanning principle first adopted for ► *Hipparcos*, Gaia **determines** the five basic astrometric parameters (two components of position, two of ► *proper motion*, and the ► *parallax*) for all objects, with end-of-mission precision exceeding that of ► *Hipparcos* by 1–2 orders of magnitude. Gaia astrometry, complemented by onboard spectrophotometry and (partial) radial-velocity information, will have the precision necessary to **revolutionize our knowledge of** the early formation and subsequent dynamical, chemical, and star formation evolution of the Milky Way Galaxy.

Overview

The Gaia mission is the new global, all-sky, astrometric initiative of the European Space Agency (ESA). Its launch occurred perfectly on schedule from the ESA's Kourou site in the French Guiana on December 19, 2013. A Soyuz-Fregat launcher took the Gaia module to a transfer orbit, which in 1 month allowed the satellite to reach its operational environment on a Lissajous orbit at Sun-Earth ► *Lagrangian point* L2, 1.5 million kilometers away from Earth. **After an extended commissioning phase, the mission started nominal operations in June 2014. Gaia monitors astrometrically** all point sources in the visual magnitude range $V = 3\text{--}21$ mag, a huge database of about 2×10^9 stars, a few million galaxies, half a million quasars, and a few hundred thousand asteroids. **Gaia completed its 5 years of operational lifetime in Summer 2019. At the time of this writing, the mission has just entered its third year of extended mission operations.**

As for the observing strategy, Gaia's mode of operation has adopted the principles successfully experimented with the *Hipparcos* mission (ESA 1997). In particular, it continuously scans the sky, implying that all detected objects, irrespective of their magnitudes, are observed for the same amount of time during each field-of-view crossing, with mission-end observing time mainly depending on ecliptic latitude (Lindgren 2010). In this way, it is anticipated that Gaia will determine the five basic astrometric parameters (two positional coordinates, two proper motion components, and the parallax) for all objects, with end-of-mission (sky-averaged) precision between 7 and 25 μas (microarcseconds) down to the Gaia magnitude $G = 15$ mag and a few hundred μas at $G = 21$ mag, depending on color. Red objects are expected to have better astrometry, while that for extremely blue targets is estimated to degrade by a factor of 2.

The main partners inside the Gaia project are (1) the European Space Agency (ESA), which has the overall project responsibility for funding and procurement of the satellite, launch, and operations; of interest is the fact that in this case, satellite procurement includes the payload and its

scientific instruments, unlike ESA's other science missions for which scientific instruments are usually principal investigator led and funded (or, at least, co-funded) by participating national space agencies; (2) *European Aeronautic Defence and Space Company* Astrium, which was selected in 2006 as the prime industrial contractor for designing and building the satellite according to the scientific and technical requirements formulated to fulfill the mission science case as approved at time of selection (ESA 2000); and (3) the Gaia Data Processing and Analysis Consortium (DPAC), charged with designing, implementing, and running a complete software system for the scientific processing of the satellite data, resulting in the edition of the "Gaia Catalogue" a few years after the end of the operational (observation) phase.

DPAC was formed in 2006 in response to an "Announcement of Opportunity" issued by ESA. The consortium lists nearly 400 individual members in more than 20 countries. Six data processing centers participate in the activities of the consortium, which is organized in eight "Coordination Units," each responsible for the development of one part of the software (e.g., core astrometric processing, photometry). The ninth coordination unit (CU9), the last DPAC coordination unit, will be in charge of the design and implementation of the Gaia archive. CU9 was created separately from the rest of DPAC through a specific Announcement of Opportunity by ESA. Most of the financial support is provided by ESA and by the various national space agencies through a legally binding long-term funding agreement, a real first for ESA-run missions.

There is no proprietary period for the scientific exploitation of the data. The final Gaia Catalogue will be produced and immediately delivered to the astronomical community worldwide as soon as ESA and DPAC will agree on the processed data having reached the targeted (science) quality. This catalogue is expected to be ready 3 years after the end of operations. Finally, an intermediate data release (DR) scenario has been established, with a preliminary schedule of four successive intermediate releases of increasingly more complete astrometric, photometric, and

spectroscopic data. The first Gaia DRs, DR1, DR2, and EDR3, have been published in September 2016 (Gaia Collaboration 2016a, 2016b), April 2018 (Gaia Collaboration 2018), and December 2020 (Gaia Collaboration 2021). The full third intermediate data release, DR3, is expected to become available by mid-2022. Photometric science alerts have instead been produced and released since early on during the mission operations. Similarly, near-Earth-asteroid information has been routinely communicated at short notice. Finally, the Gaia mission operations have been officially extended until end of 2022, with the possibility to reach a full doubling of the mission lifetime (until 2024–2025 when the thrusters' fuel is expected to run out). More information can be found in Lindegren (2010), while other organizational details and the latest news on payload and satellite developments are available on the Gaia web pages at <https://www.cosmos.esa.int/web/gaia>.

A combination of an ambitious science case, wishing to address breakthrough problems in Milky Way astronomy, and lessons learned from the Hipparcos experience brought European astronomers to realize that Gaia astrometry needed to be complemented by onboard spectrophotometry and (only for objects brighter than $G = 17$) radial-velocity information. These data will have the precision necessary to quantify the early formation and subsequent dynamical, chemical, and star formation evolution of our Galaxy. **The broad range of crucial issues in astrophysics that can be addressed by the wealth of the Gaia data was initially summarized by Perryman et al. (2001). The ongoing scientific exploitation by the community of the successive Gaia DRs has fully materialized the expectations, with >2300 Gaia-based refereed journal articles, as of August 2021. One of the relevant areas on which the Gaia observations will have great impact is the astrophysics of planetary systems (e.g., Casertano et al. 2008), in particular when seen as a complement to other techniques for exoplanet detection and characterization (e.g., Sozzetti 2010). The first results on sub-stellar companions detected by Gaia astrometry,**

photometry, and spectroscopy will be published as part of Gaia DR3. The focus in the remainder of this section will be on exoplanet detectability and impact on exoplanetary science using Gaia astrometry alone.

Basic Methodology

The problem of the correct determination of the astrometric orbits of planetary systems using Gaia data (highly nonlinear orbital fitting procedures, with a large number of model parameters) will present many difficulties. For example, it will be necessary to assess the relative robustness and reliability of different procedures for orbital fits, together with a detailed understanding of the statistical properties of the uncertainties associated with the model parameters. For multiple systems, a trade-off will have to be found between accuracy in the determination of the mutual inclination angles between pairs of planetary orbits, single-measurement precision, and redundancy in the number of observations with respect to the number of estimated model parameters. It will constitute a challenge to correctly identify signals with amplitude close to the measurement uncertainties, particularly in the presence of larger signals induced by other companions and/or sources of astrophysical noise of comparable magnitude. Finally, in cases of multiple-component systems where dynamical interactions are important (a situation experienced already by radial-velocity surveys), fully dynamical (Newtonian) fits involving an n -body code might have to be used to properly model the Gaia astrometric data and to ensure the short- and long-term stability of the solution (see Sozzetti 2005).

All the above issues could have a significant impact on Gaia's capability to detect and characterize planetary systems. For these reasons, a Development Unit (DU) has been specifically devoted to the modeling of the astrometric signals produced by planetary systems. The DU is composed of several tasks, which implement multiple robust procedures for (single and multiple) astrometric orbit fitting (such as Markov Chain Monte Carlo and genetic algorithms) and the

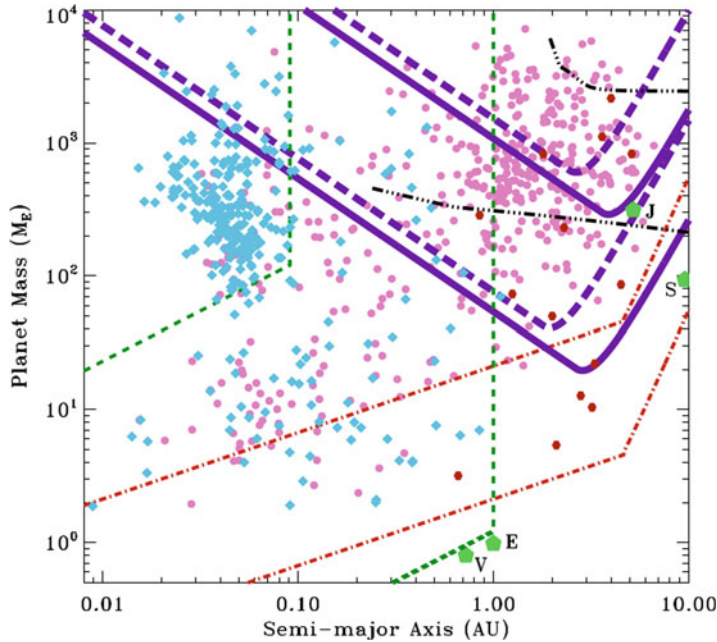
determination of the degree of dynamical stability of multiple-component systems.

Key Research Findings

Gaia's mode of operation (a signal-to-noise limited survey with uneven coverage, including time sampling and scanning geometry, depending on ecliptic latitude) is such that there cannot be any optimization to the case of extrasolar planets. The fundamental requirement, i.e., to have sufficient astrometric accuracy at magnitudes brighter than $V = 13$, was established at the time of the science case definition. Since little can be done with the photometric and spectroscopic capabilities aboard the satellite, which cannot compete with present and planned ground-based facilities for very-high-precision radial-velocity measurements (Pepe and Lovis 2008) and spaceborne observatories devoted to ultrahigh precision transit photometry (e.g., Sozzetti et al. 2010), the potential contribution of Gaia to exoplanet science must be primarily gauged in terms of its astrometric capabilities.

A number of authors have tackled the problem of evaluating the sensitivity of the astrometric technique required to detect extrasolar planets and reliably measure their orbital elements and masses (Sozzetti 2005, and references therein). The two most recent exercises on this subject (Casertano et al. 2008; Traub et al. 2010) have revisited earlier findings using a more realistic double-blind protocol. In this particular case, several teams of "solvers" handled simulated datasets of stars with and without planets and independently defined detection tests, with levels of statistical significance of their choice, and orbital fitting algorithms, using any local, global, or hybrid solution method that they judged was best. The solvers were provided no information on the actual presence of planets around a given target.

A double-blind test campaign to estimate the potential of Gaia for characterizing planetary systems (Casertano et al. 2008) showed that the following could be accurately modeled: (a) planets having an effect on the astrometric signature (α expressed in μ as) with a value around six times



Gaia Mission, Fig. 1 Exoplanet discovery space for Gaia astrometry, Doppler, transit, and direct imaging techniques. Detectability curves are defined on the basis of a 3σ (standard deviation) criterion for signal detection (except for direct imaging, for which a 5σ threshold is adopted). The purple upper and lower dashed curves are for Gaia astrometry with $\sigma_A = 20 \mu\text{as}$, assuming a $1 M_{\text{SUN}}$ G dwarf primary at 200 pc and a $0.4 M_{\text{SUN}}$ M dwarf at 25 pc, respectively. The two purple solid curves correspond to the expectations from a 10-yr extended Gaia mission. The radial-velocity curves (red lines) assume $\sigma_{\text{RV}} = 1 \text{ m/s}$ (upper curve, typical for HARPS-like instruments) and $\sigma_{\text{RV}} = 10 \text{ m/s}$ (lower curve, typical for ESPRESSO-like spectrographs), $M_* = 1 M_{\text{SUN}}$, and a 10-year survey duration. For visible-light transit photometry (green

curves), the assumptions are $\sigma_V = 5 \times 10^{-3} \text{ mag}$ (upper curve, typical for ground-based transit surveys) and $\sigma_V = 1 \times 10^{-5} \text{ mag}$ (lower curve, typical of the Kepler mission), $S/N = 9$, $M_* = 1 M_{\text{SUN}}$, $R_* = 1 R_{\text{SUN}}$, uniform and dense (>1000 data points) sampling. The upper dashed-dotted curve indicates the detection limits for SPHERE/VLT assuming a 250-Myr, $J = 8 \text{ mag}$ primary at 30 pc, while the lower curve is for a more mature primary (1 Gyr) at the same distance observed by PCS/E-ELT. Pink filled circles indicate the inventory of Doppler-detected exoplanets as of 2015. Transiting systems are shown as light-blue filled diamonds, while the red hexagons are planets detected by microlensing. Solar System planets are also shown as green pentagons. Reprinted with permission from Sozzetti and de Bruijne (2018)

the single-measurement error (σ expressed in μas) and orbital periods shorter than the nominal 5-year mission lifetime and (b) favorable configurations of two-planet systems with well-separated periods (both planets with a period inferior to 4 years, a ratio $a/\sigma > 10$, and redundancy over a factor of 2 in the number of observations). In the latter case, it is possible to carry out meaningful coplanarity tests (relative inclination of more than 10°).

Overall, Casertano et al. concluded that Gaia astrometry could allow the discovery and measurement of massive ► giant planets ($M_p > 2-3$

M_J) with an orbit semimajor axis between 1 and 4 astronomical units (au) orbiting solar-type stars as far as the nearest star-forming regions. Saturn-mass planets with similar orbital semimajor axes around late-type stars within 30–40 pc (see Fig. 1) could also be detected. From these results, using Galaxy models and with the current knowledge of frequency of exoplanets, it is possible to infer the number of planets of given mass and orbital separation that can be detected and characterized by Gaia. Table 1 demonstrates that Gaia's main strength will be its ability to accurately measure orbits and masses for thousands of giant planets

Gaia Mission, Table 1 *Top:* Number of giant planets that could be detected (N_d) and measured by Gaia around stars with $V < 13$ mag, as a function of increasing distance (Δd). Star counts (N_s) are obtained using models of stellar population synthesis (Bienaymé et al. 1987), while the

Tabachnik and Tremaine (2002) model for estimating planet frequency as a function of mass (ΔM_p) and orbital period (Δa) is used. *Bottom:* Number of planetary systems that Gaia could potentially detect and measure and for which coplanarity tests could be carried out successfully

Δd (pc)	N_s	Δa (AU)	ΔM_p (M_J)	N_d	N_m
0–50	1×10^4	1.0–4.0	1.0–13.0	1,400	700
50–100	5×10^4	1.0–4.0	1.5–13.0	2,500	1,750
100–150	1×10^5	1.5–3.8	2.0–13.0	2,600	1,300
150–200	3×10^5	1.4–3.4	3.0–13.0	2,150	1,050
Case			No. of systems		
Detection			~1,000		
Orbits and masses (<15% accuracy)			~400–500		
Coplanarity tests			~150		

and to perform coplanarity measurements of a few hundred multiple systems with favorable configurations.

Sozzetti et al. (2014) revisited the topics of giant planet detection and characterization with Gaia focusing on the sample of nearby low-mass M dwarf stars. They found that, given present-day estimates of the fraction f_p of Jupiter-mass companions to M dwarfs, comprehensive screening by Gaia of the reservoir of M dwarfs within 100 pc could result in ~2600 new detections and as many as 500 accurate orbit determinations. It would then be possible to provide estimates of f_p over ten times more precise than those available to date. Sozzetti et al. (2014) also determined that Gaia astrometry, by precisely measuring the orbital inclination, could alert us of the existence of tens of potentially transiting long-period planets. Finally, they gauged the ability of Gaia to accurately predict the ephemerides of (transiting and non-transiting) planets around M stars and its potential to help in the precise determination of the emergent flux, for direct imaging and systematic spectroscopic characterization of their atmospheres with dedicated observatories from the ground and in space.

Finally, Perryman et al. (2014) instead updated the Casertano et al. (2008) planet yield estimates based on an updated pre-launch astrometric error budget and extending the target magnitude interval to $V < 17.5$ mag.

They estimated that, for a 5-yr mission duration, 10,000–20,000 new giant planets might be discovered by Gaia within 500 pc from the Sun, a number that might as much as triple assuming a fully extended 10-yr mission. Figure 1 shows the expected improvements in accessible discovery space in terms of mass and orbital separation for a 10-yr Gaia mission.

Applications

Gaia’s main contribution to exoplanet science will be its unbiased census of planetary systems orbiting hundreds of thousands nearby ($d < 200$ pc), relatively bright ($V < 13$) stars across all spectral types, screened with constant astrometric sensitivity. **The sample of Gaia astrometrically detected planetary systems around bright stars will be the most amenable for a variety of follow-up measurements for improved system characterization.** The Gaia data have the potential to:

1. Significantly refine our understanding of the statistical properties of extrasolar planets: the predicted database of several thousand extrasolar planets with well-measured properties will allow, e.g., to test the fine structure of giant planet parameters’ distributions and frequencies and to investigate their possible changes as a function of stellar mass, metallicity, and age with unprecedented resolution.

2. Help crucially test theoretical models of gas giant planet formation and migration: for example, specific predictions on formation timescales and the role of varying metal content in the protoplanetary disk will be probed with unprecedented statistics, thanks to the thousands of metal-poor stars and hundreds of young stars screened for giant planets out to a few AU.
3. Achieve key improvements in our comprehension of important aspects of the formation and dynamical evolution of multiple-planet systems: for example, the measurement of orbital parameters for hundreds of multiple-planet systems, including meaningful coplanarity tests, will allow discrimination between various proposed mechanisms for dynamical interaction.
4. Aid in the understanding of direct detections of giant extrasolar planets: for example, actual mass estimates and full orbital geometry determination for suitable systems will inform direct imaging surveys about the epoch and location of maximum brightness, in order to estimate optimal visibility, and will help in the modeling and interpretation of giant planets' phase functions and light curves.
5. Provide important supplementary data for the optimization of the target selection for future observatories aiming at the direct detection and spectral characterization of habitable terrestrial planets: for example, all FGKM stars within the useful distance of ~ 25 pc will be screened for Jupiter- and Saturn-sized planets out to several AU. These data will help probe the long-term dynamical stability of their habitable zones, where terrestrial planets may have formed and maybe found.

Future Directions

An improvement of two to three orders of magnitude in achievable measurement precision, down to the μs level, would allow this technique to achieve in perspective the same successes as the Doppler method, for which the

improvement from the km/s to the m/s precision opened the doors for groundbreaking results in exoplanetary science. Indeed, μs astrometry is almost coming of age. The largest compilation of astrometric orbits of giant planets (in many cases, signposts of more interesting systems!), unbiased across all spectral types up to $d \sim 200$ pc, will allow Gaia to crucially contribute to several aspects of planetary system astrophysics (formation theories, dynamical evolution), in combination with present-day and future extra-solar planet search programs.

Cross-References

- [Exoplanets, Discovery](#)
- [Giant Planets](#)
- [Hipparcos](#)
- [Lagrangian Points](#)
- [Parallax](#)
- [Planetary Migration](#)
- [Proper Motion](#)

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Galactic Archaeology

Emma Fernández-Alvar¹ and Leticia Carigi²

¹Observatoire de la Côte d’Azur, Laboratoire Lagrange, Nice, France

²Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Keywords

Milky Way · Stars · Chemical tagging

Synonyms

[Near-field cosmology](#)

Definition

Galactic Archaeology aims to infer the formation, history, and evolution of the Milky Way from hints of the processes undergone in the Galaxy

and left on the stars now observable. Particularly, it focuses on the study of the chemistry, age, spatial distribution, and dynamical properties of the current stellar populations and gas clouds, and their comparison with chemical evolution models and cosmological simulations of galaxy formation.

History

The concept of Galactic Archaeology as the recovery of the Galaxy formation scenario from the detailed observations and characterization of its stellar populations was formally established by Freeman and Bland-Hawthorn (2002). They explained that the loss of orbit-information of substructures that fell into and formed the Galaxy can be partially compensated with the chemical tagging over samples of stars, that is, the identification of stellar populations formed in the same environment through their chemical abundances.

Copious research was made following this approach in the subsequent decades, mainly since 2000 with the arrival of large-scale spectroscopic surveys like the SDSS-SEGUE, RAVE, SDSS-APOGEE, GALAH, and LAMOST. However, an undoubtedly big milestone was achieved with the advent of the Gaia mission and in particular after its second data release on 25th April 2018. This mission provided distances and velocities of thousands of millions of stars in our Galaxy with unprecedented accuracy, revealing the Milky-Way configuration in a great detail and challenging our previous view about the Galaxy components.

Overview

The Universe started 13.8 billion years ago and was chemically composed of H and He, and some traces of Li; 100–200 million years after that, stars began to form, synthesizing chemical elements heavier than H (so-called metals) during their evolution. When stars died, they ejected these elements to the interstellar gas, enriching it with metals. Subsequent generations of stars formed

from such gas with increasing higher metallicity. Stars preserve most of the same chemical composition of the gas where they formed in their atmospheres.

The characteristics of a galaxy, like its mass or the surrounding environment, led to a particular star formation history that determines the galactic chemical enrichment evolution. This enrichment is reflected on the chemical composition of its stars now observable. According to the cosmological Lambda-Cold Dark Matter model, galaxies form hierarchically: small stellar systems form in sub-halos of gravitational potential that surround the main host halo into which they merge. Galactic Archaeology aims to identify such systems, the so-called building blocks of the Galaxy, based on chemical tagging and orbital, age, and spatial distribution of long-lived stars.

The interpretation of the observed stellar properties is performed based on the comparison with chemical evolution models and cosmological simulations of the galaxy formation.

Basic Methodology

Large-scale observational surveys provide comprehensive censuses of spectroscopy, photometry, astrometry, and asteroseismology of stars all over the sky. From such kinds of data, it is possible to measure the location, the orbital motion, the chemical composition, and the age of the stars. These censuses permit to build chrono-chemodynamical maps of the Milky Way with a robust statistical characterization of their stellar population properties and the better definition of their distributions across the Milky Way. The advent of large-scale surveys and the development of telescopes, spectrographs, cameras, and computational resources (and, thus, the accuracy in stellar parameters determination) significantly improved Galactic Archaeology in the last decades.

Some of the most important large-scale surveys that boosted Galactic Archaeology have been: in spectroscopy, at low-resolution, the SDSS, RAVE, and LAMOST, and at high-resolution, APOGEE, GALAH, and Gaia-ESO;

in photometry, 2MASS, SDSS, APASS, Pristine, and SkyMapper; in astrometry, UCAC, PPMXL, Hipparcos, and Gaia; finally, in asteroseismology, the Kepler Mission, K2, and TESS.

In addition, computational techniques developed for managing and processing big data, like clustering algorithms, neural networks, or data-driven modeling, also developed Galactic Archaeology optimizing the exploitation of data analysis.

The combination of spectroscopic, photometric, astrometric, and asteroseismologic products allows to derive the needed inputs for chemodynamical evolution models and estimate the Galactic star formation history. For instance, it is possible to constrain the mass of the stellar system where a stellar population was formed, the time of accretion of this system into the Galaxy, or whether the Galaxy underwent inflows or outflows of gas that boosted or quenched the star formation at different epochs.

On the other hand, the comparison of the observed properties of the Milky-Way with cosmological and N-body simulations that trace the evolution of a simulated galaxy over time allows to infer which accretion history and dynamical processes were able to configure a galaxy with similar properties as ours.

The contrast with external galaxy properties allows to understand the ubiquity of Milky Way characteristics in the Universe and the formation of galaxies based on the unique detailed individual-star analysis only available in the Milky Way.

The combination of all these patches of information builds the puzzle of the Galactic history.

Key Research Findings

The research of Galactic formation and evolution has largely benefited from Galactic Archaeology during the last decades, with some important discoveries summarized below for each galactic component:

Thick and Thin Disks

The galactic disk shows two main structures, a thin disk and a thick disk, both differentiated by

kinematics, α/Fe values, and ages of their stellar contents (see ► [Milky Way](#)). Based on cosmological simulations and the fact that thick disk stars are older than thin disk ones, most models predict that the thick disk formed before the thin disk had formed. Therefore, (i) the oldest stars of the thick disk may have formed in a gas-rich disk during burst of star formation events induced by early mergers. (ii) A fraction of these very old stars were dynamically heated by the last large merger (Gaia-Sausage-Enceladus or GSE; Belokurov et al. 2018; Helmi et al. 2018) of the Galaxy, occurred ~ 11 Gyr ago (Di Matteo et al. 2019; Gallart et al. 2019), and are now part of the stellar halo. (iii) The GSE merger also triggered a short (~ 2 Gyr) star formation event when most of thick-disk stars formed. (iv) The thin disk formed later, with some star formation induced from several gas-rich-smaller mergers. The accreted gas, after cooling down, has led the star formation up to now. (v) The galactic bar and spiral arms could have driven thin-disk stars of different ages from their birth place to other galactic locations.

Galactic Bulge

The Galactic bulge shows different stellar populations but is dominated by metal-rich, high- α/Fe , and old stars. Some of these stars present cylindrical rotation and form a barred structure, and others orbit at high altitudes tracing a box/peanut structure. These stars may have formed in the inner disk, during the first ~ 2 Gyr evolution and were heated dynamically by an early bar. Nevertheless, differences in some chemical elements (e.g., Na and Mn) between the bulge and disk stars point out that the bulge may have formed separately via another mechanism, as strong (poor/rich) gas inflows, mergers of dwarf galaxies, and migrations of clumps through the early disk toward the MW center (Queiroz et al. 2021). Its globular clusters show a tendency to be more metal poor and older than the halo ones. Some of the bulge field stars have likely been members of these globular clusters (e.g., Fernandez-Trincado et al. 2021).

Galactic Halo

It is referred to as the Galactic stellar halo those stars whose orbits differ from the rotating disc, with larger vertical and radial velocities. Thus, they populate a spherical halo that surrounds the disc. The Gaia mission helped to clarify the origin of these stars as, mainly, the remnants of the GSE-accreted satellite galaxy, and the ancient disc stars heated by such merger. Furthermore, other stellar structures have been identified in chemical and dynamical space, but it is still unclear whether they belong to the same accreted structure or are remnants of other less-massive accreted satellites.

Because the dynamical timescales are longer further from the Galactic center, the records of accretion events remain observable for several Gyrs in the halo. Indeed, several substructures like streams of stars have been detected covering the whole sky (Bernard et al. 2016), confirming the predictions of the cosmological paradigm of hierarchical galaxy formation.

Globular Clusters

Globular clusters (GC) are mainly located in the halo and bulge and mostly are constituted by more than one stellar population of metal-poor old stars. They may be fossil cores or lumps of the galactic building blocks that were tidal stripped by the main halo and sub-halos during the galactic accretion. The tidal mechanism and the interaction among the GC stars disrupted clusters, making that some of its stars escaped to the halo and the cluster became more compact. For bigger GCs, the different populations could form in bigger satellites during diverse star formation episodes, before the falling towards the halo. For smaller globular clusters (and bigger ones after being accreted), their stars were chemically auto-polluted due to the own stellar evolution, or polluted by companion stars, due to the high stellar density.

Since Omega Centauri is the most massive GCs in the Milky Way, presents metallicity-differentiated populations, and has a retrograde orbit (its rotational motion is opposite to the rotation direction of most galactic stars);

this globular is one of the best candidates for being a compact and remnant core of an accreted dwarf galaxy. More recently, Massari et al. (2019) proposed Omega Centauri would be the nucleus of the Gaia-Enceladus Sausage satellite galaxy, given its mean age and metallicity.

Future Directions

Up to date, there is still not a complete and consistent explanation about the formation and evolution of the Galaxy in the cosmological framework. Therefore, some directions have already been projected into the future.

In particular, the current instrumentation prevents to observe faint stars and, thus, a comprehensive mapping of the distant Galactic regions and the characterization of external galaxies. In addition, dust extinction hinders the observation of the inner Galaxy. Upcoming surveys aim to defy such limits, with larger telescopes like the LSST, the ELT, or the MSE, and next generations of spectrographs, like WEAVE or DESI. Some of the next high-resolution spectroscopic surveys will be MOONS, 4MOST, and PFS.

From the theoretical side, computer science development is also necessary for improving cosmological hydrodynamic simulations of Milky-Way-like galaxies. In particular, increasing the spatial resolution, including more and better physical processes, and better implementing the inter-dependence of astrophysical processes.

Finally, another future direction concerns the exploitation of the upcoming extremely large multidimensional databases. There are current claims to organize an International Consortium to pursue the optimization of Galactic Archaeology performance in terms of gathering all the information available from different sources in a database, homogenizing the measurements from data obtained by different instrumentation and derived by distinct methodologies, and exploring all the scientific potential of the data. Interdisciplinary work between mathematics, engineering, science, and data inference is desired.

Cross-References

- [Abundances of Elements](#)
- [Gaia Mission](#)
- [Galaxy](#)
- [Metallicity](#)
- [Milky Way](#)
- [Stellar Populations](#)

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Galactic Habitable Zone

Nikos Prantzos¹ and Leticia Carigi²

¹Institut d'Astrophysique de Paris, Paris, France

²Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

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Habitable zone · Intelligent life · Extraterrestrial civilization

Definition

A galactic habitable zone is the putative region inside a galaxy with physical conditions compatible with the origin, development, and long-term existence of life-as-we-know-it. Minimum requirements are the existence of enough heavy chemical elements to form Earth-like planets and a low occurrence of catastrophic events (e.g., supernovae, close stellar encounters) in order to allow the evolution of complex life forms.

Overview

The idea underlying the concept of **galactic** habitable zone (GHZ) is that various physical processes, which may favor the development or the destruction of life, may depend strongly on the temporal and spatial position in a galaxy. For instance, the risk of cosmic explosions (e.g., supernovae, gamma-ray bursts) sufficiently close to represent a threat for life is in general larger in the inner galaxy than in the outer one and so is the metallicity (for astronomers, the abundance of elements heavier than helium) of the interstellar medium, which may be important for the formation of Earth-like exoplanets. Assuming that all relevant factors (hostile or beneficial to complex life) can be properly quantified, one may use models of galactic evolution in order to evaluate the position and extent of the GHZ over time. Preliminary attempts gave

controversial results as to the extent of the GHZ of the Milky Way disk, because of the difficulty in properly evaluating the relevant factors, mainly the chemical requirement to form terrestrial planets.

It is hard to quantify the role of metallicity in planetary formation and even harder to draw any quantitative conclusions about the probability of definitive sterilization of a habitable planet. **In the coming years, ongoing (KEPLER, TESS) and future (LUVOIR, PLATO) exoplanet surveys combined with planet formation studies will help to understand the role of metallicity in planetary formation.**

Life displays unexpected robustness and a cosmic catastrophe might even accelerate evolution toward life forms that are presently unknown. Studies of GHZ focused mainly on the Milky Way disk, while the Milky Way halo (presumably too metal poor to allow for planetary formation) and bulge (presumably too dense to avoid frequent catastrophes there) appear – perhaps incorrectly – as less interesting abodes for complex life. The GHZ has recently been computed using cosmological numerical simulations for different types of galaxies (Forgan et al. 2017; Stojković et al. 2019). Few of those studies include kinematic and dynamic aspects of the stars and their planetary systems. These issues are fundamental to infer galactic regions where potentially habitable planets form, if stars have migrated. In addition, the stability of planetary orbits can be affected by the proximity of stars. The concept of GHZ is much more poorly defined than the one of circumstellar habitable zone. At present, it should be considered, at best, as a broad framework, allowing us to formulate our thoughts about a very complex phenomenon such as life (origin, development, and survival) in a galactic environment.

Cross-References

- [Abundances of Elements](#)
- [Exoplanets, Discovery](#)
- [Habitable Zone](#)

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dwarf spheroidals) are less massive than the most massive ► [globular clusters](#).

Cross-References

- [Globular Cluster](#)
- [Milky Way](#)
- [Stars](#)

Galilean Satellites

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

Galaxy

Nikos Prantzos
Institut d’Astrophysique de Paris, Paris, France

Definition

A galaxy is a massive, gravitationally bound system of ► [stars](#), which may also include stellar remnants (white dwarfs, neutron stars, black holes), gas, and dust, as well as nonbaryonic dark matter. The morphological classification of galaxies, established by E. Hubble in the 1930s, includes ellipticals, spirals, and irregulars, each class divided in subclasses and going from “early types” (generally more massive and gas poor, which is the case for ellipticals) to “late types” (less massive and gas rich, as the irregular galaxies). Galaxies are generally found in groups (up to a few tens of members), clusters (a few thousands), and superclusters. Our own ► [Milky Way](#), often called the Galaxy, is a large spiral with a baryonic mass of $\sim 5 \times 10^{10} M_{\odot}$, slightly smaller than the largest of the Local Group galaxies (M31 or Andromeda). There is no universally accepted definition of a galaxy, nor a clear lower limit on its stellar mass: some systems characterized as “galaxies” (tidal dwarfs, ultracompact

Synonyms

[Jupiter’s biggest moons](#); [Medicean Stars](#)

Definition

At the night of 7 January 1610 the Italian physicist and mathematician Galileo Galilei (1564–1642) observed the planet Jupiter with a telescope made by him and saw what he thought were three fixed stars near it. In subsequent observations made in the following nights Galileo found that the bright spots were not three but four and not fixed stars but rather planetary bodies that revolved around Jupiter, since their positions related to the planet had changed over those nights. Those four biggest Jupiter’s moons, or Medicean Stars as Galileo named them, are: Io, Europa, Ganymede, and Callisto (today Jupiter registers 50 moons and 16 provisional moons). The Galilean satellites are quite different from each other. Ganymede is the largest moon in our Solar system and is the only moon known to have its own internally generated magnetic field. Io has a volcanic nature. The surface of Europa is mostly water ice (it is believed that it has twice the water existing on Earth), and Callisto shows an extremely heavily cratered and ancient surface.

Galileo (55 Cancri b)

► 55 Cancri

Galileo Galilei

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Galileo Galilei (1564–1642) is one of the most famous astronomers over the whole history of humanity. With the telescope he designed, he was able to make major discoveries that supported and reinforced the new heliocentric theory proposed by Nicolaus Copernicus that drastically modified our view of the world.

Overview

Galileo, born in Pisa in Italy, started to learn medicine and then turned to mathematics. After a first stay in Pisa, in 1592 he got a chair of mathematics at Padua University. In 1604, on the occasion of the apparition of a new star in Sagittarius, he gave three public lectures on the “Nova,” showing from the absence of ► [parallax](#) that the star was at a great distance from Earth and thus challenging Aristotle’s views about the unchangeability of celestial bodies.

In 1609, Galileo took advantage of new research about spyglasses in Holland to develop the first concept of an astronomical telescope. In August 1609, he presented the Doge of Venice with his first instrument. In January 1610, with a 20-times magnifying instrument, he made the historical discovery of the four big satellites of ► [Jupiter](#), which he called “Medicean” in honor of Cosimo de Medici, Duke of Tuscany (they are now known as the Galilean satellites). This

discovery, together with the irregular shape of the Moon’s surface and the multitude of stars forming the Milky Way, was reported in the historical manuscript “*Sidereus Nuncius*,” published early in 1610. Still in 1610, Galileo observed Venus’ phases, supporting a heliocentric solar system, moving sunspots, and the changing shape of Saturn that he was not able to interpret, but which was in fact due to Saturn’s rings. These results were reported in Galileo’s *Discourse on Bodies in Water* in 1612 and “Letter on Sunspots” in 1613.

In 1616, after the Roman Congregation of the Index banned Copernicus’s *De Revolutionibus* as being “contrary to Scriptures,” Galileo was forced to abandon his plans for a Copernican treatise. He came back to resume his work in 1623, when Pope Urban VIII, an admirer of Galileo’s work, became elected. However, in 1632, his *Dialogue Concerning the Two Chief Worlds Systems* raised the hostility of the Roman theologians; Galileo was summoned to Rome and put on trial. He was forced to abjure publicly the prohibited claims of the Earth’s motion and the Sun’s being at rest and was sentenced to house arrest. His last manuscript “Two New Sciences,” published in Holland in 1638, was devoted to mechanics.

Among the many discoveries that were made possible by Galileo’s telescope, the discovery of the four Galilean satellites probably had the most important implications for astronomy. In contrast with Aristotle’s doctrine, they demonstrated that there is more than one center of rotation in the solar system. By computing the exact periods and the times of mutual ► [occultation](#) of the four satellites, Galileo provided navigators with a method for measuring the longitude from anywhere at sea. Later, the exact timing of Io’s occultations allowed the astronomer Olaf Roemer to get a first estimate of the speed of light; his measured speed was 30% lower than the presently accepted value.

Cross-References

- [Callisto](#)
- [Europa](#)

- [Galilean Satellites](#)
- [Ganymede](#)
- [Io](#)
- [Jupiter](#)

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Galileo Mission

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The ► [NASA](#) Galileo mission was launched from Cape Canaveral on October 18, 1989, on board the Space Shuttle Atlantis. The spacecraft and the inertial upper stage were released and fired for a 6-year trip in the solar system, heading to Venus, then to the Earth to perform three gravity-assisted maneuvers, before finally cruising toward ► [Jupiter](#).

Overview

On December 7, 1995, a Jupiter probe released from Galileo entered the Jovian atmosphere with a parachute and transmitted data, relayed by the main spacecraft, for more than 59 min. Then, using the main engine, Galileo was inserted in an elliptic 2-month-long orbit around Jupiter. During the primary (11 orbits) and the extended (14 orbits) mission, Galileo flew by and analyzed most of the Jovian satellites. The mission

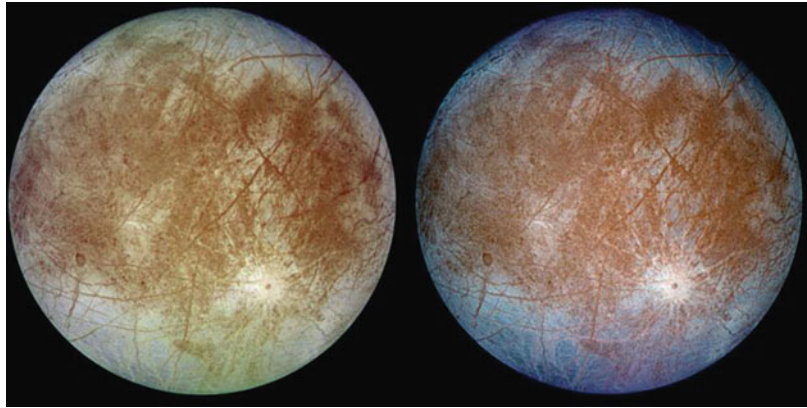


Galileo Mission, Fig. 1 The Galileo spacecraft preparation at Kennedy Space Centre. (Photo NASA)

was extended several more years. Galileo made numerous discoveries about Jupiter and its moons. One of the most striking was the evidence of an ocean below the icy crust of ► [Europa](#). The measures of the induced ► [magnetic field](#) for Europa (as for ► [Callisto](#)) while orbiting through the strong Jovian magnetic field were consistent with the presence of conducting layers. This feature may best be explained by the presence of deep salty liquid-water oceans, for which there was already indirect geological evidence (in the case of Europa, see references). Because of the potential existence of such an ocean, NASA decided to destroy the spacecraft at the end of the mission by entering Jupiter's atmosphere, in order to avoid any possible crash on, and contamination of, Europa. Galileo entered the Jovian atmosphere September 21, 2003, at 19 h 49 GMT after 35 orbits. Europa and its ocean constitute one of the major targets of relevance for astrobiology (Figs. 1 and 2).

Galileo Mission,

Fig. 2 Europa mosaic image in true and false colors. (Photo Nasa)



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Gamma Cephei

Nader Haghighipour
Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Definition

Gamma Cephei (γ Cephei, γ Cep) is a binary star system in which the primary star, Gamma Cephei A, is orbited by a Jupiter-mass planet.

Overview

In 1988, in an article on the analysis of the measurements of the variations in the radial velocities of a number of stars, Campbell, Walker, and Yang reported an interesting phenomenon: The radial velocity variations of γ Cephei seemed to suggest the existence of a Jupiter-like planet around this star (Fig. 1). This was a very exciting and, at the same time, very surprising discovery. It was

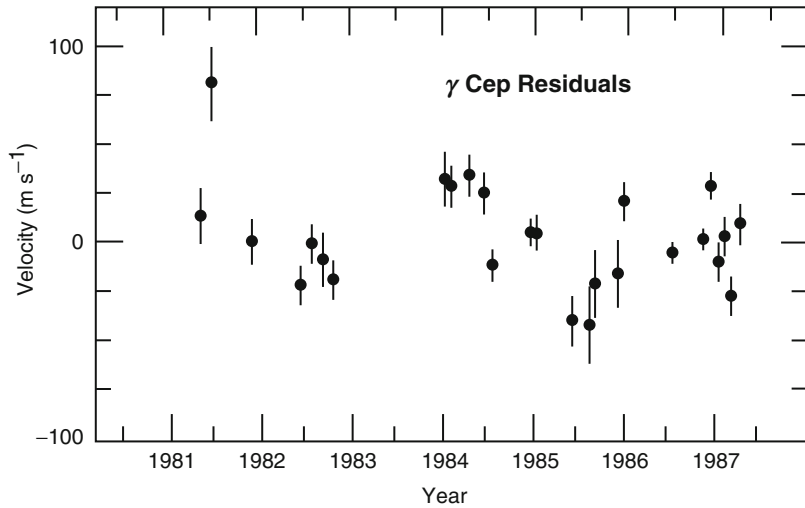
exciting because if true, it would have marked the detection of the first planet outside of our solar system. It was surprising because the planet-hosting star is the primary of a binary system with a separation of ~ 20 AU, a distance comparable to the planetary distances in our solar system.

The moderately close orbit of the stellar companion of γ Cephei raised questions about the reality of its planet. The skepticism over the interpretation of the results (which was primarily based on the idea that binary star systems with small separations would not be favorable places for planet formation) became so strong that in a subsequent paper in 1992, Walker and his colleagues suggested that the planet in the γ Cephei binary might not be real, and the variations in the radial velocity of this star might have been due to its chromospheric activities.

Despite the 1992 article, the search for planets in binaries did not stop. Gamma Cephei was continuously monitored and more precise measurements of its radial velocity variations were obtained. In 2003, 15 years after the first announcement of the planet of this system, these efforts bore fruit, and in an article in *Astrophysical Journal*, Hatzes and his colleagues confirmed the existence of a Jupiter-like planet around the primary of γ Cephei (Fig. 2). The parameters of the system were later refined by Endl et al. 2011 and Benedict et al. 2018. As the planet became real, it

Gamma Cephei,

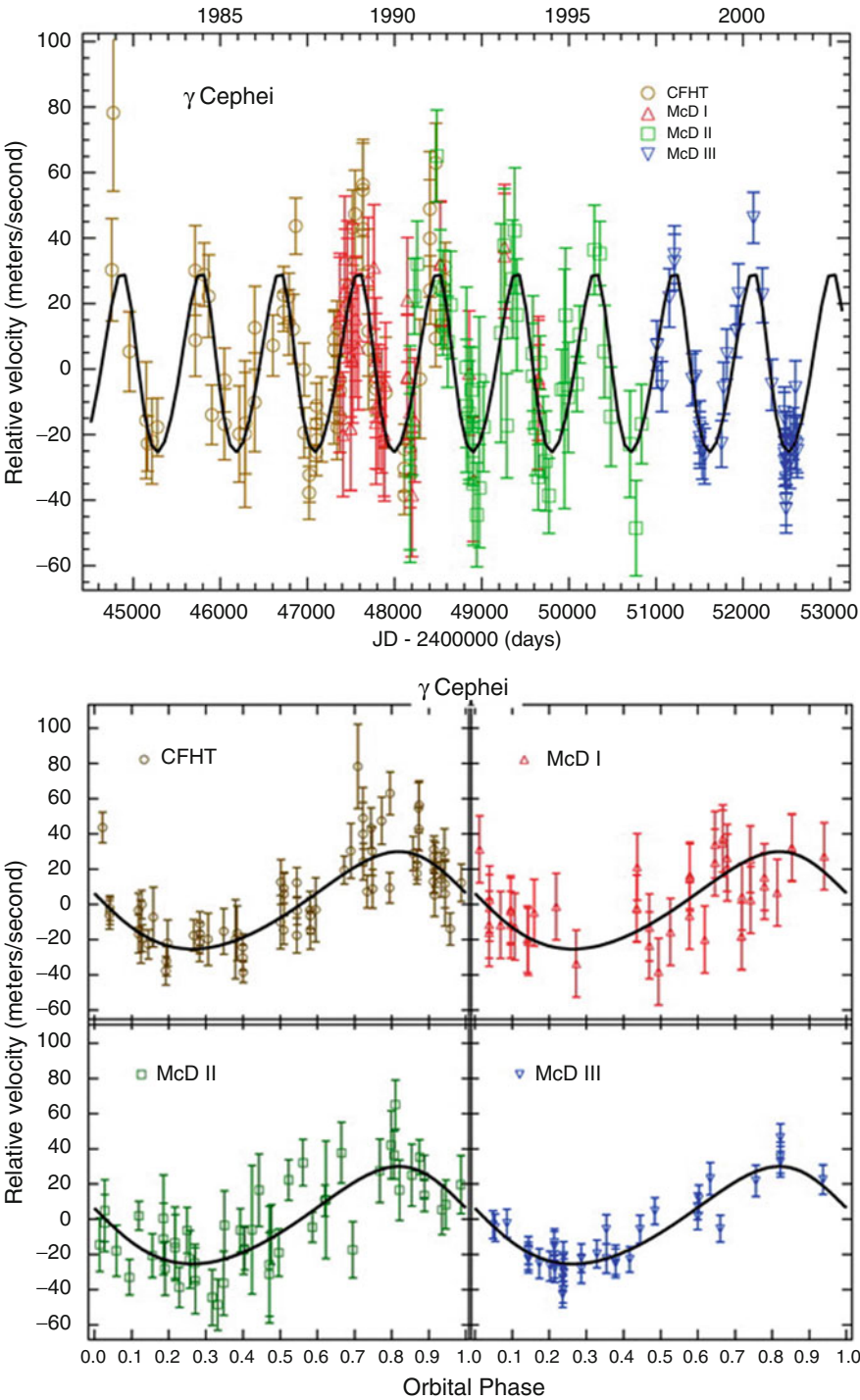
Fig. 1 Radial velocity residuals for γ Cephei after the subtraction of the second order fit to the original radial velocity data (Campbell et al. 1988)



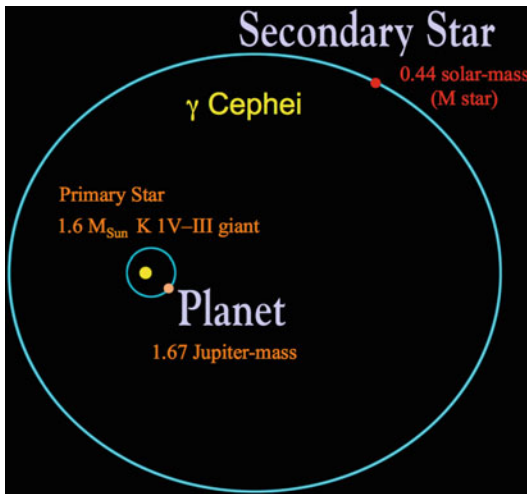
introduced many challenges to planetary science. Figure 3 shows a schematic figure of this system.

The 2003 confirmation of γ Cephei's planet, and the subsequent detection of giant planets in other moderately close binary stars such as GL 86 (e.g., Stassun et al. 2017), HD 41004 (e.g., Zucker et al. 2004), HD 196885 (e.g., Fischer et al. 2009), and HD 176051 (e.g., Muterspaugh et al. 2010), marked the beginning of a new era in theoretical and observational research on planets in dual-star systems. During the past few years,

much research has been carried out in this area, and a large number of excellent articles have been published on different aspects of observational and theoretical studies of planets in moderately close binaries. For more details, see the book, *Planets in Binary Star Systems* (Haghighipour 2010), the more recent review of Welsh and Orosz (2018) on the binaries in the Kepler data, and check the website <https://www.univie.ac.at/adg/schwarz/multiple.html>.



Gamma Cephei, Fig. 2 Radial velocity measurements of γ Cephei (As reported by Hatzes et al. (2003) obtained at the CFHT (Canadian, French, Hawaii Telescope) and the McDonald observatory)



Gamma Cephei, Fig. 3 Schematic view of the binary star and planetary orbits of γ Cephei system

Cross-References

- [Binary Stars, Young](#)
- [Radial-Velocity Planets](#)

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Gamma Rays

Kazumichi Nakagawa

Sanken, Osaka University, Ibaraki City, Osaka, Japan

Keywords

Electromagnetic wave · Radiation

Synonyms

[High-energy photons](#); [High-energy radiation](#)

Definition

Gamma rays are electromagnetic waves with high photon energy. Gamma rays are emitted (1) via transitions between quantum levels of nuclei and elementary particles, (2) via particle-antiparticle annihilation, and (3) via bremsstrahlung (photon emission due to interaction between the strong magnetic field of nuclei and high-energy particles in the vicinity of the nuclei). Gamma rays interact with matter through (1) photoelectron emission, (2) Compton scattering with electrons, (3) creation of electron-positron pairs, and (4) nuclear photoreactions.

Overview

As the result of the interaction of a gamma ray with matter, the gamma ray photon is annihilated and its energy is transferred to an electron. The

resulting high-energy electron will interact with other electrons in the matter to ionize or excite molecules or atoms and will gradually dissipate its energy to produce large numbers of high-energy electrons in the system. Subsequent radiation chemistry due to these high-energy electrons will be responsible for chemical processes. Chemical evolution or molecular damage are the result of this radiation chemistry. According to Platzman (1962), the magnitude of the radiation chemical effect G due to an electron with initial kinetic energy E_0 is expressed as

$$G \propto \int_{IP}^{E_0} \frac{1}{E} \frac{df}{dE} dE$$

where IP is the ionization potential of the system and df/dE the optical oscillator strength distribution, which is proportional to the absorption cross sections.

In order to evaluate the radiation chemical effect caused by gamma rays, the energy efficiency G -value (number of chemical events per 100 eV absorbed) is essential, instead of the photon efficiency or quantum yield (number of chemical events per one absorbed photon). For radiation chemistry, the magnitude of the G -value should be proportional to the incident photon energy $h\nu$ of the gamma rays because the incident photon energy is divided into the small value of IP . The value of $h\nu/IP$ is about 10^5 in the case of $h\nu = 1$ MeV and $IP = 10$ eV.

On the contrary, for photochemistry in which photon energy is ordinarily smaller than 10 eV, the reaction cannot occur if the photon energy is not resonant with the excited state which is responsible for the characteristic transition.

Chemical effects induced by higher-energy photons such as gamma rays, X-rays, and ultraviolet light are similar to each other. It is known that the chemical effects include decomposition, dimerization, polymerization, and ionization. Gamma ray-induced racemization and decomposition of amino acids was reported by Bonner et al. (1985). Dimer formation of alanine molecules induced by X-rays was reported by Kaneko et al. (2005).

Cross-References

- [Radiation Biology](#)
- [Radiochemistry](#)
- [Radiolysis](#)

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Ganymede

Therese Encrenaz
Observatoire de Paris – Section de Meudon,
LESIA, Meudon, France

Keywords

Galilean satellites

Definition

Ganymede is the third Galilean satellite in terms of its distance from Jupiter; on the other hand, it is the biggest satellite in the solar system: it is bigger than the planet Mercury. Like the other Galilean satellites, Ganymede was discovered in January 1610 when Galileo Galilei first pointed his refractor toward Jupiter. It was named by Simon Marius (1614) after a lover of Zeus, who corresponds to Jupiter in Greek mythology. Ganymede's average distance to Jupiter is slightly above 1 million kilometers or about 15 Jovian radii. Ganymede's density is 1.9 g/cm^3 , typical of a 1:1 mixture of water ice and rocks. Water ice was identified at Ganymede's surface as early as 1971 through ground-based near-infrared spectroscopy.

Overview

The space exploration of Ganymede started with the Voyager 2 flybys in 1979 and was followed after 1995 by the Galileo orbiter that operated until 2003.

The surface of Ganymede, as revealed by Voyager and Galileo images, is composed of dark and bright terrains. The old dark terrains are heavily cratered and made up of patchy features of different albedos; the dark material probably corresponds to organic deposits provided by asteroid and comet impacts. The dark regions are fractured by tectonic activity and impact craters, many of them being the signature of the ► [late heavy bombardment](#). Bright terrains show smooth, young areas with grooves and stripes resulting from tectonic activity. These terrains cover three quarters of Ganymede's surface and seem to have been resurfaced mostly by tectonic activity and also partly by active volcanism (possibly ► [cryovolcanism](#)).

The unexpected discovery of an intrinsic magnetic field on Ganymede, by the radio science instrument and the magnetometer of the Galileo mission, strongly suggests that the satellite's interior is differentiated and contains a melted iron nucleus at the center. This magnetic field induces a small stable ► [magnetosphere](#) 5000 km in radius where high-energy particles, radiation belts, and auroras have been observed. Ganymede's magnetosphere, generated by its magnetic field, is in electrodynamical interaction with the Jovian magnetic field through a permanent magnetic reconnection. It acts like a shield that allows the existence of an extended ionosphere, uncompressed by the Jovian magnetic flux.

The interior of Ganymede appears to be differentiated in four layers, with a central metallic core, a silicate mantle, a deep layer of soft ice, and a water ice crust. According to models, a liquid layer of salted water could be present below the surface, sandwiched between two layers of ice. Convection through the icy outer layer transfers the internal heat to the surface. The internal heat comes from radioactive elements within the silicate mantle, from gradual cooling, and possibly

from tidal heating (although less efficiently than in the case of ► [Io](#) and ► [Europa](#)) in Ganymede's past history.

In 2012, ESA selected a space mission devoted to the exploration of Ganymede and the Galilean satellites, with the main purpose of exploring habitability conditions in icy moons. The JUICE mission (JUperiter and ICy moons Explorer) is planned for a launch in 2022. It will approach Jupiter in 2031 and, after a series of flybys, will enter the orbit around Ganymede in 2034 for an in-depth monitoring of the satellite.

Cross-References

- [Cryovolcanism](#)
- [Europa](#)
- [Io](#)
- [Jupiter](#)

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Gas Chromatography

Jennifer C. Stern
Planetary Environments Laboratory, NASA
Goddard Space Flight Center, Greenbelt, MD,
USA

Synonyms

[GC](#)

Definition

Gas chromatography is a laboratory analytical method for separating volatile components of a mixture as they are passed in a gaseous mobile

phase past a stationary phase or through a column. Separation of molecules is based on differences in the affinity of species for the mobile and stationary phases, which may be influenced by polarity, molecular weight, and volatility. Gas chromatography is often coupled with a detector to quantify and/or identify molecular species. Detection methods include flame ionization, thermal conductivity, and mass spectrometry. Gas chromatography has been used for organic analysis on Mars missions, including ► [Viking](#) and the 2011 Mars Science Laboratory (MSL).

Cross-References

- [Chromatographic Coelution](#)
- [Chromatography](#)
- [GC/MS](#)
- [Viking](#)

Gas Chromatography/Mass Spectrometry

- [GC/MS](#)

Gas Drag

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Keywords

Migration

Definition

Gas drag is a force operating on a body moving through a gaseous medium, which causes the body to lose momentum and energy. The dynamical interactions with the surrounding gaseous

material act in the opposite direction to the motion of the body. Gas drag is primarily important in planetary dynamics because it functions as one of the main processes that remove energy from orbiting bodies in a dense gaseous ► [protoplanetary disk](#), where it causes loss of orbital momentum and decrease in orbital eccentricity, inclination, and semimajor axis of a body in ► [orbit](#) around the central star. Gas drag is more significant for small (less than 100 km) bodies.

Cross-References

- [Orbit](#)
- [Protoplanetary Disk](#)

Gas Giant Planet

Daniel Rouan
LESIA Observatoire de Paris - PSL, Meudon,
France

Definition

A Gas Giant Planet is an expression often used to designate the class of extrasolar planets that are of a type analog to the most massive giant planets in the Solar System, Jupiter and Saturn. They are characterized by a big mass (say larger than 100 times the Earth's mass) which implies that they must have an extended gaseous envelope and a rather low density. Indeed, in the various cases where both the mass and the size were measured, massive exoplanets feature a density well within the expected range where are found the solar system's giant planets ($0.7\text{--}1.7\text{ g cm}^{-3}$).

Cross-References

- [Jupiter](#)
- [Saturn](#)

Gas-Grain Chemistry

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA
Goddard Space Flight Center, Greenbelt,
MD, USA

Keywords

Molecular clouds · Interstellar chemical processes

Definition

Gas-grain chemistry is the study of the chemical processes involving solid dust grains embedded in interstellar/circumstellar gas. Generally, these are loss of atoms and molecules from the gas to the grains, catalytic reactions on surfaces, and return of surface species to the gas phase.

Overview

There are four basic processes: (1) Gaseous atoms and molecules collide with, and stick to, dust grains at low temperatures. The net effect is the depletion of these species in the gas. (2) Adsorbed surface species can migrate, meet, and react leading to new ► [radical](#) and closed shell molecules. Such reactions lead to the conversion of hydrogen atoms to molecules and to the growth of ice mantles on the grain cores. These ices are dominated by water and also contain CO, CO₂, methanol, methane, and ammonia as well as more complex organic molecules. (3) The third is desorption and the consequent return of surface species to the gas. Several processes can remove material from the icy mantles, including photoejection by UV photons, thermal evaporation due to grain heating by cosmic ray impacts or by photon absorption near ► [protostars](#), and ► [sputtering](#) in ► [shock waves](#). (4) The last is the chemistry in the hot gas into which whole or partial removal of the ice mantles has occurred. In this case, it is possible to synthesize many even

more complex molecules by gas-phase ► [neutral-neutral](#) and ► [ion-neutral reactions](#).

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Molecular Depletion](#)
- [Molecules in Space](#)
- [Protostars](#)
- [Radical](#)

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Gaspra

Stefano Mottola
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

(951) Gaspra is a main-belt asteroid named after a Crimean town located on the Black Sea. It was the first asteroid to be visited by spacecraft, when the NASA Galileo probe approached it on its course to Jupiter. The analysis of the Galileo images revealed a body approximately $18 \times 10 \times 9$ km in size, with an irregular shape and with a comparatively young surface age between 30,000 and 300,000 years. The body probably originated in a disruptive collision that created the Flora asteroid family, which is believed to comprise about 10^3 objects. Gaspra is classified as an S-type asteroid,

and its surface displays the spectral signature of mafic minerals. Galileo images confirmed the presence of subtle color variations across its surface, which had been previously detected by ground-based observations and which are interpreted as the manifestation of downslope movement of regolith.

GC

► [Gas Chromatography](#)

GC/MS

Henderson James CleavesII
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Gas chromatography/mass spectrometry](#)

Definition

In chemistry, gas chromatography/mass spectrometry (GC/MS) is an analytical method that combines a gas chromatograph and a mass spectrometer. GC/MS was first developed in the 1950s by Gohlke and McLafferty. The gas chromatography uses a capillary column, which may have variable column dimensions (length and diameter) and stationary phase attributes (composition and thickness). The differences in the chemical properties between the molecules in a mixture cause them to migrate with different velocities as they travel the length of the column. As the molecules exit the GC, they are fed into the mass spectrometer where they are ionized and detected using their mass to charge ratio.

These two components, used together, allow a much more precise identification of compounds than would be accomplished using either instrument alone. Sometimes two different molecules can have similar retention times, as measured by GC, or have a similar mass spectrum, but it is extremely unlikely that two different molecules will have the same GC and MS response. Often a third dimension is added to GC/MS analysis, either an extra GC column in GC/GC/MS or an extra MS dimension in GC/MS/MS, both of which further refine the quality of analysis.

Several GC/MS instruments have been sent on space missions. The Viking landers both carried GC/MS instruments to Mars and the Huygens probe studied the atmosphere of Saturn's moon ► [Titan](#) using GC/MS. However, the American Pioneer and Russian Venera 11 and 12 landers analyzed Venus' atmosphere using GC and MS separately.

Cross-References

- [Gas Chromatography](#)
- [Huygens Probe](#)
- [Mass Spectrometry](#)
- [Rosetta Spacecraft](#)
- [Titan](#)
- [Viking](#)

GCM

Thomas Navarro
McGill Space Institute, McGill University,
Montréal, QC, Canada

Keywords

Atmosphere · Climate · Numerical model ·
Atmospheric circulation · Clouds ·
Habitability

Synonyms

[General Circulation Model](#), [Global Climate Model](#)

Definition

A General Circulation Model (GCM) is a three-dimensional numerical model of the atmosphere of a planetary body, based on universal physical equations. It aims to simulate all the physical processes in an atmosphere, such as the air motions, temperature structure, or cloud formation. The development of a GCM usually requires extensive amounts of work. GCMs are a cornerstone in the fields of meteorology, weather forecast, and climate sciences. In particular, a GCM is a tool of choice to obtain hints on the possible climate for atmospheres distant in space (extraterrestrial planets) and time (e.g., early Earth).

History

The development of a numerical model of the atmosphere has long been driven by the need to predict weather. In the early twentieth century, Richardson attempted to integrate the equations governing the atmospheric motions by hand, and failed spectacularly because high frequency waves – that could not be handled in his numerical scheme – were present in the initial conditions. With the advent of computers, the first numerical weather predictions were made in 1950 with operational real-time forecast in 1960s, and such subsequent efforts became a great incentive to develop supercomputers for GCMs (Kalnay 2003).

While GCMs were initially developed for weather purposes (hence their initial name “General Circulation Model”), they became a crucial aspect of climate projections to assess climate change and were eventually dubbed “Global Climate Model.” GCMs have become key for revealing the mechanisms and the expected impacts of climate change and thorough, vast efforts of intercomparison of the most advanced GCMs are regularly conducted to assess their accuracy (Eyring et al. 2016).

The adaption of Earth GCMs to extraterrestrial atmospheres was first conducted for Mars (Leovy and Yale 1969), with tremendous success in predicting the global circulation patterns and

temperature structure before detailed observations became available. Later on, successful adaptations to other planets and moons in the Solar System (Venus, Titan, Jupiter, Saturn, Triton, and Pluto) confirmed that GCMs are able to catch the main features of any planetary climate. This led to the exploration of the habitability of Earth and Mars and their distant past, and the climate of exoplanets, for which observations are very scarce or nonexistent.

Today, a plethora of GCM codes exist, developed and maintained by various research teams all over the world.

Overview

A GCM is a numerical model of the atmosphere and possibly other systems, such as the ocean, the land, the surface and sea ice, or the upper atmosphere. It has been applied for Earth and all planetary bodies with an atmosphere. GCMs are very important, and often indispensable, tools to assess the palette of climates of a planet or a moon. They provide crucial information for worlds difficultly accessible (Solar System planets), completely out of our reach (ancient or future climates, exoplanets). Although GCMs are based on the universal laws of physics, they are perfectible and have been increasing in complexity and capability, notably to address the habitability of distant worlds.

Basic Methodology

A GCM is a numerical model built on the universal laws of physics, which ultimate purpose is to build a virtual planet able to give a realistic view of the climate of any planetary body. At the core of a GCM is the atmosphere, made of two main distinct components: a dynamical core (dubbed the “dynamics” part) and physical parameterizations (the “physics” part). The dynamics part numerically solves the Navier-Stokes equations, whereas the physics part takes into consideration all other physical processes taking place into the atmosphere. The physics part generally includes

the radiative transfer of gas and aerosols, convection, cloud formation, chemistry, and exchanges of energy and materials with surface. The division between dynamics and physics allows scientist to run each part independently for model development, validation, or simplified atmospheric modeling. This modularity also opens the possibility to swap parts of independently developed GCMs to further develop and validate models. A GCM can be coupled with other components of the climate system, for instance with numerical model for the oceans, atmospheric chemistry, thermosphere, surface processes, or biosphere.

Dynamics

The primitive equations are a set of equations that described the motions of an atmosphere, by the conservation of momentum, energy, and mass, and an equation of state. The primitive equations are derived from the Navier-Stokes equations, with the approximation of a thin, rotating spherical shell (e.g., Kalnay 2003). This assumption is usually true for most planets, but may be challenged in certain cases, such as for Titan with a vertically extended atmosphere compared its radius.

The primitive equations are discretized either on a spectral or a spatial grid to form the dynamical core. For a spectral grid, the equations are decomposed in spherical harmonics, the resolution being defined by the highest specified harmonics. For a spatial grid, the most convenient choice is a latitude-longitude grid. Other options for the tessellation of the sphere are possible, such as an icosahedral grid. The advantage of a spectral grid over a spatial one is that there is no particular point on the planet, unlike, e.g., the singularity at the poles for a latitude-longitude grid that requires filtering at high latitudes. However, in the case of a spectral grid, a conversion to a from a spatial grid is necessary to communicate with the physics anyways.

The typical horizontal resolution of a GCM is a few hundred kilometers or more, making the hydrostatic equilibrium a reasonable assumption. Under that assumption, pressure monotonically decreases with altitude and therefore forms a natural vertical coordinates system. The hydrostatic

equilibrium is not valid for high-resolution models that can be used for weather prediction on Earth, or the details of the regional circulation on Earth and other planets.

Physics

While the dynamical core simulates the atmospheric motions, physical parameterizations are required to simulate all other atmospheric processes. Unlike the primitive equations of the dynamical core, the physical parameterizations are by definition not explicitly solved because they would require an unrealistically high spatiotemporal resolution for a GCM. Instead, they mimic the overall effect of a physical process at the GCM resolution – typically a few hundred kilometers and ~10 min timestep – guessed and calibrated from the universal laws of physics. Physical parameterizations are implemented for a vertical, one-dimensional column, as they do not require horizontal motions that are mostly driven by the atmospheric circulation, and dealt with the dynamical core. Therefore, the physics can be simulated as a stand-alone 1D model, and it gives GCMs a natural framework for parallel computing. The main physical parameterizations used in GCMs are radiative transfer, convection turbulence, clouds and aerosols, exchanges with the surface, and others.

Radiative Transfer

The most straightforward approach for calculating the heating and cooling rates for each gases and aerosols in an atmosphere is to use a line-by-line code, but this approach is too computationally intensive for a GCM. Instead, a limited number of infrared and visible bands are defined and carefully selected for a given atmospheric composition and aerosols, to statistically represent the photon behaviors for each band based on a line-by-line code. Another technique, called “correlated-k,” consists of approximating the line-by-line calculations by an analytical solution of spectral lines ordered by intensity. This later solution is more versatile than the band model and can be adapted to a cocktail of different atmospheric compositions.

Convection Turbulence

Convection and turbulence are processes occurring at a smaller scale than most GCMs resolution. They play an important role as they are a strong contribution of the energy and materials redistribution on the vertical scale by mixing. Theory, measurements of Earth atmosphere, and high-resolution numerical models constitute the source materials for designing parameterization schemes that aims to predict how vertical mixing occurs on the average on a large scale in various atmospheric conditions.

Clouds and Aerosols

The local presence of clouds and aerosols depend on transport, done by the dynamical core, and on microphysical processes. The latter are controlled by processes at a microphysical scale for clouds (nucleation, sedimentation, coagulation, chemical reactions) and solid aerosols (saltation, lifting) that require simplifications and approximations on a large scale. The accuracy of this parameterization for determining the cloud and aerosols properties is crucial for the radiative transfer calculations that depend on it.

Exchanges with the Surface

The surface exchanges heat and matter with the atmosphere. Heat conduction in the ground is explicitly solved. Ice and liquids at the surface can be a major source of volatiles in the atmosphere (e.g., CO₂ and water at the poles of Mars), and the changes of phase at the surface must be accounted for. More importantly, the horizontal transport of heat by an oceanic circulation, or mass by glaciers, requires specific models to be coupled to the GCM.

Others

It can be necessary to take into account photochemical reactions for some atmospheres (e.g., the sulfur cycle and production of clouds on Venus, the methane cycle on Titan).

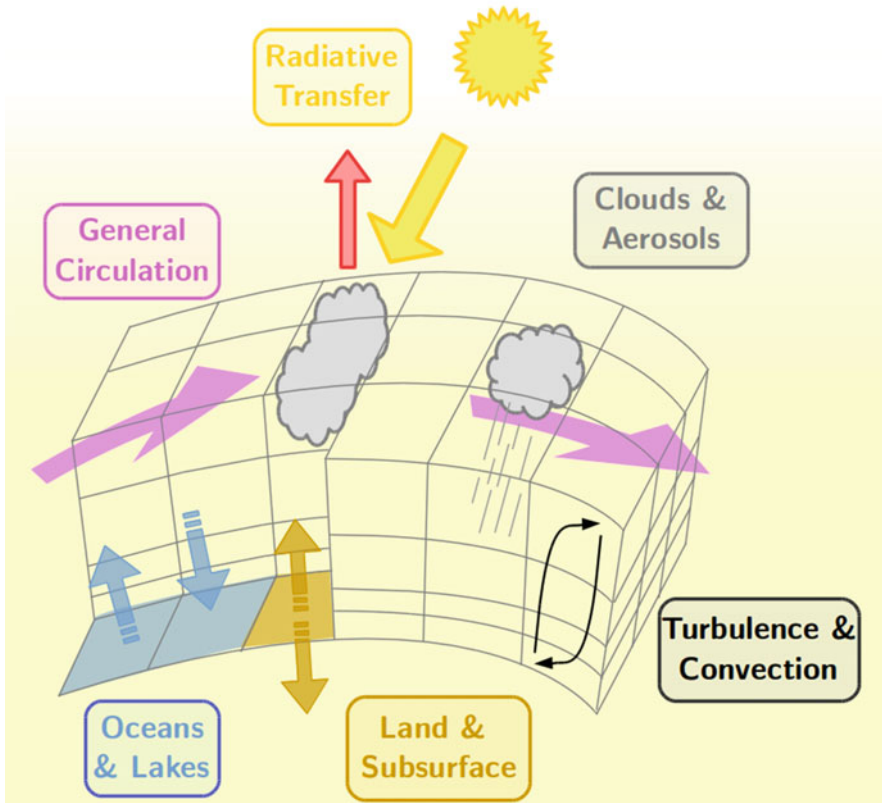
In the upper atmosphere, particular thermodynamical processes play an important role, such as UV absorption, molecular conduction, and non-local thermal equilibrium effects on the radiative balance (Fig. 1).

Key Research Findings

Considerable amount of findings have been made by GCMs in numerous scientific fields since their inception in the 1960s, far beyond the scope of this entry. Nevertheless, it is worth mentioning among this wealth of findings some key examples of their application to extraterrestrial planets and ancient climates. They are examples of studies which have greatly contributed to the advancement of our knowledge of habitability on Earth and other planets.

First, GCMs have revealed the circulation of terrestrial planets and gas giants in our Solar System. Based on the simulations of a Mars GCM with a treatment for photochemistry, the observations of methane in the Martian atmosphere were deemed incompatible with all the known chemical processes and source estimates (Lefevre and Forget 2009). Moreover, GCMs are generally able to reproduce the superrotating circulations of Titan and Venus, but the variable results across models do not permit to conclude on the mechanism creating superrotation (Read and Lebonnois 2018). The atmospheres of gas giants can also be simulated by a GCM, with a boundary at an arbitrary pressure level instead of a surface. Spiga et al. (2020) reproduced Saturn's jets, revealing the roles of eddies and seasonal cycles in its atmosphere (Fig. 2). These simulations require a higher computational capability than for their terrestrial counterparts due to the greater size of the gas giants.

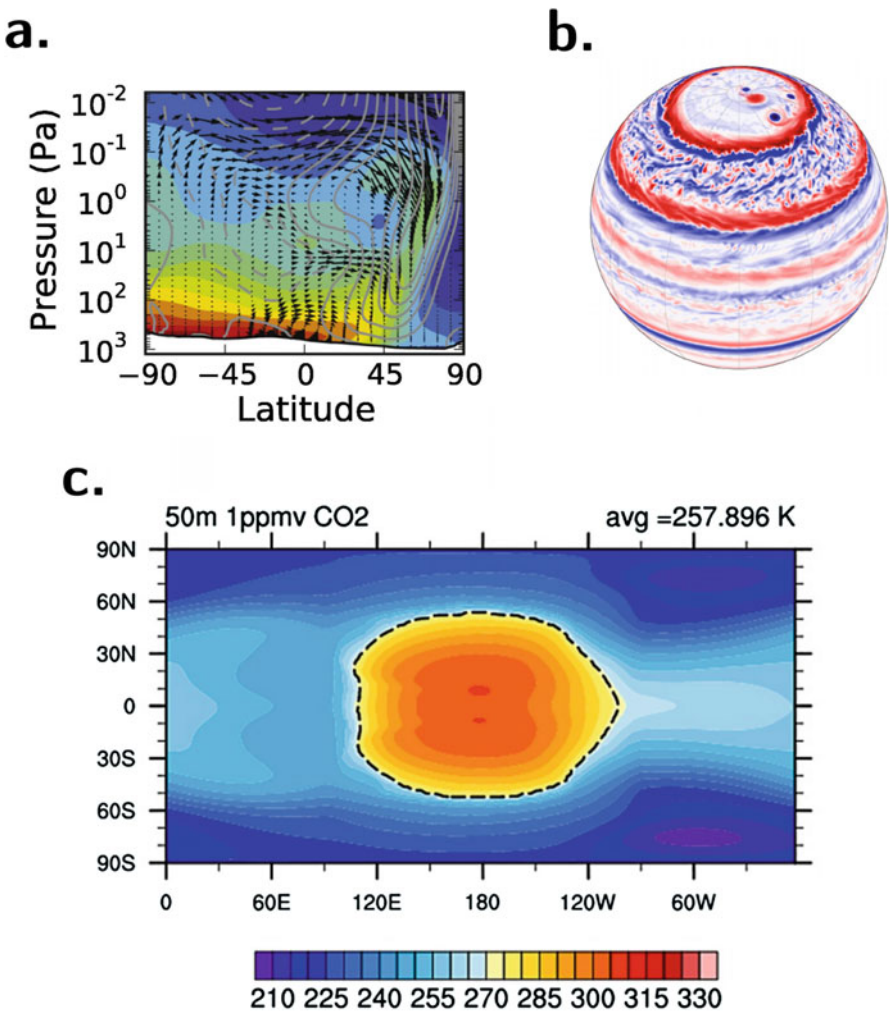
Second, the habitability of planets in the Solar System have been extensively studied with GCMs. For instance, adapting a GCM to Venus ancient conditions, Way and Del Genio (2020) found that it could have been habitable in 3 billion years ago. Similarly, Yang et al. (2014) showed that Venus could be habitable today under with its slow rotation rate, under the conditions that enough water is present in its atmosphere to form clouds on its dayside and cool the surface. To this date, GCMs simulating the climate of early Mars (3–4 billion years ago) have struggled to reproduce the conditions necessary for the warming inferred from surface geomorphological features (Wordsworth 2016),



GCM, Fig. 1 Main components usually modeled in a Global Climate Model

leaving the mystery of the past habitability of Mars still unresolved. Simulations of the recent climate changes driven by obliquity on Mars showed that water glaciers used to build up on the flank of equatorial volcanoes a few million years ago (Forget et al. 2006). One-dimensional atmospheric simulation of a column of Earth's atmosphere initially showed that Earth will not be habitable within a few hundred millions years. Taking into account the three-dimensional circulation, GCM simulations instead revealed that Earth will remain habitable until at least another billion years as the sun luminosity increases, before its atmosphere enters in a runaway greenhouse (Leconte et al. 2013). All in all, these studies suggest that the notion of a habitable zone is a complex, multi-factorial concept for which the climate plays a key role, with GCMs being used to explore this space of possibilities.

Third, GCMs are also a crucial tool to gain insight on the conditions reigning at the surface of exoplanets. As an example, the climates of close-in tidally locked planets orbiting M dwarfs have been explored for Proxima Centauri b, showing that many different climates are possible based on the assumptions made on the main atmospheric properties, and that some of them were habitable (Turbet et al. 2016). In the same vein, several planets of the TRAPPIST-1 system were found to be habitable thanks to a GCM (Turbet et al. 2018). Coupling an atmospheric model with an ocean one including sea ice, Yang et al. (2020) stressed the importance of coupling advanced models to assess the climate of exoplanets. Besides their climate, GCMs can also give crucial information on the planetary state. Leconte et al. (2015) found that with as little as 1 bar of surface pressure, the atmospheric torque exerted on



GCM, Fig. 2 Examples of GCM outputs. (a) Temperature (colors), winds (contours and arrows) of Mars (Toigo et al. 2012). (b) Potential vorticity of Saturn (Spiga et al. 2020). (c) Surface temperature of an exoplanet orbiting a M dwarf (Bin et al. 2018)

the solid body is sufficient to drive a planet out of synchronous rotation, despite its close orbit to its star.

While a GCM cannot, is not designed to, provide an accurate prediction for distant or ancient climates, the use of GCMs beyond Earth’s present-day climate have revealed universal patterns of circulation (Hadley-like cells, jets), and are an unique tool to dwell on past and future climates, and on synchronously rotating atmospheres, that have not equivalent in our Solar System.

Applications

Comparing observations to GCMs in a mathematically optimal way is done by a technique called “data assimilation,” in which sets of observations are extrapolated with a GCM. Data assimilation is the keystone of weather prediction (Kalnay 2003), and, outside of Earth, has been applied to Mars (Lewis et al. 2007) and Venus (Sugimoto et al. 2019) so far, given the increasing amount available data for those two planets.

As observations of exoplanets increase in accuracy and quantity, GCMs provide light curves for characterizing the atmospheres of exoplanets in order to probe their atmospheres and discriminate between different climate scenarios.

Future Directions

With their ever-increasing complexity, GCMs are poised to head towards systematic coupling of their atmospheric part with ocean, land, ice, and chemical models. The increase in resolution is also a trend in climate modeling, bridging the gap between regional and global models, allowing for more accurate parameterizations, and even removing the need for some of them. In that regard, GPU computation is an interesting alternative to the usual CPU one.

Cross-References

- [AOGCM](#)
- [Atmosphere, Structure](#)
- [Atmospheric Circulation](#)
- [Atmospheric Modeling: 1D Model](#)
- [Climates, Diversity in the Solar System](#)
- [Climates, Exoplanets](#)
- [Climates, Terrestrial Planets](#)
- [Habitability, Role of the Atmosphere](#)

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Gegenschein

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

[Counter glow](#)

Definition

The gegenschein or counter glow is a faint brightness enhancement in the night sky in the direction opposite to that of the Sun (i.e., in the antisolar direction; the Sun, of course, is below the horizon at this time). The gegenschein is actually a slight brightness peak in the ► [zodiacal light](#) and is produced by back-scattering of sunlight from ► [interplanetary dust particles](#). The gegenschein is only visible under very dark sky conditions.

Cross-References

- [Exozodiacal Light](#)
- [Interplanetary Dust Particle](#)
- [Zodiacal Light](#)

GEMs

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

The matrices of some interplanetary dust particles, particularly the anhydrous chondritic porous (CP) class of ► [interplanetary dust particles \(IDP\)](#), include glassy, submicron-sized silicate grains that have been called GEMs (glasses with

embedded metal and sulfides). It has been proposed that the GEMs are interstellar in origin and were incorporated into the IDPs or their parent bodies during the formation of the solar system.

Cross-References

- [Interplanetary Dust Particle](#)

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Gene

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

Central dogma of molecular biology · Exon · Gene expression · Genome · Intron · mRNA · rRNA · Splicing · tRNA

Synonyms

[Cistron](#); [Transcription unit](#)

Definition

Various definitions of the term “gene” occurred and still coexist. Genes are the units of heredity, and this remains true since the pioneering contribution of G.J. Mendel in 1866. ► [DNA](#) is the substrate of heredity, as it was shown by O.T. Avery and his collaborators in the 1940s; thus, ► [genetics](#) and molecular biology have been able to localize genes on this molecular

substrate. Nevertheless, some hereditary information lies also outside the classical or “true” genes. In cells, the classical genes are segments of their DNA genome that can be transcribed into a messenger ► **RNA**, which will be finally translated into a protein, a ribosomal RNA, a transfer RNA, or other kinds of RNAs. Viral genes are fragments of their DNA or RNA ► **genome** that, in most cases, code for the structural or regulatory proteins that will be expressed by the molecular machinery of the infected cell.

Overview

Inheritance in organisms occurs by means of factors or “determinants,” as first concluded by G.J. Mendel in his classic experiments aimed at studying the segregation of heritable traits in peas and other garden plants. Later on, the Mendel’s factors were called “genes” and assigned to particular positions or “loci” on the chromosomes and DNA molecules. The different versions of the same gene are called alleles and, in diploid species – those showing two copies of their genetic material – one allele is inherited from each parent. Diploid organisms can be homozygous for a given gene if they contain two copies of the same allele or heterozygous if they possess a copy of two different alleles (Watson et al. 2008; Lewin 2008).

Genes are specific functional units of a genome potentially transcribed into RNA which possibly will code for a protein. In the decade of the 1940s, it was clear that specific genes code for specific proteins, thus leading to the so-called “one gene-one enzyme” hypothesis. The determination of the ► **genetic code** permitted molecular biologists to unveil the correspondence between coding nucleotide triplets – called ► **“codons”** – in either the DNA gene or the transcribed mRNA and the amino acid they specify. It was further demonstrated that the majority of eukaryotic genes – and a low number of the bacterial and archaeal ones – are not collinear with their protein products. Instead, they are split into segments called ► **“exons”** that code for different protein

fragments. Exons are separated by intervening sequences called ► **“introns”** (Roy and Gilbert 2006). After the ► **transcription** of the gene, a reaction called “RNA splicing” – either protein-catalyzed or autocatalyzed by the intron – allows for the excision of the introns and the covalent joining of the exons in a mature RNA molecule. If such a mature RNA is an mRNA, further posttranscriptional modifications are needed – including capping and polyA addition – before becoming ready to be translated into the coded protein. Due to their mosaic structure, discontinuous genes may code for more than one protein if alternative splicing of their pre-mRNA occurs.

In addition to the transcribed sequences – called “transcription units” or “units of transcription” – all genes have additional sequences, among them regulatory regions that control their expression. Thus, a common structural organization of a protein-coding eukaryotic gene can be summarized as follows: 5'-enhancer-promoter-exon1-intron1-exon2-...-exonN-termination signal-polyadenylation sequence-downstream regulators-3'. In bacteria and archaea, introns are rare and the average length of genes is shorter. Two extreme examples of gene size are the 21 nt-long gene *mccA*, coding for the heptapeptide antibiotic microcin C7 in *Enterobacteria*, and the 2.3×10^6 nt-long human dystrophin gene, which includes 79 exons and very long introns. The first sequenced gene was that of the bacteriophage MS2 coat protein (Min Jou et al. 1972), an RNA ► **virus** whose genome was also the first to be sequenced in its entirety.

The number of genes in different genomes ranges from 1 in the simplest viruses – viroids lack genes in their genomes – to up to 10^5 in certain eukaryotes. The relationship between genome size and gene content has been investigated based on the data from completely sequenced and annotated genomes. Viral, bacterial, and archaeal genomes are mostly composed of gene-coding sequences, with median values of gene-coding percentages between 85% and 90% in the three groups (range: 47–97%). In turn, in eukaryotes only a small proportion of their genomes is ever transcribed as bona

fide informational RNAs – mRNA, rRNA, or tRNA “true” genes – showing a median gene-coding percentage of about 32% (range: 1–82%). For example, the gene content of the bacterium *Escherichia coli* genome is 88%, whereas in *Homo sapiens* the coding sequences represent less than 2% of our genome (Hou and Lin 2009; Snustad and Simmons 2010).

Cross-References

- [Codon](#)
- [DNA](#)
- [Exon](#)
- [Genetic Code](#)
- [Genetics](#)
- [Genome](#)
- [Genotype](#)
- [Intron](#)
- [Replication \(Genetics\)](#)
- [RNA](#)
- [Transcription](#)
- [Translation](#)
- [Virus](#)

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Gene Editing

- [Genome Editing](#)

Gene Expression

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

Gene expression is the overall process by which information stored in a gene is used to produce a gene product that may be either a protein, including enzymes and structural proteins, or a functional RNA, including ribosomal RNA, transfer RNA, small nuclear RNA, and other non-translated RNAs. Gene expression involves several sequential steps that are highly regulated, such as transcription, splicing, translation, and posttranslational modifications of proteins.

Cross-References

- [Gene](#)
- [Genetics](#)
- [Protein](#)
- [RNA](#)
- [Splicing](#)
- [Transcription](#)
- [Translation](#)

Gene Sequencing

- [DNA Sequencing](#)

Gene, Selfish

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Gene selfish is a metaphoric expression coined for the first time in 1976 by the British biologist

Richard Dawkins. Dawkins claimed that gene is the “unit of selection” of the evolutionary process. In his conception, organisms are only systems that permit to genes to reproduce. This idea was central on the debate about the unity of selection that put in opposition Dawkins and S. J. Gould.

Dawkins R., *The Selfish Gene*, Oxford University Press, 1976.

General Circulation

► [Atmospheric Circulation](#)

General Circulation Model

► [GCM](#)

Genetic Code

Stephen Freeland
Astrobiology Institute, University of Hawaii
NASA, Honolulu, HI, USA

Keywords

Amino acid · aaRS · Codon · mRNA · Protein · tRNA · Translation

Synonyms

[Codon table](#)

Definition

A genetic code defines how genetic information (stored within a polymerized ► [nucleotide](#) sequence) translates into a ► [protein](#) (a polymerized ► [amino acid](#) sequence): specifically it is the set of rules that maps each possible triplet nucleotide subsequence (► [codon](#)) to its corresponding amino acid. For example, the genetic code operating within the human nuclear genome translates the mRNA codon containing uridine-cytidine-

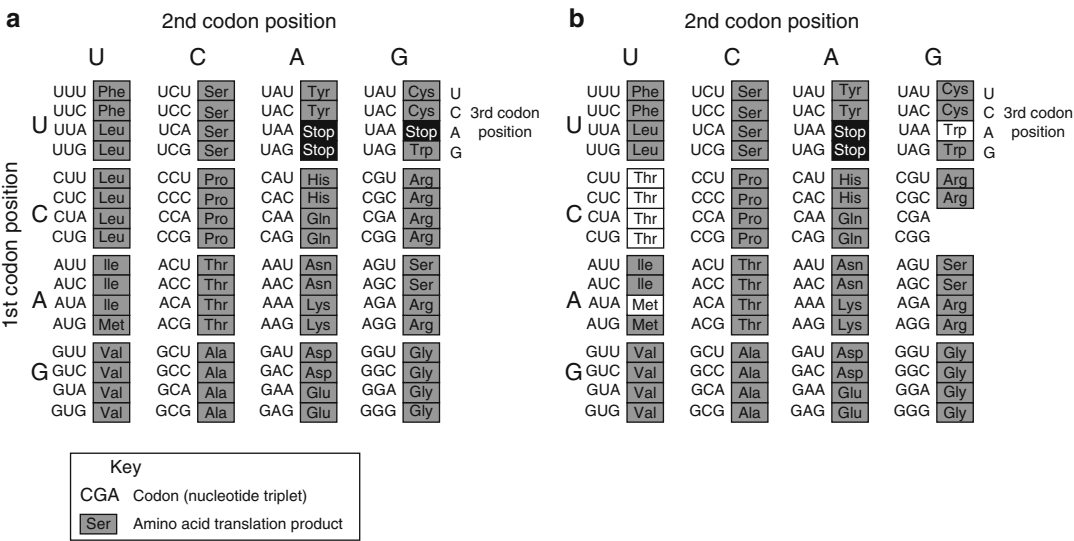
adenosine into the amino acid serine. These rules emerge through base pairing between a codon and the anticodon of an appropriate tRNA (“adaptor molecule”) that was previously charged with a specific amino acid by an appropriate aminoacyl tRNA synthetase enzyme (aaRS).

Overview

The phrase “genetic code” is widely associated with two misunderstandings that obscure its relevance to astrobiology.

First, popular media increasingly use the phrase “genetic code” to refer to the genetic information contained within an organism. However, biologists use genetic code to refer to the system of rules by which organisms translate their genetic information into protein-based metabolism. All known living systems require a genetic code precisely because they partition biochemistry into two different types of polymers – one (nucleic acids) for storing genetic information and another (proteins) for catalyzing the chemical reactions of metabolism. At present, it remains largely unknown whether we should expect an independent origin of life to do likewise. Relevance to the origin, evolution, distribution, and future of life in the universe thus hinges upon understanding how and why genetic coding emerged as a central phenomenon of life on our planet (Freeland 2009).

Second, despite the continuing and widespread use of the phrase “universal genetic code,” no such thing exists. Most known living systems share in common a standard genetic code (Fig. 1a) that maps the 64 possible codons (i.e., each possible triplet combination of nucleotides bearing the bases uracil, thymine, ► [adenine](#), or ► [cytosine](#)) into 1 of 20 amino acid meanings. However, research over the past four decades has revealed numerous non-standard genetic codes at work within naturally occurring genomes (Knight et al. 2001) (e.g., Fig. 1b). Nonstandard codes are widely distributed across diverse evolutionary sub-lineages,



Genetic Code, Fig. 1 Two examples of genetic codes: (a) the standard genetic code at work in most genomes and present within LUCA. (b) An example of a nonstandard genetic code – in this case the one at work within the mitochondria of *Saccharomyces cerevisiae*

and all involve relatively minor changes to the standard genetic code which predominates within all three fundamental domains of life (Archaea, Bacteria, and Eukaryota). It therefore seems likely that the standard genetic code was present within the ► last universal common ancestor (LUCA) of extant life and that all nonstandard codes are subsequent evolutionary diversifications. This shows that while genetic coding is fundamental to biology, it is not fully determined by physics or chemistry: it is an evolved and evolvable phenomenon. Indeed, any genetic code under consideration is usually represented as an exact table of correspondence between individual codons and specific amino acids (e.g., Fig. 1). However, this view is misleading because the process of genetic coding is not exact: it is the outcome of a series of complex molecular interactions; thus a tabulated summary is a statistical approximation. For a codon to be translated into an amino acid, an appropriate tRNA must first be charged with that amino acid by an appropriate aaRS enzyme. In some lineages this amino acid is then modified by further enzymes (e.g., see Wong 2005). The charged tRNA must then compete against others in

order to base-pair with the codon within the molecular context of a ► ribosome (Betney et al. 2010). Errors are inherent to all of these processes, and mismatching an amino acid to a given tRNA species (mischarging) or mismatching an incorrect codon to a correctly charged tRNA species (misreading) causes deviations from the code as written. While mischarging of tRNAs appears comparatively rare (Ling et al. 2009), patterns and frequencies of misreading vary widely between different lineages (Drummond and Wilke 2009). Thus, while the phrase “codon ambiguity” has been coined to describe codons that are routinely translated into more than one amino acid at an unusually high frequency (Moura et al. 2009), a wealth of related research has shown that the fidelity of protein translation depends to a significant (but widely varying) extent on “codon context,” where this is taken to mean the identity of neighboring codons or of RNA motifs located outside of the codon itself (Buckingham 1994). This shows how the precise rules of genetic coding can and do change during evolution, even for such a fundamental and complex feature as the standard genetic code.

Against this background, ongoing research is aimed at understanding better the origin of genetic coding (including the emergence of the standard genetic code), the diversity of genetic codes found within present-day organisms (and how these emerge), and the processes by which biological engineers can manipulate a given genetic code to deviate from anything that occurs naturally (e.g., by incorporating amino acids that have never been part of any naturally occurring genetic code).

Regarding the origin of genetic coding and the emergence of the standard genetic code, an expansive and often speculative literature has converged around three major themes. First, that genetic coding may have originated through direct interactions between ► RNA motifs and the amino acids that they encode (this may also explain the codon assignments of the standard genetic code, though to an unknown extent) (Yarus et al. 2009). Second, it seems likely that the standard genetic code emerged from a simpler genetic code comprising fewer codons and/or fewer amino acids (more than 50 different versions of this broad idea are collated in Trifonov 2000). The most thoroughly developed version, coined “genetic code coevolution,” holds that we can see clues to the order by which amino acids entered genetic coding by comparing the codon assignments of the standard genetic code with conserved metabolic pathways of modern organisms, in which chemically complex amino acids are still formed through biosynthetic manipulation of their simpler amino acid precursors (Wong 2007). An alternative view is that all codons and amino acids were present from the start, but coding was originally highly ambiguous (i.e., groups of codons were translated probabilistically into a meaning drawn from a group of amino acids) (Fitch and Upper 1987). A third major theme is that within the standard genetic code, the distribution of codons to amino acids appears very nonrandom in that amino acids with similar biochemical properties are assigned to codons that differ by only one of their three nucleotides (Freeland et al. 2003). In general, this observation has been used to argue that natural selection shaped the distribution of amino acid meanings to codons so as to

reduce the harmful effects of point mutation. More recently, it has been suggested that the same property may actually enhance the efficiency of natural selection as it acts to adapt protein-coding genes within a changing environment (Zhu and Freeland 2006). These different major lines of research into the origin and emergence of a standard genetic code do not necessarily compete as explanations. In particular, far less attention has been given to the fundamental variables involved: for example, why are codons three nucleotides in length? Why does genetic coding use only four nucleobases and only 20 amino acids of the thousands of examples of each type of compound found in biological systems (see Freeland (2009) for a review of ideas on these topics)? It remains entirely possible, though unknown, whether the standard genetic code emerged as some sort of optimal trade-off involving the steric affinities between mRNA motifs and amino acids, natural selection for an adaptive distribution of codon/amino acid assignments, and the growth of a standard amino acid alphabet from a near-infinite set of possibilities.

Meanwhile, research over the past four decades has uncovered numerous slight variants to the standard genetic code at work within the present-day biosphere (reviewed in Knight et al. 2001). Variations typically involve the reassignment of one or more codons to a different amino acid meaning from that found in the standard genetic code (e.g., within the human mitochondrial genome, the codon AUA corresponds not to isoleucine but to methionine). Many occur within the highly reduced genomes of mitochondria (e.g., eight codons have changed amino acid assignments within the genetic code that operates on the mitochondrial genome of yeast, *Saccharomyces cerevisiae* – Fig. 1b), but others exist within free-living microbes. Nonstandard codes also include examples that use one of two nonstandard amino acids (► selenocysteine and pyrrolysine) (Yuan et al. 2010). Although some maintain that these amino acids are not truly encoded in the same sense as the standard 20, owing to unusual features associated with the process of their translation, this argument fails under careful examination (Freeland 2009). Owing to recent discoveries

of enormous, largely uncharacterized microbial biodiversity (Fierer et al. 2007), it seems likely that current science is far from knowing the full range of nonstandard codes that currently exist within nature. This may well include the presence of additional coded amino acids (although bioinformatics analyses of the world's repositories of protein-coding sequence data suggest that further such discoveries are unlikely to occur within species whose genes have been sequenced so far) (Freeland 2009). Debate still surrounds the mechanisms by which codons become reassigned to new amino acid meanings (e.g., see Sengupta et al. 2007), but a large quantity of empirical data shows that mistakes routinely occur in the process by which tRNAs bond with their cognate codons. In some cases, this mismatching reaches levels at which a codon is declared “ambiguous” with respect to its amino acid meaning (e.g., Moura et al. 2009). More generally, evidence is growing that many features of an mRNA sequence can influence the accuracy with which a codon is translated. As an evolutionary route to codon reassignment, this is consistent with the finding that the two nonstandard amino acids to have been incorporated into coding are typically associated with mRNA motifs that lie outside of the codon itself (reviewed in Yuan et al. 2010).

More recently, researchers have begun to demonstrate success in manipulating the rules of genetic coding within the laboratory. In particular, the emerging science of synthetic biology has successfully incorporated additional amino acids into the standard genetic code within model organisms (Xie and Schultz 2006). Given the recent origin of this research, its rapid success, and the inherent economic and biomedical potential, significant future progress seems likely. In particular, scientists elsewhere have successfully incorporated additional bases into DNA (e.g., see Geyer et al. 2003). This offers the potential for a combination of the two technologies to greatly enlarge the complexity of the genetic code, producing proteins that have no analogs within nature, without disrupting current genomes and their translation into metabolism.

Cross-References

- ▶ [Activated Nucleotide](#)
- ▶ [Adenine](#)
- ▶ [Amino Acid](#)
- ▶ [Anticodon](#)
- ▶ [Aptamer](#)
- ▶ [Biopolymer](#)
- ▶ [Cytosine](#)
- ▶ [Gene](#)
- ▶ [Genetics](#)
- ▶ [Guanine](#)
- ▶ [L-Amino Acids](#)
- ▶ [Last Universal Common Ancestor](#)
- ▶ [Nucleic Acid Base](#)
- ▶ [Nucleotide](#)
- ▶ [Peptide](#)
- ▶ [Protein](#)
- ▶ [Ribosome](#)
- ▶ [RNA](#)
- ▶ [Selenocysteine](#)
- ▶ [Thymine \(T\)](#)
- ▶ [Translation](#)
- ▶ [Uracil \(Ura\)](#)

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Genetic Edition

► Genome Editing

Genetic Map

Carlos Briones

Centro de Astrobiología (CSIC/INTA),
Consejo Superior de Investigaciones Científicas,
Madrid, Spain

Synonyms

[Linkage map](#)

Definition

A genetic map is a representation of the genes on a linear map on which the distances are expressed as frequency of crossing-over or percent ► [recombination](#). Genetic distance in the map has no physical units: Its unit – m.u or centiMorgan – corresponds to 1% of recombination. Genetic distance describes the tendency of two given genes on the same chromosome to be inherited together: If they are physically close to each other, they will tend to stay together withstanding the recombination events produced during meiosis, a form of cell division in eukaryotes essential for sexual reproduction. In turn, genes far away from one another will have a long genetic distance since they show a higher probability to be separated as a result of recombination. Thus, the physical proximity on a same chromosome explains the correlation with the degree of genetic linkage evidenced in the crossing experiments. Overall, a ► [genome](#) has as many linkage groups as chromosomes. For example, humans have 24 linkage groups: the 22 autosomes – chromosomes that contain genetic information available to both sexes – plus the sex chromosomes X and Y. Gene mapping has important applications, including the production of the first drafts during a genome sequencing project.

Cross-References

- [Chromosome](#)
- [DNA Sequencing](#)
- [Gene](#)
- [Genome](#)
- [Genomics](#)
- [Recombination](#)

Genetics

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

DNA · Flow of genetic information · Gene · Genome · Inheritance · Molecular biology · Protein · RNA

Definition

Genetics is the discipline of Biology which studies inheritance, variation, function, and the physical nature of the genetic material. Historically, genetics has proceeded along several major pathways including experimental breeding, pedigree analysis, population genetics, cytogenetics, molecular genetics, and genetic engineering. Among them, molecular genetics is mainly concerned with the molecular bases of the inheritance and variation of the ► [genotypes](#) and investigates the relationship between the information-bearing macromolecules – DNA and RNA – and the proteins encoded by them. Applied branches of genetics rely on the established genetic principles and are used in medicine, agriculture, and biotechnology.

Overview

Early naturalists essentially observed the heritable traits of animals or plants in an empirical manner,

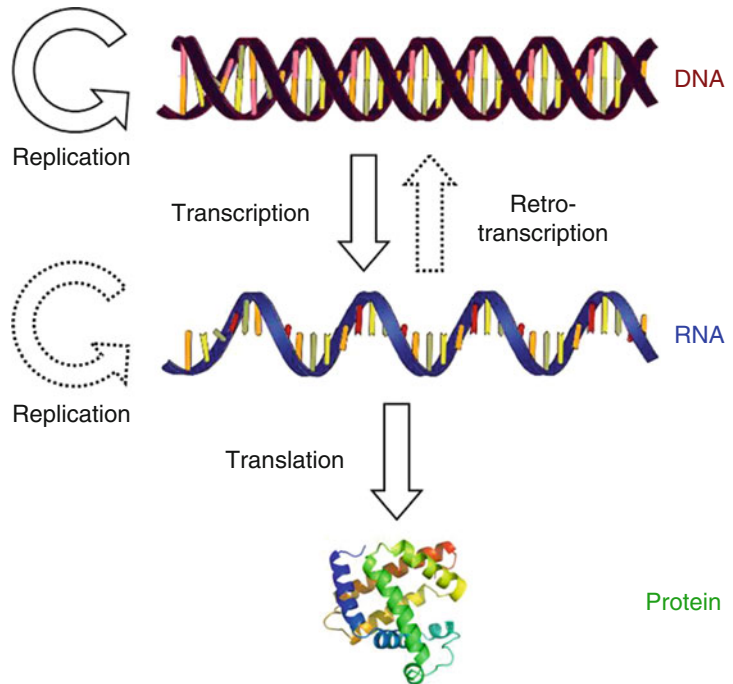
based on a long tradition of experimental breeding dating back several centuries. This approach was followed by pedigree analysis, by which the inheritance of some specific traits was traced in all members of a family line. For example, human pedigrees traced the inheritance of certain diseases such as polydactylism, hemophilia, or albinism. G. J. Mendel, considered the father of genetics, described in 1866 the basis of inheritance of traits from one generation to the next. At the beginning of the twentieth century, after the rediscovery of Mendel's work and following an increasing interest in cytology and biochemistry, the term “genetics” was coined in 1905 by W. Bateson to describe the study of heredity and variation (Bateson [1907](#)). The field of population genetics came into being in the 1920s to study the distribution of ► [genes](#) in biological populations and their change under the influence of evolutionary processes. It was based on the synthesis of the principles of Mendelian genetics with Darwinian natural selection (Sturtevant [2001](#)).

The observation that DNA is the genetic material in all ► [cells](#) and the discovery of the structure of DNA as a double helix inaugurated the era of molecular genetics in the decade of the 1950s. The investigation within this field has shown that all cells and a fraction of ► [virus](#) families have DNA genomes, while RNA is the genetic material of other viruses and all ► [viroids](#). The overall flow of genetic information in cells and viruses can be represented as $\text{DNA} \leftrightarrow \text{RNA} \rightarrow \text{Proteins}$, as schematized in Fig. 1. The spectacular progress produced in molecular biology opened the possibility to introduce tailored modifications in the genetic material of organisms, which gave rise to genetic engineering in the 1970s (Alberts et al. [2002](#); Lewin [2008](#)).

Since 1990, the advances in DNA sequencing and bioinformatics opened the possibility to study whole genomes of organisms as well as their set of encoded products, thus initiating the current era of genomics and proteomics. The publication of the first draft of the human ► [genome](#) in 2001 and its relevance for modern medicine has expanded broadly the subfield of human molecular genetics (Strachan and Read [2004](#); Watson et al. [2008](#)). In turn, recent advances in biotechnology allowed

Genetics,

Fig. 1 Schematic representation of the flow of genetic information. Cellular processes are shown by *solid arrows*, while those found only in viruses are depicted as *dotted arrows*



the study of the ► “**metagenome**” of communities containing different species (e.g., Venter et al. 2004), as well as the analysis of genetic material from extinct organisms, in the interdisciplinary field of paleogenetics (e.g., Poinar et al. 2006).

In summary, the tools and developments of genetics are currently integrated into all biological disciplines, including origin and evolution of life, taxonomy, microbiology, virology, molecular biology, biochemistry, biophysics, biotechnology, cytology, physiology, and development. Additionally, advances in genetics have permeated other fields such as medicine, forensics, psychology, sociology, paleontology, and astrobiology.

Cross-References

- [Cell](#)
- [Evolution, Biological](#)
- [Gene](#)
- [Genetics, History of](#)
- [Genome](#)
- [Genotype](#)
- [Metagenome](#)
- [Proteome, Proteomics](#)

- [Replication \(Genetics\)](#)
- [Transcription](#)
- [Translation](#)
- [Viroid](#)
- [Virus](#)

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Genetics, History of

Michel Morange

Centre Cavallès, USR 3308 CIRPHLES, Paris, Cedex 05, France

Keywords

Chromosome · Development · DNA · Gene · Genetic code · Genome · Mendel · Phenotype-genotype

History

It is quite impossible to pinpoint the origin of ► [genetics](#). The resemblances, but also the differences, between children and their parents (or grandparents), as well as the experience of breeders with animals, represent common ancestral knowledge. The evidence that characteristics, but also potentialities, were transmitted from one generation to the next was widely accepted. These spontaneous “prescientific” observations coexisted with the theory of impregnation, the conviction that characteristics acquired during life could be transmitted, and the idea that the thoughts and imagination of the mother might imprint their shapes on the future newborn. These empirical observations did not constitute a science of heredity, the systematic study of the transmission of characters through generations. The father of the science of heredity is Gregor J. Mendel, who in the garden of the monastery of Brno discovered the so-called laws of heredity. The work of Mendel was ignored by his contemporaries (including Charles R. Darwin), but was rediscovered 35 years later, on the eve of the twentieth century, by Hugo de Vries, Carl Correns, and Erich von Tschermak.

Mendel is the emblematic example of a “precursor,” a man or woman who anticipates the future progress of knowledge. Historians have done much to dispel the legend surrounding Mendel and his discovery. He was not a monk isolated in his monastery, but a recognized scientist, in contact with other scientists of his time, and well aware of the most recent scientific developments. His project was not the establishment of the laws of heredity, but the search for an answer to a practical question faced by all gardeners and breeders: why are some hybrids stable and others unstable? And when the hybrids are not stable, how do they return to the parental types? He had the merit to look for (and discover) quantitative laws of transmission of characters. But he had no clear idea of “what” transmitted these characters from one generation to another.

The 35 years which separated Mendel from the rediscovery of his laws was necessary to convince biologists of the existence and importance of the mechanisms of heredity. In 1859, simultaneously but independently of Mendel’s work, Darwin proposed his theory of evolution, which called for the existence of a mechanism of transmission through generations of the spontaneous variations screened by ► [natural selection](#). Ten years later, Darwin proposed his model of pangenesis. This model was neither original nor based on experimental evidence. But it triggered the work of many biologists, including August Weismann and Hugo de Vries, who proposed alternative models of heredity. In parallel and in relation with cytological observations on the nucleus, the chromosomes, and the mechanisms of fertilization, these authors elaborated what the historian of biology Garland E. Allen has described as corpuscular and mechanistic models of heredity (Allen 2000). Minds are now ripe for the rediscovery of Mendel’s laws.

The first 10 years of the science of genetics (1900–1910) was necessary to separate characters from genes or, as Wilhelm Johannsen said, ► [phenotype](#) from ► [genotype](#) and to propose that the chromosomes were the bearers of the genes (a hypothesis made by W. S. Sutton and Th. Boveri in 1902). A brilliant confirmation of

this hypothesis and the choice of an appropriate experimental system (the fruit fly *Drosophila melanogaster*) were due to Thomas H. Morgan and his small group of collaborators working at Columbia University in New York (Allen 1978). Sturtevant and Morgan rapidly demonstrated that the genes present on the same chromosomes were not always transmitted together. They interpreted this observation thanks to the 1909 discovery by the Belgian cytologist R. A. Janssens of the recombination of the chromosomes during meiosis (the cell division mechanism by which germ cells eliminate half of their chromosomes). This explanation allowed the drawing of genetic maps: the probability of genes being separated by chromosome breaks is proportional to the physical distance separating these genes on the chromosome.

Rapid progress was made in genetics, not only with *Drosophila* but also with maize and humans. Despite this intense effort of genetic mapping, the questions of the nature of the ► [gene](#) and of the mechanisms by which genes were responsible for the formation of characters not only were not addressed but were ignored. In his Nobel lecture (1934), Morgan still stated that defining the nature (material or not) of the genes would not alter the research program of geneticists.

Geneticists' apparent lack of interest in the nature and mechanism of action of genes probably has its roots in the empiricist philosophical tradition which permeated the minds of many scientists and biologists at the beginning of the twentieth century. Establishing the laws by which characters were transmitted through generations, and ignoring the mechanisms by which they were reproduced at each generation, was also a strategy to maintain the separation between genetics and embryology and the autonomy of the former. Indeed, the nature of genes and the mechanisms by which genes control the formation of characters were difficult scientific questions, experimental approaches to which were still lacking.

This abstract nature of the gene did not prevent the wedding between genetics and Darwinism which occurred in the 1930s through the work of

John Haldane, Sewall Wright, and Ronald A. Fisher. They elaborated the sophisticated mathematical models of population genetics, which provided a precise definition of ► [fitness](#), and demonstrated that mutations of small amplitude and low selective pressures were sufficient to drive the transformation of organisms. The modern synthesis, the new theory of evolution, emerged in the 1940s from the transfer of genetic studies done in the laboratory to fieldwork (Theodosius Dobzhansky), from an elaboration of complex mechanisms of speciation (Ernst Mayr), and from an interpretation of paleontological data in the light of the models of population genetics (George Simpson).

Meanwhile, the abstract notion of the gene was progressively replaced by a pure chemical description. In the 1930s, cytochemical studies demonstrated that ► [DNA](#) and proteins were the main constituents of chromosomes. In 1944, Oswald Avery and his collaborators produced strong arguments in favor of a major role of DNA in the process of heredity. The double-helix model proposed by Jim Watson and Francis Crick paved the way to the explanation of how the DNA molecule was faithfully replicated and suggested that the order of bases in DNA was probably the basis of genetic information. At the beginning of the 1960s, the genetic code was deciphered, demonstrating how the nucleotide ► [sequence](#) of DNA controlled the order of amino acids in proteins and therefore their structures. Genes had been reduced to DNA. The identification of the gene with an object seemed complete.

But the situation rapidly deteriorated. The discovery of regulatory sequences, located upstream of the coding regions of the genes, initiated a process of structural deconstruction of the gene. These sequences cannot belong to the gene, since they can be shared by different genes. Nevertheless, they are necessary for the proper activity (expression) of the gene. Other difficulties emerged: the existence of split genes in eukaryotes, the capacity for a DNA sequence to generate different messenger RNAs and proteins, the editing process, and the existence of DNA sequences coding in different frames for

totally distinct proteins. These were some of the observations preventing a simple definition of the gene.

The same difficulties also emerged at the functional level. Initially, it was admitted that a gene coded for an enzyme, a ► [protein](#) with a well-determined chemical function. Other protein functions were progressively discovered: ligand receptors, transcription factors, adaptors, etc. These new functions only find their meaning at a more integrated level, by conjunction with other proteins. Many genes participate in the formation of one single character. This was not a real surprise for geneticists, but it found its explanation in the progressive description of these molecular actors. In most cases, the expression “gene for” has no meaning!

The present situation is not simple, and efforts to provide a general definition of a gene have failed. Is the solution to be found in the replacement of the single notion of gene by different well-defined concepts (Keller 2000)? Many have argued for this and have even proposed these new concepts. But the notion of gene is still alive and well. Its vagueness allows this “boundary object” to circulate between different disciplines and to fertilize each of them.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [DNA](#)
- [Evolution, Biological](#)
- [Fitness](#)
- [Gene](#)
- [Genetics](#)
- [Genetic Map](#)
- [Genome](#)
- [Genomics](#)
- [Genotype](#)
- [Monod's Conception on the Origins of Life](#)
- [Natural Selection](#)
- [Phenotype](#)
- [Protein](#)
- [RNA](#)
- [Sequence](#)

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Genome

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

Chromosome · DNA · Gene · Genetic information · RNA · Sequencing project

Definition

The genome is the total amount of the genetic information of a ► [species](#). It can also be defined as the basic haploid chromosome set of a species. The term “genome” has also been used to refer to the full hereditary information of an organism. Nevertheless, the term ► [“genotype”](#) is preferred for individual organisms, since the “genome” of a given species is in practice an average or consensus of the genetic information of a number of individuals belonging to that species. Thus, the genome of one species does not capture the genetic polymorphisms within it.

Overview

All cellular genomes are composed of double-stranded (ds) ► [DNA](#), while viruses can have DNA or ► [RNA](#) genomes as both single-stranded

(ss) and ds molecules. In turn, all ► **viroids** show ssRNA genomes. Genomes can have linear or circular topologies, and they are composed of either a single DNA or RNA molecule or a set of different ones, each of them carrying a fragment of the whole genetic information. Genome sizes vary from less than 300 nucleotides (nt) in the smallest viroids to up to 10^{11} base pairs (bp) in certain vertebrate animals and higher plants. Some species have haploid genomes with a single copy of their genetic information, while others harbor multiple copies of the information in their

diploid, triploid, or polyploid genomes (Lewin 2008; Gibson and Muse 2009).

Cellular genomes show one or more ► **chromosomes** – molecules of dsDNA with a certain degree of structural organization – together with, in most microorganisms, extrachromosomal elements such as ► **plasmids**, viruses, or transposons. In eukaryotes, apart from the chromosomes composing their nuclear genome, two organelles – mitochondria and chloroplasts – harbor dsDNA genomes contributing to the overall genome of the species. Genomes contain both the coding

Genome, Table 1 Sequenced genomes from representative viroids, viruses, and cellular organisms from the three domains of life

Species	Genomic material	Genome size (nt)	Release year
Viroid			
Avocado sunblotch viroid (ASBVd)	ssRNA	2.5×10^2	1981
Potato spindle tuber viroid (PSTVd) ^a	ssRNA	3.6×10^2	1978
Virus			
Hepatitis delta virus (HDV) ^b	ssRNA	1.7×10^3	1987
Duck circovirus	ssDNA	2.0×10^3	2005
Hepatitis B virus (HBV)	ss/dsDNA	3.2×10^3	1987
Bacteriophage MS2 ^a	ssRNA	3.6×10^3	1976
Tobacco mosaic virus (TMV)	ssRNA	6.4×10^3	1983
Simian rotavirus SA11 ^c	dsRNA	1.9×10^4	1990
Bacteriophage KVP40	dsDNA	2.4×10^5	2003
Mimivirus	dsDNA	1.2×10^6	2004
Bacteria			
<i>Buchnera aphidicola</i> strain Cc	dsDNA	4.2×10^5	2006
<i>Haemophilus influenzae</i> ^a	dsDNA	1.8×10^6	1995
<i>Bacillus subtilis</i>	dsDNA	4.2×10^6	1997
<i>Escherichia coli</i> strain K-12	dsDNA	4.6×10^6	1997
<i>Chitinophaga pinensis</i>	dsDNA	1.8×10^7	2009
Archaea			
<i>Nanoarchaeum equitans</i>	dsDNA	4.9×10^5	2003
<i>Methanocaldococcus jannaschii</i> ^a	dsDNA	1.7×10^6	1996
<i>Pyrococcus furiosus</i>	dsDNA	1.9×10^6	1999
<i>Sulfolobus solfataricus</i>	dsDNA	2.7×10^6	2009
<i>Haloarcula marismortui</i>	dsDNA	4.3×10^6	2004
Eukarya			
<i>Saccharomyces cerevisiae</i> ^a	dsDNA	1.2×10^7	1996
<i>Plasmodium falciparum</i>	dsDNA	2.3×10^7	2002
<i>Vitis vinifera</i>	dsDNA	4.9×10^8	2007
<i>Homo sapiens</i>	dsDNA	3.2×10^9	2001
<i>Monodelphis domestica</i>	dsDNA	3.5×10^9	2007

^aFirst complete genome sequenced within each group

^bDefective virus

^cSegmented viral genome

► **genes** – nucleic acid sequences that will be translated into proteins – and the noncoding genetic information. The latter includes the rRNA, tRNA, and other small RNA genes, as well as different kinds of regulatory sequences, structural elements, and sequences whose function is at present unknown. Comparative genomic methods have been widely used to identify genes and regulatory regions in different species, as well as to trace patterns of genome evolution (Gibson and Muse 2009; Nielsen et al. 2010).

Genome projects are aimed at determining the sequence of the entire genome of one species. Upon completion of a sequencing project, the physical or ► **genetic map** of the genome and the inventory of annotated genes and regulatory regions become available. The first complete genome sequenced belonged to an RNA virus, the bacteriophage MS2 (Fiers et al. 1976), followed by the DNA genome of the bacteriophage PhiX174 (Sanger et al. 1977). Since then, thousands of complete viral and cellular genomes have been already sequenced or are in progress. Table 1 shows representative examples of sequenced genomes. The sequencing projects of long and complex genomes, such as those from higher plants and animals, require years of joint experimental and bioinformatic work. Among them, the Human Genome Project produced the first draft of the complete genome of our species in 2001 (Lander et al. 2001; Venter et al. 2001). This achievement was followed by a rapid acceleration in genome science and ► **DNA sequencing** techniques, what has opened the door to a future genome-based, personalized medicine (Collins 2010). Apart from their applications in biomedicine and biotechnology, the advances in genomics have largely influenced our current view of different disciplines of biology (Snustad and Simmons 2010).

Cross-References

- **Bioinformatics**
- **Cell**
- **Chromosome**
- **DNA**

- **DNA Sequencing**
- **Gene**
- **Genetic Map**
- **Genetics**
- **Genotype**
- **Metagenome**
- **Plasmid**
- **RNA**
- **Species**
- **Viroid**
- **Virus**

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Genome Editing

Montoliu Lluís
National Centre for Biotechnology (CNB-CSIC),
Madrid, Spain

Keywords

Genome · CRISPR-Cas · TALEN · ZFN · Meganuclease · Homologous recombination · DNA repair

Synonyms

Gene editing; Genetic edition; Genome edition; Genomic edition

Definition

Genome editing stands for the capacity to modify and manipulate a genome at will, using specific tools triggering specific alterations in selected DNA sequences at target genome sites. The first experimental observations of genome editing events were reported in yeast cells. Subsequently, homologous recombination strategies were implemented in higher eukaryotes as part of the gene targeting approaches in mice using embryonic stems cells. Genome editing tools that have been developed include yeast meganucleases, Zinc-Finger nucleases (ZFN), transcription activator-like effector nucleases (TALEN), and clustered regularly interspaced short palindromic repeats (CRISPR), and CRISPR associated proteins (Cas) systems.

History

Genome (or gene) editing was first reported in yeast cells (*Saccharomyces cerevisiae*) in 1979, with specific genome alterations generated by homologous recombination. Oliver Smithies used homologous recombination to target a mammalian gene in 1985, and this approach was combined with the isolation of mouse embryonic stem cells by Martin Evans in 1981 into a general strategy to target specific genes in mice by Mario Capecchi in 1988. Subsequently, specific tools were developed to trigger genome editing events. First using yeast meganucleases, in 1995. Then combining artificial ZF domains with nucleases, for ZFN, since 2001. Thereafter, TALEN come into play in 2010, although they were rapidly replaced by the nascent CRISPR-Cas technology, envisaged in 2012 and demonstrated from 2013.

Overview

The ability to modify a genome at will was first demonstrated in yeast cells, using a homologous

recombination approach, activating the homology drive repair (HDR) endogenous mechanism. Thereafter, a most similar strategy was confirmed in mammalian cells by Smithies and converted to a general approach to edit mouse genes at will. The three researchers involved in this seminal innovation: Smithies, Evans, and Capecchi, were awarded the Nobel Prize in Medicine in 2007. The fact that genome editing events were triggered by specific double-strand breaks at the target DNA sequence and the observation that the subsequent chromosomal repair could progress through HDR, in the presence of DNA homologous sequences, or through NHEJ (non-homologous end joining), in their absence, was further explored with several types of endonucleases. At first, using yeast meganucleases, capable of detecting and cutting long target DNA sequences (20–40 base pairs) but with limited versatility. Next, a combination of artificial ZF domains targeting specific DNA sequences with a prokaryotic nuclease domain from restriction enzyme *FokI* created the ZFN, first tested in 2001, thus expanding the target genomic sites to any desired DNA sequence. However, ZFNs were difficult to generate, and their fabrication was proprietary of a company. In contrast, the TALE nucleases, in place since 2010 and derived from bacteria infecting plants, could be generated at any laboratory, although with significant efforts, and transiently resulted in the preferred choices for triggering genome editing. Eventually, the proposal of CRISPR-Cas systems as easier, cheaper, more efficient, and most amenable genome editing tools, presented by Charpentier and Doudna in 2012, disrupted the entire field. The two reports by Zhang and Church in January 2013 confirmed these would be the future reagents of choice for effective genome editing experiments.

Cross-References

- CRISPR
- DNA
- DNA Damage

- [DNA Repair](#)
- [Genome](#)
- [Nucleic Acids](#)
- [Recombination](#)
- [Replication \(Genetics\)](#)
- [Yeast](#)

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Genome Edition

- [Genome Editing](#)

Genome, Minimal

Rosario Gil
Institute for Integrative Systems Biology,
Universitat de València - CSIC, Paterna
(Valencia), Spain

Keywords

Minimal cell · Minimal gene-set · Core genome

Synonyms

[Minimal gene-set](#)

Definition

A minimal genome was defined in 1999 by Arcady Mushegian as a genome containing the smallest number of genetic elements sufficient to build a modern-type free-living cellular organism (Mushegian 1999). Consequently, the concept of a minimal genome is fundamentally related to the definition of a minimal cell.

Overview

The functional elements of a living cell are (lipid) membranes, proteins, and RNA molecules. The instructions for making these parts are encrypted in genes (i.e., DNA) and decoded by the molecular cell machinery in a controlled manner. In order to delineate a set of essential and sufficient genes to make a living cell, it is first necessary to define the essential functions that need to be achieved. Most attempts to define a minimal genome focus on protein-coding genes, ignoring functional

RNAs, regulatory and other noncoding sequences, and the organization of these elements on chromosomes. Therefore, they only represent the core of a hypothetical minimal modern-cell genome. Several estimates indicate that such minimal genome core must contain at least about 200 genes, although some authors point out that additional genes might be necessary to improve cell efficiency (Fang et al. 2015; Jewett and Forster 2010).

It is not possible to specify a universal minimal genome. First, it needs to be tied to a particular level of biological organization. The increasing knowledge on bacterial genomes and the simplicity of prokaryotic cells make bacterial cells a suitable choice. Second, metabolism is extremely variable and highly dependent on the environment. Therefore, a plethora of minimal genomes, composed by a universal informational core plus a variable metabolic gene-set, can be envisaged (Gil et al. 2004; Gil and Peretó 2015).

Experimental and computational methods have been used to define the core of a minimal bacterial genome (Gil 2015). Experimentally, essential genes are determined based on indirect evidence from systematic and genome-wide inactivation or inhibition of each individual gene present in a genome (compiled in <http://origin.tubic.org/deg>; Luo et al. 2021). Computational comparative genomics has been also extensively employed, assuming that genes shared between distant organisms are likely to be essential. Naturally reduced genomes from bacteria with a host-associated lifestyle have been used for comparisons because they must be closer to a minimal genome (Gil et al. 2003; Mushegian and Koonin 1996). These studies showed the importance of considering that essential functions can be performed by alternative and unrelated (non-orthologous) proteins. Comparative analyses only retrieve genes involved in functions for which there is no alternative in nature (e.g., the complex translational machinery), while a minimal genome must also include all genes essential to maintain metabolic homeostasis (Gil et al. 2004).

A third approach to a minimal genome searches for the biochemical and modular description of well-defined pathways needed to perform all essential functions (Jewett and Forster 2010). Although some important challenges still need to be faced, this approach allows a function-by-function debugging to reach self-replication, and it seems a good start to approach the goal of synthesizing a minimal genome able to sustain an artificial minimal cell, the ultimate goal of synthetic biology.

The possibility of chemically synthesizing complete genomes and transplanting them into pre-existing cells has revolutionized the study of minimal genomes (Hutchison et al. 2016). With only 543 kbp and 493 protein-coding genes, the *Mycoplasma mycoides* JCVI-syn3A genome is close to a minimal one and has proven to be able to sustain a robust free-living near-minimal cell. It includes essential and quasi-essential genes, some of which (79 genes) have poorly defined functions, and later studies indicate that it can still be reduced (Breuer et al. 2019). The design of a truly minimal genome can also benefit from computational whole-genome sequence rewriting and a design-built-test in silico approach prior to the chemical synthesis of a customized genome (Venetz et al. 2019; Zhang et al. 2020, 2021).

Cross-References

- Cell, Minimal
- Endosymbiosis

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Genomic Edition

► Genome Editing

Genomics

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

Genomics is the field of ► [genetics](#) which studies the structure, organization, and function of entire genomes. This global and integrative approach was initiated in the decade of the 1980s, thanks to the advances in automatic ► [DNA sequencing](#) and the availability of new bioinformatic tools for analyzing increasingly large amounts of genetic information. Four milestones in genomics were the sequencing of the first viral genome in 1976, the completion of the first bacterial genome in 1995, the first eukaryotic genome in 1996, and the release of the first draft of the human genome in 2001. Different current subfields of genomics include structural genomics, functional genomics, metagenomics, pharmacogenomics, and comparative genomics.

Cross-References

- [Bioinformatics](#)
- [DNA Sequencing](#)
- [Genetics](#)
- [Genome](#)
- [Metagenome](#)
- [Proteome, Proteomics](#)

Genotype

Susanna Manrubia
Systems Biology Program, Centro Nacional de
Biotecnología (CSIC), Madrid, Spain

Definition

The genotype is the genetic makeup of an organism, its full hereditary information. The genotype of an organism is a characteristic fingerprint. Genotype is different from ► [genome](#) (usually describing a species), which is a representative average over individuals. For example, a viral ► [quasispecies](#) contains a particularly large number of different genotypes, though the ► [virus](#) is characterized by a precise genome. In diploid organisms, the genotype is the pair of alleles inherited for each particular gene. The expression of the genotype in a given environment is the ► [phenotype](#) of an organism.

Cross-References

- [Genetics](#)
- [Genome](#)
- [Mutation](#)
- [Phenotype](#)
- [Quasispecies](#)
- [Virus](#)

Genus

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Genus is a taxonomic group of related ► [species](#) sharing one or more major properties. The term comes from the Latin genus meaning “descent,

family, type, and gender,” cognate with Greek: γένος-*genos*, “race, stock, and kin.” A genus is defined through the characterization of different species. In order for a genus to be descriptively useful, it must have monophyly, reasonable compactness, and distinctness. In the binomial nomenclature used in biology, the genus is used as the first word of a scientific name. The genus name is always capitalized and italicized. In the hierarchy of the binomial classification system, genus comes above species and below family. In the past, the taxonomic adscription of organisms was based on phenotypic properties, but since the introduction of molecular biology, techniques allowing the use of genotypic properties have facilitated the establishment of phylogenetic relationships among organisms.

Cross-References

- [Genotype](#)
- [Phenotype](#)
- [Phylogeny](#)
- [Species](#)

Geobiology Society

Kurt O. Konhauser
Department of Earth and Atmospheric Sciences,
University of Alberta, Edmonton, AB, Canada

Definition

The Geobiology Society is a nonprofit international society formed in 2016 to advance the science of geobiology. Its aims are to foster collaboration and the exchange of ideas between geobiologists worldwide; promote the study of geobiology as a core Earth and life science discipline for the twenty-first century; enhance scientific communication by means of publications, lectures, meetings, and collaboration with other relevant societies; support and encourage young

scientists entering the field of geobiology; encourage the development and use of new analytical techniques; and promote the relevance of geobiology to society at large.

Geocentric Worldview

Sun Kwok

Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada

Keywords

Ptolemy · Epicycles · Eccentric · Equant · Two-sphere universe

Definition

A cosmological worldview where the Earth is located at the center of the Universe.

History

Because the ground is apparently flat, and the Sun, the Moon, and the stars rise from one horizon, move across the sky in circular paths, and set in the opposite horizon, many cultures developed the flat Earth-spherical sky model as their first cosmological model. However, this model has difficulty accounting for the fact why some stars (e.g., Canopus) are visible from some locations (e.g., Alexandria), but not from others (e.g., Athens). From the shape of the shadow of the Earth during lunar eclipses, Greek astronomers deduced that the Earth is round in the fifth century B.C. A spherical Earth means that observers at different latitudes will have different horizons, and thus explains the trajectory of the Sun and the visibility of stars are dependent on observer's location.

Overview

The realization that the Earth is round led to the two-sphere universe model where a spherical

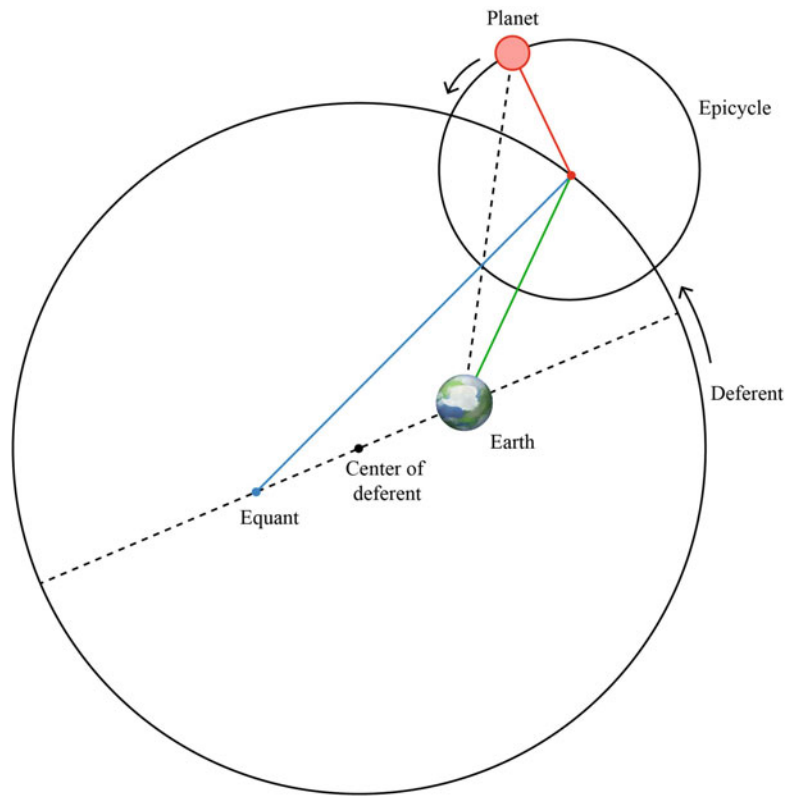
Earth is situated at the center of a celestial sphere upon whose surface the stars lie. In this model, the celestial sphere revolves around the Earth from east to west each day. Because of the rotation of the celestial sphere, stars rise above the horizon in the east and set below the horizon in the west. The Sun also revolves around the Earth, but its motion is slower than that of the stars by 4 minutes each day. Over the course of a year, the Sun travels across the celestial sphere relative to the stars from west to east along the plane of the ecliptic, which is inclined 23.5° with respect to the equator of the spherical Earth. Because of this inclination angle, the Sun goes through a north-south annual motion in addition to its daily east-west motion. This model explains the cause of the seasons, and quantitatively predicts the daily changing positions and times of sunrise/sunset. Most significantly, it can predict the trajectories of the Sun as observed from anywhere on Earth, even from places that no one has visited (e.g., the north pole).

While the two-sphere universe model achieved great success in explaining the movement of celestial objects, there are other complications. Although the seasons return in regular annual intervals, the lengths of each season are unequal. This anomaly was known as early as 330 B.C. by Callippus (370–330 B.C.), and the different lengths of the seasons were accurately measured by Hipparchus (185–120 B.C.). Although the planets generally revolve around the Earth from west to east, as does the Sun, they appear to reverse directions (retrograde motion) from time to time. Hipparchus also found that the sphere of fixed stars is not oriented permanently with respect to the ecliptic. The intersection point between the celestial equator and the ecliptic shifts about 1° every 100 years; a phenomenon known as the precession of the equinox.

To explain these anomalies, Ptolemy in the first century A.D. introduced additional elements into the two-sphere universe model. Epicycles (cycles upon cycles) were introduced to explain the retrograde motions of the planets. A planet moves uniformly around an epicycle whose center

Geocentric Worldview,

Fig. 1 The use of eccentric, epicycle, and equant in Ptolemy's model of planetary motion. The Earth and the equant are placed at equal distances on opposite sides of the center of the deferent. The planet moves uniformly around the center of the epicycle which revolves around the deferent centered on a point eccentric from the Earth. The angular speed of the center of the epicycle is uniformly relative to the equant point



revolves along a large circle called the deferent. When the planet is in the inside of the deferent, it is in retrograde motion (Fig. 1).

The concepts of eccentric and equant were also needed to explain the unequal lengths of the seasons, the uneven motion of the planets, and the precession of the equinox. The center of the deferent is separated from the position of the Earth by the eccentric. The center of the epicycle revolves uniformly relative to the equant.

Ptolemy's model was described in detail in his book *Almagest*. Planetary tables produced from his model were used to predict future solar and lunar eclipses, and planetary conjunctions. It was the dominant cosmological model for over 1400 years. In the thirteenth century, St. Thomas Aquinas integrated Ptolemy's model with Aristotle's physical worldview and the Bible to form a comprehensive geocentric cosmology. Earth is centrally located with Hell in its center, and Heaven is located beyond the celestial sphere.

In this picture, humans are special and unique, and there are no other living worlds. This geocentric worldview was finally challenged by the heliocentric model of Copernicus (1473–1543).

Cross-References

- [Cosmogony: Greece](#)
- [Heliocentric Worldview](#)

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Geochronology

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Keywords

Age · Absolute age · Ion microprobe · Isochron · Isotope · Radioactivity · Radioactive decay · Mass spectrometer · Extinct radioactivity

Synonyms

[Age measurement](#); [Radiochronology](#)

Definition

Geochronology is the scientific field dedicated to providing absolute ages of geological and planetary material. It is based on the measure of the accumulated isotopes produced by the ► [radioactivity](#) of some long-lived ► [nuclides](#). The radioactivity of now extinct nuclides can be used to date the early evolution of the solar system. Most of the techniques involved in this field are based on ► [mass spectrometry](#).

History

French physicist Henri Becquerel discovered radioactivity in 1896, and, at the turn of the century, Marie and Pierre Curie successfully separated several radioactive elements. The idea of dating rocks by using the rate of accumulation of helium produced by the decay of uranium was conceived by English physicist Sir Ernest Rutherford in 1904. In the early part of the twentieth century, J. J. Thompson, A. J. Dempster, and F. W. Aston developed the first mass spectrometers. Subsequently A. O. Nier built an instrument that could be used to determine precise isotopic ratios. He is also

credited for the determination of the isotope compositions of most elements in the 1930s and 1940s. Between 1920 and 1953, significant advances in the understanding of the potential of Pb isotopes for chronology are due to A. Holmes, H. N. Russell, F. G. Houtermans, and E. Gerling. In 1955, C. C. Patterson obtained the first Pb-Pb ► [isochron](#) age on meteorites and dated the solar system at 4.55 Ga, a number that has hardly changed today. G. W. Wetherill should be credited for the introduction of the Concordia in 1956 and, together with T. Aldrich, for pioneering the ^{40}K – ^{40}Ar and the ^{87}Rb – ^{87}Sr methods. The merit of discovering extinct radioactivities falls on J. H. Reynolds in 1960 for ^{129}I – ^{129}Xe and on T. Lee and D. A. Papanastassiou in 1974 for ^{26}Al – ^{26}Mg . In 1961, L. Nicolaysen proposed the first isochron for the ^{87}Rb – ^{87}Sr pair. R. Castaing and G. Slodzian constructed the first effective ion probe in the early 1960s and in the late 1970s, which opened the way to the in situ U-Pb ages of zircons, developed then by W. Compston. C. Merrihue and G. Turner invented the ^{39}Ar – ^{40}Ar method in 1965. In 1969, D. A. Papanastassiou and G. W. Wasserburg constructed the first computer-assisted mass spectrometer, which established the post-Apollo standard for isotope geochemistry. The first ICP-source mass spectrometers dedicated to isotopic measurements and geochronology appeared in the mid-1990s.

Overview

Radioactive decay is a random process that reflects the instability of some nuclei. Its probability of occurrence per unit of time is independent of time: atoms do not age. This probability, also known as the decay constant λ , is specific to each radioactive nuclide. A parameter related to the decay constant is the ► [half-life](#) $T_{1/2}$, which is equal to $\ln 2/\lambda$. Radioactive decay is described as a random “Poisson” process, in which the number of events is proportional to the duration of the

observation. In the absence of any other loss or gain (the closed-system assumption), the proportion of parent atoms P (or radioactive nuclides) disappearing per unit of time t is constant:

$$\frac{dP}{Pdt} = -\lambda \quad (1)$$

The number of decay events per unit time dP/dt is known as the “activity” of the radioactive nuclide. For a number of parent atoms $P = P_0$ at time $t = 0$, this differential equation is equivalent to

$$P = P_0 e^{\lambda t} \quad (2)$$

To determine the age of a system from the measurement of the number of parent atoms at the present time, we must know P_0 , and therefore, in this form, this equation is not a chronometer (a notable exception is the ^{14}C method). For each parent atom, a daughter atom (or radiogenic nuclide) is created, usually of a single element, whose number can be denoted D . In a closed system and for a stable daughter nuclide D , the number of parent and daughter atoms is constant; hence,

$$D = D_0 + P_0 - P = D_0 + P(e^{\lambda t} - 1) \quad (3)$$

The term $P(e^{\lambda t} - 1)$ is a measure of the accumulation of the radiogenic nuclide during time t , and therefore,

$$t = \frac{1}{\lambda} \ln \left(1 + \frac{D - D_0}{P} \right) \quad (4)$$

Even if D and P are measured, this equation is no more a timing device than Eq. (2) unless we know the number of daughter atoms D_0 at time $t = 0$.

“Rich” Chronometers: U-Pb and K-Ar

A first class of chronometers arises when the condition $D_0 \ll D$ or

$$D \approx P(e^{\lambda t} - 1) \quad (5)$$

applies, as for the ^{206}Pb – ^{238}U dating of zircons, a ubiquitous mineral of granites with formula ZrSiO_4 into which U^{4+} easily substitutes but not Pb^{2+} . With this condition applying, Eq. (4) becomes

$$t = \frac{1}{\lambda_{238\text{U}}} \ln \left(1 + \frac{^{206}\text{Pb}}{^{238}\text{U}} \right) \quad (6)$$

When $y = ^{206}\text{Pb}/^{238}\text{U}$ and $x = ^{207}\text{Pb}/^{235}\text{U}$ are plotted against each other, the widely used concordia diagram is obtained (Fig. 1). The Concordia is the locus of points for which the two ages of zircons agree, i.e., they are concordant:

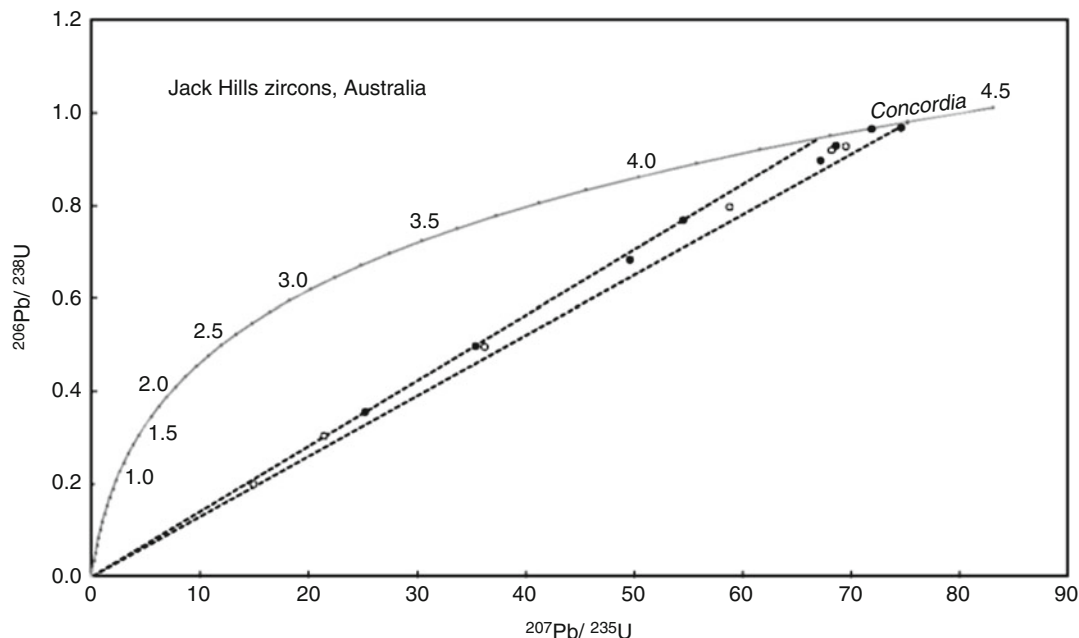
$$x = \frac{^{207}\text{Pb}^*}{^{235}\text{U}} = e^{\lambda_{235\text{U}} T} - 1 \quad (7a)$$

$$y = \frac{^{206}\text{Pb}^*}{^{238}\text{U}} = e^{\lambda_{238\text{U}} T} - 1 \quad (7b)$$

where T stands for the geological age and the asterisk refers to radiogenic Pb (total Pb minus common or contamination Pb). The main limitation of this method is the presence of common Pb introduced by inclusions, impurities, or contamination during mineral processing.

The ^{40}K – ^{40}Ar method also belongs to this family and dates the isolation of the host mineral. These days, it is mostly used in its ^{39}Ar – ^{40}Ar version, that is, after irradiation of the sample in a nuclear reactor, fast neutrons with an energy >1 MeV react with ^{39}K , which is in constant proportions with ^{40}K , to produce ^{39}Ar . The age is deduced from the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio, in lieu of $^{40}\text{Ar}/^{40}\text{K}$, after proper calibration of the yield of the nuclear reaction through a mineral standard of known ^{40}K – ^{40}Ar age T_m referred to as the monitor:

$$\frac{\left(^{40}\text{Ar}/^{39}\text{Ar} \right)_{\text{spl}}}{\left(^{40}\text{Ar}/^{39}\text{Ar} \right)_{\text{m}}} = \frac{e^{\lambda_{40\text{K}} T_{\text{spl}}} - 1}{e^{\lambda_{40\text{K}} T_m} - 1} \quad (8)$$



Geochronology, Fig. 1 The concordia plot, with U and Pb analyses of two detrital zircon grains from the Jack Hills (Western Australia) by Wilde et al. (2001). The concordia is the locus of points for which the ^{206}Pb – ^{238}U and

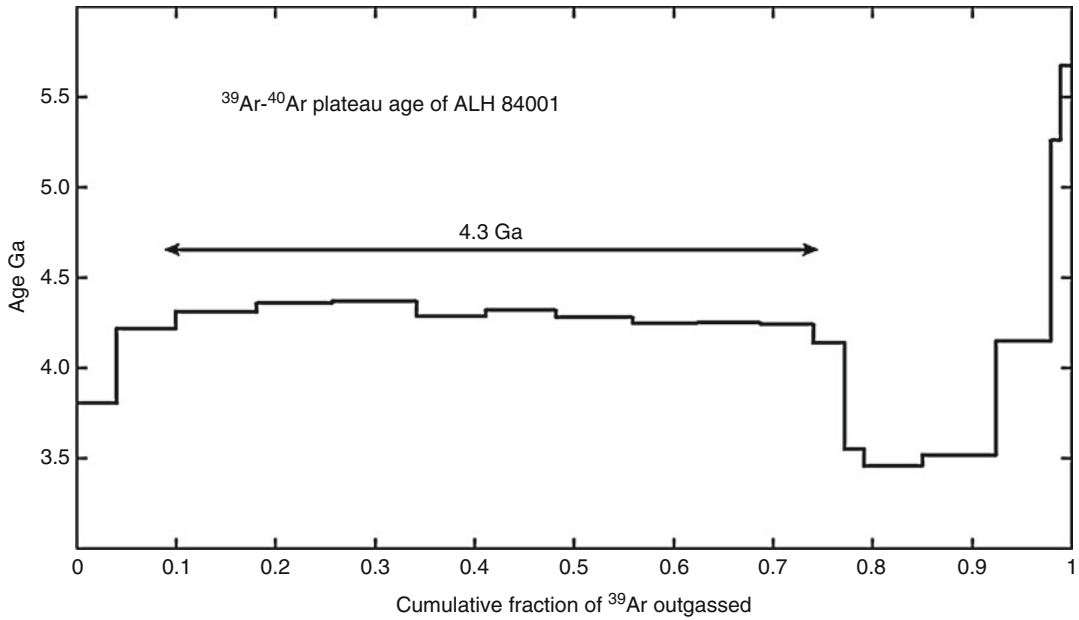
^{207}Pb – ^{235}U ages (here shown in Ga) agree. When zircons plot significantly off the concordia, the age used in practice is deduced from the upper intercept with the line going through the origin ($^{207}\text{Pb}^*/^{206}\text{Pb}^*$ age, dashed lines)

A major advantage of this technique is that resetting of the chronometer by thermal reheating or weathering and the presence of excess Ar can be easily identified. Argon is released by laser ablation or, most commonly, by stepwise heating: undisturbed minerals show very large “plateaus” with $^{40}\text{Ar}/^{39}\text{Ar}$ remaining constant over a broad range of ^{39}Ar degassing, whereas, for perturbed samples, $^{40}\text{Ar}/^{39}\text{Ar}$ reflects old ages only for high-temperature steps. In the case of inherited Ar, the high-temperature steps may be anomalous. Figure 2 shows a ^{39}Ar – ^{40}Ar dating of the famous Martian meteorite ALH84001 (Bogard and Garrison 1999), which has been suggested to harbor microfossils. A limitation of this technique is the presence of atmospheric ^{40}Ar , which is corrected for by measuring ^{36}Ar and using $(^{40}\text{Ar}/^{40}\text{Ar})_{\text{atm}} = 295.5$. Argon loss also happens easily, because it is a rare gas with no ionic or covalent bonding in crystals: only the weak van der Waals forces bind Ar to other species.

“Poor” Chronometers: Isochrons

For a second class of chronometers, the condition $D_0 \ll D$ does not apply, and we replace it by the principle of isotopic homogenization. Isotope fractionation (both natural and analytical) is simply corrected for by internal normalization against some arbitrary reference ratio of stable isotopes, for example, $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ for Hf. In marine carbonates, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is exactly the same in calcite as in the seawater from which it precipitated; as the mantle melts, $^{176}\text{Hf}/^{177}\text{Hf}$ is the same in the molten liquid as in the residue. Let us therefore divide Eq. (3) by the number D' of atoms of a stable isotope of the same element as the radioactive nuclide represented by D . Because the system is closed, D' remains constant, and therefore,

$$\left(\frac{D}{D'}\right)_t = \left(\frac{D}{D'}\right)_0 + \left(\frac{P}{D'}\right)_t (e^{\lambda t} - 1) \quad (9)$$



Geochronology, Fig. 2 ^{39}Ar – ^{40}Ar in the gas fractions released by stepwise heating of the Martian meteorite ALH 84001 (Bogard and Garrison 1999), which has been suggested to host microfossils. By irradiation in a nuclear reactor, fast neutrons change the ^{39}K of the sample (which is in constant proportion with ^{40}K) into ^{39}Ar . The $^{39}\text{Ar}/^{40}\text{Ar}$ is a substitute for the $^{40}\text{K}/^{40}\text{Ar}$ ratio. The ages are plotted as

a function of the progressive release of ^{39}Ar . A plateau age (here 4.3 Ga) indicates that large fractions of the sample kept the memory of the same chronological event. Anomalous ages at low temperatures (small fractions of ^{39}Ar released) indicate partial resetting by weathering or reheating. Anomalous ages at high temperatures indicate trapping of anomalous Ar components

This is the standard “isochron” equation. Figure 3 shows how an isochron based on the system ^{176}Lu – ^{176}Hf :

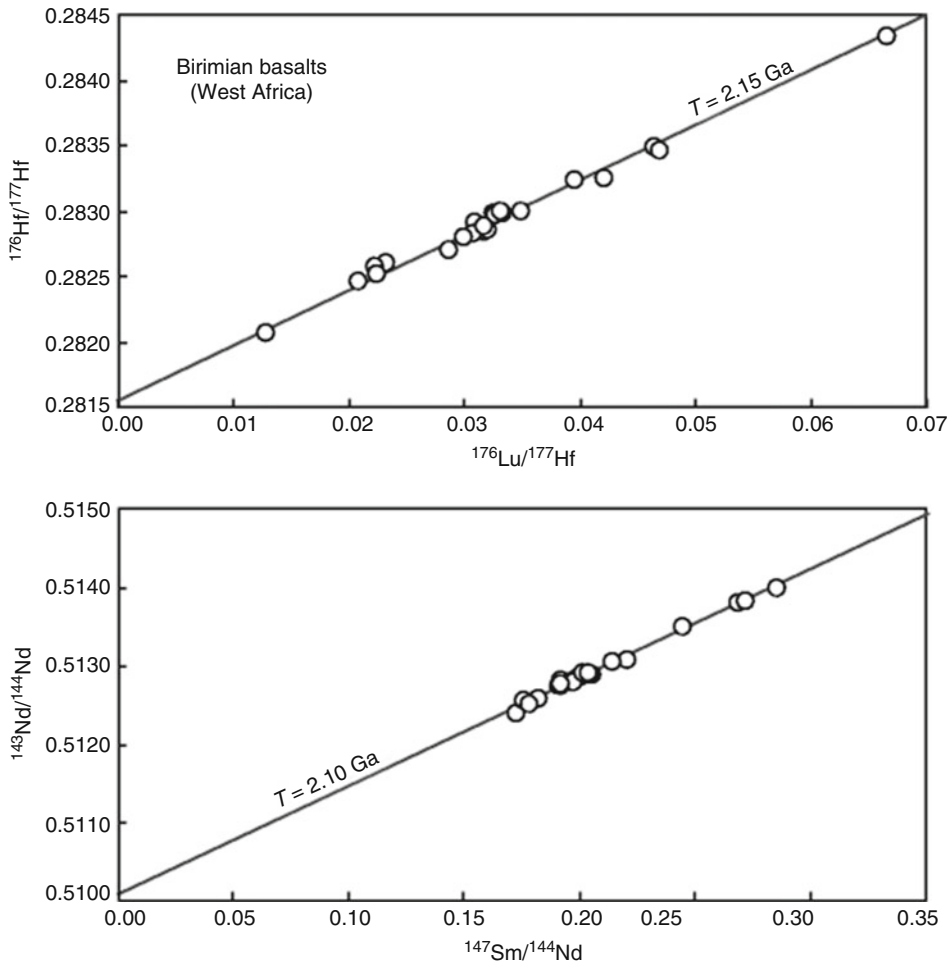
$$\left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}}\right)_t = \left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}}\right)_0 + \left(\frac{^{176}\text{Lu}}{^{177}\text{Hf}}\right)_t (e^{\lambda_{176}\text{Lu}t} - 1) \quad (10)$$

and a similar isochron based on the system ^{147}Sm – ^{143}Nd date 2.1 Ga old Birimian basalts from West Africa (Blichert-Toft et al. 1999). D/D' represents the ratio of the radiogenic nuclide to its stable isotope (e.g., $^{176}\text{Hf}/^{177}\text{Hf}$), and P/D' is the “parent/daughter” ratio, in most cases proportional to an elemental ratio (e.g., $^{176}\text{Lu}/^{177}\text{Hf}$). If two samples 1 and 2 formed at the same time from an isotopically homogeneous medium (ocean, magma), they share the same $(D/D')_0$, and, taking

the ^{176}Lu – ^{176}Hf system as an example, the time is obtained from

$$t = \frac{1}{\lambda_{176}\text{Lu}} \ln \left[1 + \frac{\left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}}\right)_2 - \left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}}\right)_1}{\left(\frac{^{176}\text{Lu}}{^{177}\text{Hf}}\right)_2 - \left(\frac{^{176}\text{Lu}}{^{177}\text{Hf}}\right)_1} \right] \quad (11)$$

This age dates the time at which the two samples last shared the same $^{176}\text{Hf}/^{177}\text{Hf}$ ratio, and their parent/daughter ratios (here Lu/Hf) were fractionated. This method is commonly used for parent/daughter systems with a long half-life, typically ^{147}Sm – ^{143}Nd , ^{176}Lu – ^{176}Hf , and ^{187}Re – ^{187}Os . The ^{87}Rb – ^{87}Sr technique is broadly used to date medium-temperature metamorphic events, ^{147}Sm – ^{143}Nd for the emplacement of ancient basalts and komatiites, ^{176}Lu – ^{176}Hf in



Geochronology, Fig. 3 Two examples of isochrons, using the ^{176}Lu - ^{176}Hf (top) and ^{147}Sm - ^{143}Nd (bottom) systems on the same early Proterozoic basalts from West

Africa (Blichert-Toft et al. 1999). Slopes of these isochrons give the age at which these volcanic rocks were extracted from the mantle

garnets for high-temperature ($>600^\circ\text{C}$) metamorphic events, and ^{187}Re - ^{187}Os for the deposition of reduced sediments (black shales) and some ores.

A particular application is the Pb-Pb method, which combines the two chronometers ^{206}Pb - ^{238}U and ^{207}Pb - ^{235}U . Equation (6) for the former system slightly modified as

$$\left(\frac{^{207}\text{Pb}}{^{204}\text{Pb}}\right)_t - \left(\frac{^{207}\text{Pb}}{^{204}\text{Pb}}\right)_0 = \left(\frac{^{235}\text{U}}{^{204}\text{Pb}}\right)_t (e^{\lambda_{235}t} - 1) \quad (12)$$

is divided by the equation for the latter

$$\left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_t - \left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_0 = \left(\frac{^{238}\text{U}}{^{204}\text{Pb}}\right)_t (e^{\lambda_{238}t} - 1) \quad (13)$$

to give

$$\begin{aligned} \frac{\left(\frac{^{207}\text{Pb}}{^{204}\text{Pb}}\right)_t - \left(\frac{^{207}\text{Pb}}{^{204}\text{Pb}}\right)_0}{\left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_t - \left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_0} &= \frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*} \\ &= \frac{1}{137.88} \times \frac{e^{\lambda_{235}t} - 1}{e^{\lambda_{238}t} - 1} \end{aligned} \quad (14)$$

where we used the observation that, today, the $^{238}\text{U}/^{235}\text{U}$ ratio is constant and equal to 137.88.

The asterisk stands for radiogenic Pb. Here the two parent nuclides on the one hand and the two daughter nuclides on the other hand are isotopes of the same element, which dispenses the analyst from measuring the U and Pb contents. In a plot of $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$, samples formed at the same time from the same reservoir define a straight line (another isochron) (Fig. 4), and the formation age can be retrieved from the slope. Historically, this is how Clair C. Patterson determined the age of the solar system. For statistical reasons, it is today common practice to use a $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{204}\text{Pb}/^{206}\text{Pb}$ isochron plot instead, in which the intercept, and not the slope, of the isochron gives the $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ratio and therefore the age. Figure 4 shows an isochron representing the Pb-Pb data on chondrules, little spherical blebs of molten material, and calcium-aluminum-rich refractory inclusions (► CAIs) from the ► carbonaceous chondrite Allende (Connelly et al. 2008), which represents one of the finest attempts to date an early sample of planetary material.

Extinct Radioactivities

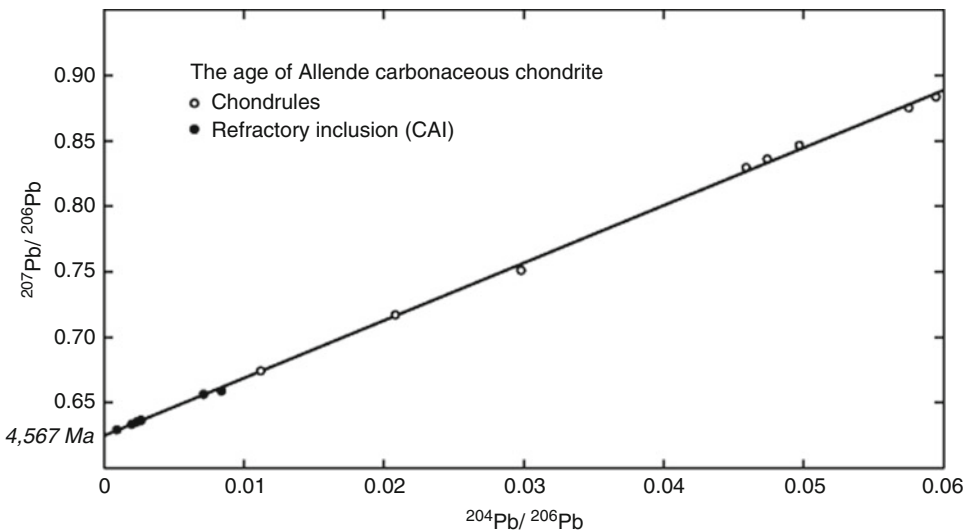
A third class of chronometers relevant to astrobiology is that of extinct radioactivities. These have a short half-life (and therefore a large λ). For large values of λt , P becomes negligible, and therefore the closed-system condition reads

$$D_{\text{today}} = P_t + D_t \quad (15)$$

Let us write this equation for a sample (spl) and divide it by the abundance $(D')_t = (D')_{\text{today}}$ of a stable isotope of D

$$\left(\frac{D}{D'}\right)_{\text{today}}^{\text{spl}} = \left(\frac{D}{D'}\right)_t^{\text{Earth}} + \left(\frac{P}{P'}\right)_t^{\text{Earth}} \left(\frac{P'}{D'}\right)_{\text{today}}^{\text{spl}} \quad (16)$$

in which we introduce P' , a stable isotope of the parent nuclide ($P'_t = P'_{\text{today}}$). Using Eq. (9), this equation is equivalent to



Geochronology, Fig. 4 A Pb-Pb “inverse” isochron of refractory calcium-aluminum-rich inclusions and chondrules (small blebs of molten silicates) (Connelly et al. 2008), which accounts for most of the material in the

carbonaceous chondrite Allende. The age given by the intercept (no stable ^{204}Pb , so Pb is purely radiogenic) gives 4567 Ma, one of the oldest estimates of the age of the solar system

$$\left(\frac{D}{D'}\right)_{\text{today}}^{\text{spl}} = \left(\frac{D}{D'}\right)_{\text{today}}^{\text{Earth}} + \left(\frac{P}{P'}\right)_t^{\text{Earth}} \times \left[\left(\frac{P'}{D'}\right)_{\text{today}}^{\text{spl}} - \left(\frac{P'}{D'}\right)_{\text{today}}^{\text{Earth}} \right] \quad (17)$$

For the example of the ^{182}Hf – ^{182}W chronometer ($T_{1/2} = 8.9$ Ma) (Fig. 5), this equation reads

$$\left(\frac{^{182}\text{W}}{^{183}\text{W}}\right)_{\text{today}}^{\text{spl}} = \left(\frac{^{182}\text{W}}{^{183}\text{W}}\right)_{\text{today}}^{\text{Earth}} + \left(\frac{^{182}\text{Hf}}{^{180}\text{Hf}}\right)_t^{\text{Earth}} \times \left[\left(\frac{^{180}\text{Hf}}{^{183}\text{W}}\right)_{\text{today}}^{\text{spl}} - \left(\frac{^{180}\text{Hf}}{^{183}\text{W}}\right)_{\text{today}}^{\text{Earth}} \right] \quad (18)$$

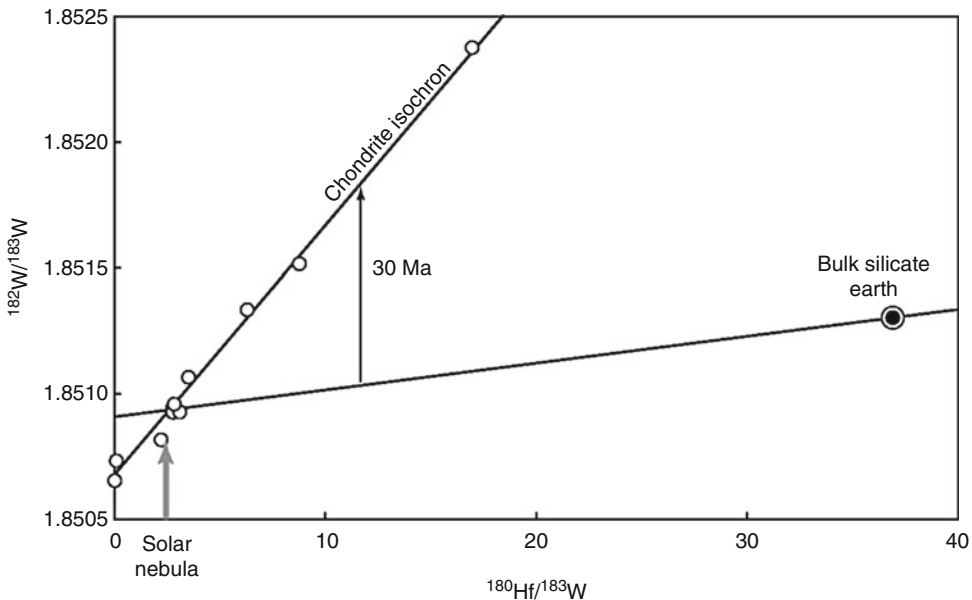
This is the equation of the extinct radioactivity isochron. The conventional isochron cannot be used when all the parent nuclides have decayed away. When $^{182}\text{W}/^{183}\text{W}$ is plotted against $^{180}\text{Hf}/^{183}\text{W}$ (note that the two nuclides of the latter ratio are both stable), samples formed at the same time in isotopic equilibrium within the

Earth (e.g., mantle and core) define a straight line. The slope of this isochron varies with time as

$$\frac{\left(\frac{^{182}\text{W}}{^{183}\text{W}}\right)_{\text{today}}^{\text{spl}} - \left(\frac{^{182}\text{W}}{^{183}\text{W}}\right)_{\text{today}}^{\text{Earth}}}{\left(\frac{^{180}\text{Hf}}{^{183}\text{W}}\right)_{\text{today}}^{\text{spl}} - \left(\frac{^{180}\text{Hf}}{^{183}\text{W}}\right)_{\text{today}}^{\text{Earth}}} = \left(\frac{^{182}\text{Hf}}{^{180}\text{Hf}}\right)_t^{\text{spl=Earth}} = \left(\frac{^{182}\text{Hf}}{^{180}\text{Hf}}\right)_0^{\text{Earth}} e^{-\lambda_{^{182}\text{Hf}} t} \quad (19)$$

Extracting time from this equation requires that $(^{182}\text{Hf}/^{180}\text{Hf})_0$ of the Earth is known. However, dividing this equation for the core ($^{182}\text{Hf} \approx 0$) by the same equation for the mantle gives the age mantle-core separation.

This method is employed for a number of “extinct” short-lived nuclides. The chronometers ^{26}Al – ^{26}Mg ($T_{1/2} = 700,000$ Ma), ^{60}Fe – ^{60}Ni ($T_{1/2} = 2.6$ Ma), ^{53}Mn – ^{53}Cr ($T_{1/2} = 3.7$ Ma), ^{182}Hf – ^{182}W ($T_{1/2} = 8.9$ Ma), and ^{129}I – ^{129}Xe ($T_{1/2} = 15.7$ Ma) provide essential chronological information on the accretion of planetary material



Geochronology, Fig. 5 Dating of core-mantle segregation by the ^{182}Hf – ^{182}W method (Yin et al. 2002). The difference in slope between the alignment of the points representing the chondrites and that representing the silicate Earth is a measure of the last fractionation of the Hf/W

ratio. Tungsten fractionates into the metal and Hf into the silicate. The point of intersection of the two lines represents the unfractionated solar nebula. The difference in slopes show that core-mantle separation in the Earth occurred some 30 Ma after the formation of the solar system

from the solar nebula, its thermal history, and metal-silicate (core-mantle) segregation, while the ^{146}Sm – ^{142}Nd ($T_{1/2} = 103$ Ma) system proved essential to demonstrate the existence of very early crust.

Closure Temperatures

What chronology dates is actually not discrete formation events. Upon cooling, minerals keep exchanging radiogenic isotopes with their surroundings: the chronometric system is open. In most cases, what a chronometer records is therefore the time at which diffusion stopped (Fig. 6). Diffusion of a particular ion is a thermally activated molecular process of exchange between adjacent minerals or between a phase and the interstitial medium and is characterized by the energy of activation E and the so-called pre-exponential term D_0 . If cooling is fast, the closure temperature T_c (in K) is given by Dodson's (1973) implicit equation:

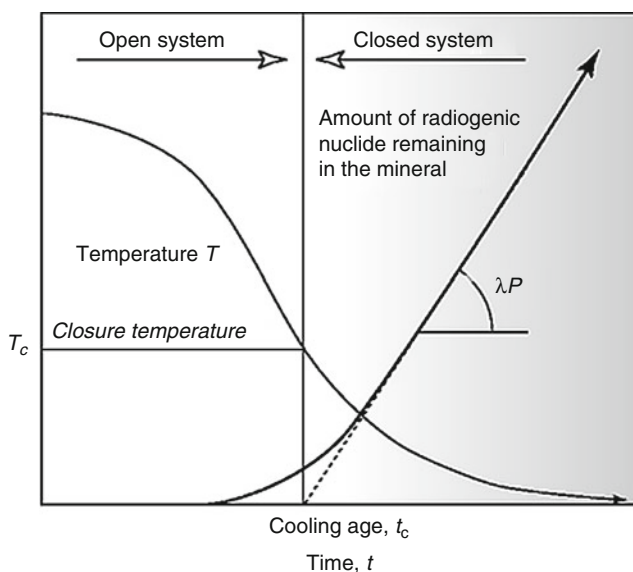
$$T_c = \frac{E}{R \ln [AD_0RT_c^2/Ea^2(-dT/dt)]} \quad (20)$$

in which R is the gas constant, a the grain size, $-dT/dt$ the cooling rate, and A a constant equal to 55. If cooling is fast, the radio-metric system dates the time at which temperature in the rock dropped below a particular value. The transition is usually fast (a few tens of degrees). Typical closure temperatures vary from 1000 °C for U-Pb in zircons to 800 °C for Pb-Pb in pyroxene and Lu-Hf in garnet and to 300 °C for K-Ar in feldspar and Re-Os in sulfides. If cooling is very slow, the system remains ajar for a long time, the demise of diffusion is sluggish, and the significance of the date is blurred.

Diffusion loss is one of the major issues of geochronology. Rocks from the sublithospheric mantle evolve for long times above the closure temperature and therefore cannot be dated by isotopic chronometers. The closure temperature varies as $2 \ln a$, so chronometers in smaller systems, first and foremost isolated crystals, close at a lower temperature than in the larger ones and may be easily reset by mild thermal events. Isochrons of large whole-rock samples are often used to mitigate this problem.

Geochronology,

Fig. 6 Cooling age and closure temperature of a chronometric system with decay constant λ . The cooling time and the corresponding cooling age t_c are defined by linearly extrapolating the ingrowth of radiogenic nuclides at zero, while the closure temperature T_c is the temperature of the mineral at this time. The system is open and loses the daughter isotope for $T > T_c$ and is closed for $T < T_c$. The slope of the daughter isotope evolution curve is the activity λP



Basic Methodology

Choosing a particular chronological system to use for a given problem depends on the duration of the age or age difference to be assessed. Enough decay must have happened that it measurably affects the abundance of the daughter isotope. In practice, a chronometer gives no useful information if this interval exceeds five to eight half-lives.

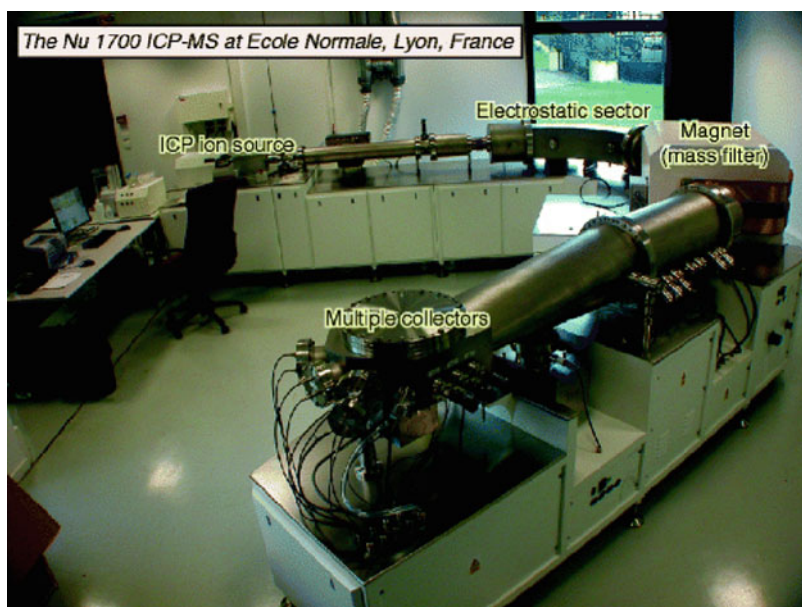
The elements for which the isotope composition is sought are isolated in a variety of ways. Gases are extracted by heating and purified in high vacuum enclosures. Solid samples are normally digested with strong acids (HF, HNO₃, HCl) in pressurized vessels and the metals usually separated by ion chromatography. Isotope ratios are measured on mass spectrometers, which combine a source of ions, electrostatic acceleration, a magnetic filter, and a set of detectors. These instruments differ by the nature of their ion sources. Gas sources use the bombardment of an electron beam to ionize atomic gases and are used for O, C, He, Ar, Xe, etc. Thermal ionization mass spectrometers (TIMS) produce ions by evaporative ionization at the surface of a hot filament and are used for Sr, Nd, Pb, and Os. Inductively coupled plasma mass spectrometers (ICP-MS) (Fig. 7) use Ar ions produced in a coil submitted to rapidly

fluctuating currents to ionize the other elements: this relatively new technique accounts for most measurements for Hf, W, Mg, and Fe. Sputtering of the sample by a $\sim 30\ \mu\text{m}$ primary ion beam (SIMS or ion probe) is the method of choice for the in situ measurement of U-Pb ages in zircons (Fig. 8).

The precision of measurements is first and foremost limited by counting statistics: a mass spectrometer can be seen as a device counting ions arriving on a detector. The measurement can therefore be seen as another Poisson process, which for n “events” must be associated with a standard deviation of $\sqrt{n}$ and a relative error of $1/\sqrt{n}$. Let us assume that we use an ion probe with a $30\ \mu\text{m}$ beam size to measure the abundance of ^{207}Pb in a zircon crystal with density of $4.65\ \text{g cm}^{-3}$ and which contains 100 ppm Pb. We also assume that the beam excites a hemispherical volume below the spot and a 1% ion yield. We must therefore divide the weight of sputtered material by the molecular weight of Pb and multiply by the isotopic abundance of ^{207}Pb and finally multiply by the Avogadro number to obtain $\sim 0.01 \times (2/3 \times 3.14) \times (15 \times 10^{-4})^3 \times 4.65 \times 100 \times 10^{-6} / 207.2 \times 0.22 \times 6.0 \times 10^{24} = 2.1 \times 10^8$ counts (approximate numbers suffice), i.e., an excellent precision of 0.007%. Reducing the

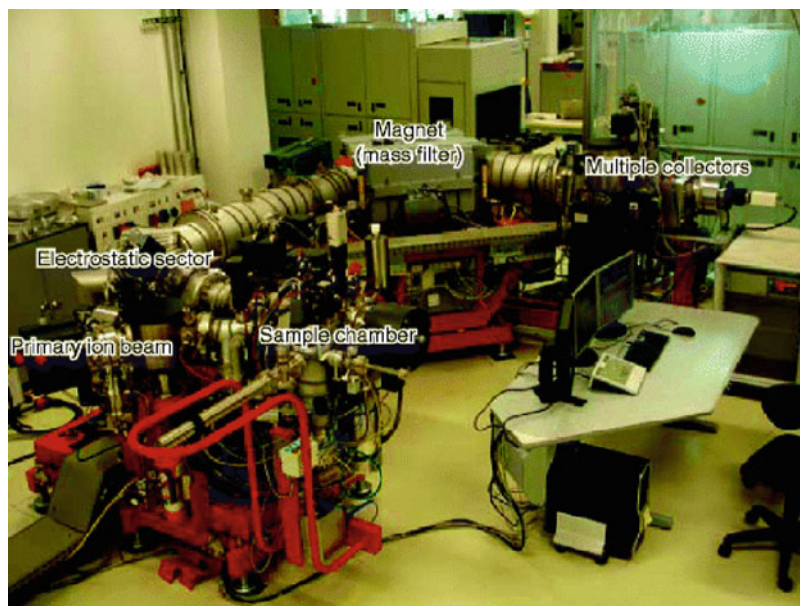
Geochronology,

Fig. 7 The Nu 1700 large radius MC-ICP-MS (multiple-collector inductively coupled plasma mass spectrometer) of Ecole Normale Supérieure in Lyon, France. The essential parts of the mass spectrometer are shown. This instrument can measure the isotope composition of most ions on quantities as small as 10 ng (one billionth of a gram) with a precision of 0.005% or better



Geochronology,

Fig. 8 The Cameca 1280 ion probe (secondary ion mass spectrometer) of the Centre de Recherches Pétrographiques et Géochimiques de Nancy, France



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beam size to 1 μm would deteriorate the precision to 1% and make the measurement essentially worthless. The quest for ages on smaller and smaller objects is intrinsically limited by the desired precision.

A second stringent limitation is contamination, which for many elements such as Pb forces the analyst to work in ultra-clean environments with filtered air and distilled reagents. Not all contamination and common Pb can be removed and hence constitutes a significant source of uncertainty on ages. A third problem affects the chronometers based on beta decay: the kinetic energy of some emerging electrons is so small that they go undetected, and the corresponding decay constant cannot be accurately determined. This is a limitation for the ^{87}Rb – ^{87}Sr , ^{176}Lu – ^{176}Hf , and ^{187}Re – ^{187}Os techniques, which can be mitigated to some extent by a cross-calibration with U–Pb ages.

Finally, a general limitation arises when data expected to form an alignment actually scatter beyond analytical errors. This can be due to (1) a lack of isotopic homogeneity at $t = 0$; (2) the failure of the closed-system assumption because of weathering or thermal resetting; and (3) a long duration of the event to be dated, for example, in case of slow cooling. The literature on least-

square regression with correlated or noncorrelated errors is abundant, but a standard reference is that of York (1969). Among all the codes used to evaluate alignments, the most broadly used software is ISOPLOT created by Ludwig (2003).

Cross-References

- [Absolute and Relative Ages](#)
- [Earth, Age of](#)
- [Isochron](#)
- [Isotope](#)
- [Isotopic Ratio](#)
- [Mass Spectrometry](#)
- [Radioactivity](#)

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Geoethics

Jesús Martínez-Frías

Instituto de Geociencias, IGEO (CSIC-UCM), Madrid, Spain

Definition

Geoethics (from Greek γῆ/γῆ “Earth” and -ἠθικός/ἠθικός “ethics”) is an interdisciplinary field between Geosciences and Ethics which involves Earth and Planetary Sciences as well as applied ethics. It deals with the way of human thinking and acting in relation to the significance of the Earth as a system and as a model. Geoeducational, scientific, technological, methodological, and social-cultural aspects are included (e.g., sustainability, development, geodiversity and geoheritage, prudent consumption of mineral resources, appropriate measures for predictability and mitigation of natural hazards, geoscience communication, museology). In addition, the necessity of considering appropriate protocols, scientific integrity issues,

and a code of good practice – regarding the study of the abiotic world – is covered by this discipline. Studies on planetary geology (sensu lato) and *astrobiology* also require a geoethical approach (Martínez-Frías 2008; IAGETH 2011).

History

The term Geoethics was born in 1991 in Příbram (Czech Republic) and Dr. Vaclav Nemec is considered the father of this discipline (Nemec 1992). Meetings, symposia, workshops and specific sessions, and various initiatives on Geoethics have been organized in various countries (Czech Republic, China, Germany, Japan, Mozambique, Paraguay, Poland, Spain, among others) and more regularly in Russia and Italy. The international institutionalization of geoethics was established in 2004, by forming a working group with the backing of the Association of Geoscientists for International Development (AGID). In 2008, Geoethics was, for the first time, incorporated in the official program of the 33rd International Geological Congress under the auspices of AGID, in Oslo. In 2011, a new international, peer review, open access journal *Geosciences* was introduced, which, for the first time, comprised Geoethics as one of its subject areas (Martínez-Frías 2011), and the First International Declaration on Geoethics was launched in Příbram, under the AGID umbrella (AGID_Geoethics 2011). 2012 was a key year for geoethics: (a) two international organizations about this discipline were affiliated to the IUGS; (b) geoethics was included and mentioned in the United Nations Conference on Sustainable Development (UNCSD) or Earth Summit Rio + 20 (Riccardi 2012), which was held in Rio de Janeiro (Brazil), and (c) the first monograph about geoethics (Nikitina 2012) was published in Russia.

Geoethics is a discipline which covers all the key subjects, essential knowledge, deontological behavior, and methodological and practical issues linking Ethics and Geosciences. A significant development in space science and technology has been achieved in the past century. Geoscientists have new skills and tasks linking different

disciplines, applying different methodological procedures and technologies, and facing new scientific, social, and cultural challenges, from micro- to macroscale studies, and from land, atmosphere, and oceans to planetary exploration (including their responsibility and implications in the search for life beyond Earth – given the significant role of planetary geology in *astrobiology*) (Martínez-Frías et al. 2011). Hence, Geoethics refers basically to all ethical subjects related to the abiotic world on Earth and also in other planets, moons, and planetary bodies. In this sense, it has been proposed that the incorporation of the geoethical and geodiversity issues in planetary geology and astrobiology studies would enrich their methodological and conceptual character (Martínez-Frías 2008; Martínez-Frías et al. 2009a, b). The International Association for Geoethics (IAGETH), which is affiliated to the IUGS and IUGG, is the only organization, linking ethics and geosciences, which included planetary geology and *astrobiology* in its foundational definition and goals (IAGETH 2011), and it has supported several symposia and initiatives about these subjects (ICOG 2018). The incorporation, through geoethics, of new questions associated to the *abiotic world* is, besides widening the classical concept of Planetary Protection (Rummel et al. 2002), giving an additional dimension to the geological research of the solar system. *Astrobiology* is part of the “Geoethical dilemmas through the prism of new challenges of time,” which were included in the IAGETH Plan of Activities (IAGETH 2013) and, in this framework, several initiatives linking geoethics and astroethics were developed (e.g., an international working group on astroethics was founded in 2016 in close collaboration with the TD 1308 COST Action ORIGINS) (Martínez-Frías 2016; Martínez-Frías and Gargaud 2016). One of the main tasks of the WG (IAGETH 2017) is to analyze the potential societal and ethical implications related to *astrobiology*, taking into account the complexity of the connections between its main scientific issues and goals, and considering the synergies between both bioethical and geoethical approaches (from microbes to humans and from the Earth to space environments).

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Geolipids

► Molecular Fossils

Geological Time Scale, History of

Pierre Savaton

Université de Caen Basse-Normandie, Caen, France

Keywords

Chronology · Radiometric dating · Stratigraphic scale

History

Geology is the first historical science. Concept of time is a key concept in geology. Even if some geological processes operate over time of a few seconds (e.g., earthquake waves), most of them operate over million to hundreds of millions of years. Thus, to tell the Earth's history, we need to build a geological time scale to place geological events and measure their length. This scale results from a combination of time and space relations between rock formations (relative age) and from the measure of spontaneous decay of radioactive nuclides contained in rocks (absolute age). The only record we have of past geological events is the rock preserved from erosion, alteration, and plate tectonics.

The geological time scale was first a chronological one, without date. Study of sedimentary rocks had allowed first "geologists" to establish the simple basis for the stratigraphic scale.

Danish naturalist Nicolas Steno (1638–1686) noted that gravels, sands, and clays were laid down in more or less horizontal layers, which he called strata. In 1669, in his *Prodromus (De solido intra solidum naturaliter content dissertations prodromus)*, he enunciated principles of stratigraphy: original horizontality, superposition, and lateral original continuity of layers. Using these

principles, it was possible to arrange layers in a chronological succession, and some attempts were tempted and offered local descriptions of the pile of stratas. Steno identified in these successions some angular unconformities, which represented breaks in the stratigraphical record, but without understanding their possible use in dating of geological events, even if he showed that "geology" revealed a history. By contrast, he recognized that fossils were the remains of once living organisms. In 1667, working in Tuscany, he noted that shark teeth bore a striking resemblance to some stony objects found embedded within rock formations, called "tongue stones."

English philosopher Robert Hooke (1635–1703) considered fossil's shells as medals or monuments of nature, as greatest and more lasting monuments and records of antiquity. He claimed that animals living today might not have been alive in the past and animals presented in the past were no longer present today. He interpreted the differences between past and actual faunas by imagining a kind of transformation of species in time. This idea was taken back later by Leibniz before being developed and theorized by Jean-Baptiste Lamarck. But it was too premature for the 1600s. Hooke used for the first time the word "chronology" and suggested a powerful tool to date geological layers. These medals (fossils) allowed establishing continuity between layers separated by great distance or layers of different lithology. They allowed replacing geographical isolated layers in a succession. Robert Hooke might be considered a precursor of the idea of index fossil, that is, fossils of organisms that lived in a short time span but widely distributed geographically. But the time-keeper aspect of fossil's records remained marginal for a long time.

German geologist and mineralogist Abraham G. Werner still had neglected them in his *Kurze Klassifikation und Beschreibung der verschiedenen Gebürsarten* (1783), a stratigraphical framework attempt that was widely adopted like scheme of the succession of geological times. Fossils were just used to characterize his *formations*, but no more. Faunal succession, as the lithologic succession, could be used directly to identify rocky formations. This approach was that

used by British geologist William Smith to build his *Geological Map of England and Wales and part of Scotland* (1815). His *Strata identified by organized fossils* (1816–1819) paved the way for the development of the biostratigraphy. George Cuvier's and Alexandre Brongniart's map and *Description géologique des environs de Paris* (1811) proposed to use fossils to distinguish marine from continental sediments and to explain succession of sedimentological events. They used them as indicators of paleoecological conditions rather than strict stratigraphical tools.

In a few decades in the early 1800s, the geologists who mapped the world established a time scale based on assemblages of fossils, far more complex than the earlier succession of rocks (primary, secondary, tertiary) of the 1700s based on a lithological time scale.

Time and history of the Earth was divided in time units chronologically distinguished both by their vertical spatial relationships and their fossils content. Fossils determined a major division between the early time of the Earth, without visible fossils and the Phanerozoic time (today the fourth *eon*) characterized by its fossil diversity. Phanerozoic was subdivided into eras, periods, and epochs. The development of a systematic palaeontology during the nineteenth century and studies of some of the less visible one revealed new fossil discontinuities in the time and justified new subdivisions. French naturalist Alcide d'Orbigny showed how microscopic fossils, especially Foraminifera, could be used to characterize Cenozoic stratas. Paleontologists who studied the Jurassic ammonites identified species with a very short time range and suggested to use them to define small biostratigraphic units (biozones).

The theory of the Evolution of Darwin (1859) wasn't necessary to think a biostratigraphic scale, but gave a new breath to the fossil's tool. The succession of changing fauna could be explained by successive destructions and creations, migrations, or evolution. In the continuity of Cuvier thinking, most of the first stratigraphers favored extinctions. Proposing that new species emerged as a result of modifications to earlier species was more powerful. But the theory of evolution obliged to reconsider the age of the

Earth, because progressive changes required longer time.

The Archbishop Ussher of Ireland wrote in 1664 that the Earth was created 4,004 years before Christ. He had not been alone to interpret the Bible word for word to determine the antiquity of the Earth. All these biblical ages were very short. George Buffon, who believed in a cyclical history of the Earth, clearly longer than that given in the biblical accounts, published in his *Epoques de la Nature* (1778) an empirical calculation of the age the Earth. Following the idea that the Earth might originally have been molten, he measured the cooling time of iron balls of different sizes, and other materials, and concluded through this model that Earth should have been 75,000 years old. This duration was to great enough for many of his contemporaries.

The uniformitarian's ideas spread by British geologist Charles Lyell suggested estimating the actual age of the Earth using sediment accumulation or denudation rate as indicators of time. John Phillips transformed the unit of geological time into an equivalent term of years and proposed in 1860 in *Life on the Earth* an age of Phanerozoic time between 38 and 96 million of years. It wasn't enough for explaining the evolution theories of Darwin but compatible with ages calculated by British physicist William Thomson (better known as Lord Kelvin) through his model of a cooling Earth. Most of the geologists of the 1800s believed that Earth of the first time had been molten. Solid today, still hot, it would lose heat by conduction, compatible with the increasing temperatures recorded in mines or boreholes. In 1862, using Fourier's laws of cooling, Thomson estimated the Earth's center temperature to about 3,800 °C and the age of the Earth to about 20–400 million years. In 1897, Thomson, now Lord Kelvin, ultimately settled on an estimate that the Earth was 20–40 million years old.

The discovery of radioactivity by Henri Becquerel in 1896 and the isolation of radium by Pierre and Marie Curie in 1898 changed the classic view of a cooling Earth and offered to geology the tool it needed to measure time. The work of Rutherford and Soddy about radioactive decay series and the discovery that lead was the end

product of the uranium decay chain by American chemist Bertram Boltwood in 1905 stated the fundamental basis of radiometric dating and allowed geologists to put absolute dates in their geological column. Using what he knew about radium-lead decay, Boltwood aged rocks from 250 million to 1.3 billion years old. Although his estimate of the Earth's age was inaccurate, his paper, published in 1907, made clear that sediments from the same layers had similar uranium-lead ratios and that generally samples from younger layers had a lower proportion of lead.

In 1911, British geologist Arthur Holmes determined an age of 1,640 million years for Archean rocks and published in 1913, in *The Age of the Earth*, the first stratigraphic time scale with radioactive ages for the boundaries of the main units. He estimated the beginning of the Phanerozoic time at about 600 million years before present (today this limit is fixed at 542 Ma). Arthur Holmes's time scale established in 1947 was very similar than these of today. Working on lead isotopes in iron and stone meteorites, American geochemist Clair Patterson established and published in 1956 an age of the Earth of $4,550 \pm 70$ million years.

With fossil's chronology of sedimentary rocks and radioactive age of crosscutting igneous rocks, geologists have built the geological time scale. Earth history could finally be told.

Cross-References

- [Cuvier's Conception of Origins of Life](#)
- [Darwin's Conception of the Origins of Life](#)
- [Earth, Age of](#)
- [Geochronology](#)
- [Geological Timescale](#)
- [Lamarck's Conception of Origins of Life](#)

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Geological Timescale

Felix M. Gradstein

University of Oslo, Oslo, Norway

Definition

The Geologic Time Scale is the framework for deciphering and understanding the long and complex history of the Earth. Understanding the physical, chemical, and biological processes since the Earth formed requires a detailed and accurate timescale. The timescale is the tool “par excellence” of the geological trade (Gradstein et al. 2004; Ogg et al. 2008).

History

British geologist Arthur Holmes (1890–1965) was the first to combine radiometric ages with geologic formations in order to create a geologic timescale. His book, *The Age of the Earth* (1913, 2nd edition 1937), written when he was only 22, had a major impact on those interested in ► [geochronology](#). For his pioneering scale, Holmes carefully plotted four radiometric dates, one in the Eocene and three in the Paleozoic from radiogenic helium and lead in uranium minerals against estimates of the accumulated maximum thickness of Phanerozoic sediments. If we ignore sizable error margins, the base of Cambrian interpolates at 600 Ma, curiously close to modern estimates (541 ± 1.0 Ma). The new approach was a major improvement over a

previous “hour-glass” method that tried to estimate maximum thickness of strata per period to determine their relative duration but had no way of estimating rates of sedimentation independently.

Overview

Calibration to linear time of the succession of events recorded in the rocks on Earth has three components: (a) the international stratigraphic divisions and their correlation in the global rock record; (b) geochronology, the means of measuring linear time or elapsed durations from the rock record; and (c) the methods of effectively joining the two scales, the stratigraphic one and the linear one.

For clarity and precision in international communication, the rock record of Earth history is subdivided into a “chronostratigraphic” scale (Fig. 1) of standardized global stratigraphic units, such as “Devonian,” “Miocene,” “*Zigzag* ammonite zone,” or “polarity Chron C25r.” This chronostratigraphic calendar is not unlike a historical calendar in which civilization periods, such as the Minoan Period, Reign of Louis XIV, or American Civil War are used as building blocks, devoid of a linear scale. Archeological relics deposited during these intervals, such as the Palace of Minos on Crete, Versailles, or spent cannon balls at Gettysburg, comprise the associated physical chronostratigraphic record.

The chronostratigraphic scale is thus assembled from rock sequences stacked and segmented in relative units based on their unique fossil and physical content. This scale becomes meaningful and useful through correlation of the unique fossil and physical record to other sections of sedimentary or volcanic rocks in outcrops or wells across the globe.

The standard chronostratigraphic scheme, in downloadable graphic format and available from the International Commission of Stratigraphy (ICS) website (<http://www.stratigraphy.org/index.php/ics-chart-timescale>), is made up of successive stages in the rock record, for example, Cenomanian, Turonian, then Coniacian, etc.,

within the Cretaceous System. The chronostratigraphic scale is an agreed convention, whereas its calibration to linear time is a matter of discovery or estimation. The estimation comes from radiometric dating and astrochronology (orbital tuning of long sets of cycles) in the sedimentary rock record and is continually refined. Thus, the chronostratigraphic chart is updated, usually once a year.

In contrast to the Phanerozoic which has an agreed-upon chronostratigraphic scale with formal stage boundary stratotypes, Precambrian stratigraphy is formally classified chronometrically (see ► [Proterozoic Eon](#)).

Cross-References

- [Archean Eon](#)
- [Earth, Age of](#)
- [Geochronology](#)
- [Geological Time Scale, History of](#)
- [Hadean](#)
- [Proterozoic Eon](#)

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Geology of mars

- [Areology](#)

Geomicrobiology

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Geomicrobiology examines the role of microbes in geological processes. Examples of such processes are the weathering of rocks, soil and sediment formation and transformation, the genesis and degradation of minerals, and the genesis and degradation of fossil fuels. Due to its transdisciplinary essence and the subject of study, geomicrobiology is of special astrobiological interest.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [Bacteria](#)
- [Biogeochemical Cycles](#)
- [Chemolithotroph](#)
- [Deep Subsurface Microbiology](#)
- [Environment](#)
- [Hot Spring Microbiology](#)
- [Iron](#)
- [Iron Cycle](#)
- [Lithotroph](#)
- [Magnetotactic Bacteria](#)
- [Prokaryote](#)
- [Sulfate Reducers](#)
- [Sulfur Cycle](#)

Geotherm

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Within a planet, the *geotherm* is the functional relationship between temperature T and depth

z below the surface. The geothermal gradient defines the increment of temperature per increment of depth, typically 30 °C per kilometer. Next to the surface, the geotherm is dominated by heat conduction. At steady-state, the curvature of the (T, z) curve reflects the distribution of heat sources, including radioactive heat production. The shallow geotherm is perturbed by porous fluid migration. At depth, mantle convection controls the geotherm, and variations in the properties of rocks (conductivity, thermal expansion, and compressibility) should be taken into account.

Cross-References

- [Geothermal Gradient](#)
- [Heat Transfer, Planetary](#)

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Geothermal Flux

- [Heat Flow, Planetary](#)

Geothermal Gradient

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble, France

Definition

The *geothermal gradient* is the increase in temperature with increasing depth, beneath the Earth's surface. This gradient is due to the outward heat flow from the hot interior (around 46 terawatts at the Earth's surface). Old geophysical models suggested that Earth's internal heat derives from a combination of residual heat from

planetary ► [accretion](#) (20%) and heat produced through radioactive decay of U, Th, and K (80%). Geoneutrinos measurements suggest however that the heat flow from radioactive decay could be much less, around 50% of the total heat (e.g., Korenaga, 2011). The magnitude of the geothermal gradient depends on the rate of heat production at depth, the dynamics of the system, and the conductivity of rocks. The highest gradients, 40–80 K km⁻¹, are measured at oceanic spreading centers (► [mid-ocean ridges](#)) or at island arcs where magma is close to the surface. The lowest gradients occur at ► [subduction](#) zones where cold lithosphere descends into the mantle. The gradient in old stable ► [continental crust](#) is ~30 K km⁻¹ and is somewhat lower in ► [cratons](#). Upwelling parts of the mantle ascend nearly adiabatically (i.e., they lose little to no heat to the surroundings), and the gradient is very low, about 0.3 K km⁻¹.

Cross-References

- [Accretion](#)
- [Continental Crust](#)
- [Mid-Ocean Ridge](#)
- [Radioactive Heating](#)

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Geothermobarometers

Jean-Emmanuel Martelat
LST UMR5570, Université Claude Bernard Lyon
1, Grenoble, France

Keywords

Geobarometer · Geothermometer ·
Metamorphic rocks · Metamorphism

Definition

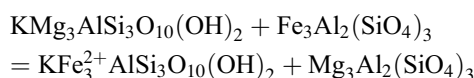
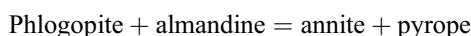
Geothermobarometers refer to all types of reactions that are useful to estimate temperature and pressure recorded in a magmatic or a metamorphic rock when it crystallizes or recrystallizes.

Overview

Minerals have different physical properties (e.g., volume, density, or entropy). When pressure increases, minerals such as quartz (density ≈ 2.66 g/cm³) may be metamorphosed into high-pressure polymorphs (e.g., for quartz: coesite, density ≈ 3.0 g/cm³). This kind of reaction is called polymorphic: the chemical composition remains SiO₂, but the atoms are rearranged in a more compact manner. On the other hand, as temperature increases, minerals such as kyanite (Al₂SiO₅) (standard entropy “S” at T = 298 $\approx$ 83 J/mol-K) may be metamorphosed into a high-temperature polymorph, sillimanite (Al₂SiO₅) (S at T = 298 K $\approx$ 93 J/mol-K), displaying a higher atomic disorder. Hence, a mineral or a mineral assemblage is sensitive to P-T conditions and is only stable within a given range of those conditions (see also ► [“Metamorphic Rock”](#) and ► [“Metamorphism”](#): metamorphic facies). Moreover, mineral compositions corresponding to a specific chemical equilibrium allow a quantitative estimate of P-T conditions: this method is called geothermobarometry. We use the term “geothermometer” for metamorphic reactions (or chemical equilibrium) that are highly sensitive to temperature and “geobarometer” for reactions that are sensitive to pressure.

Our ability to estimate or calculate the quantitative P-T conditions of a given rock depends on (1) the observation of the sample’s texture under the microscope, (2) the quality of the experimental calibration of the chemical reactions (stability field of mineral phases), (3) the accuracy of the thermodynamic properties of the minerals (database), and (4) the precision of chemical analyses on the minerals (e.g., with electron microprobes reaching a 1 μm^2 spot resolution).

On well-studied samples bearing relevant mineral assemblages, quantitative results can be obtained with an accuracy of ± 50 °C and ± 1 – 1.5 kbars. Several chemical reactions can help constrain the temperature. One of the most broadly used geothermometers is based on the diffusional exchange of Fe^{2+} and Mg^{2+} between garnet and biotite. Fe^{2+} and Mg^{2+} cations are easily exchangeable since they have similar electron valence and atomic radii. This exchange occurs without change in size of both the garnet and the biotite. The reaction is



where phlogopite and annite are the Mg- and Fe-pure end-member of biotite whereas pyrope and almandine are the Mg- and Fe-pure end-members of garnet, respectively. When temperature decreases, the Fe/Mg ratio decreases in biotite and increases in garnet. The most critical assumption behind temperature and pressure obtained by geothermobarometry is that equilibrium reactions were frozen during cooling. As diffusivity depends on temperature and on the distance between the exchange zones in the biotite and garnet in contact, one can obtain temperature gradients from the rim to the core of the given mineral pairs. Other equilibria can constrain temperature: e.g., polymorphic thermometer, solvus thermometer (e.g., feldspar exsolution), net transfer reaction thermometer (some minerals are consumed while others are produced), trace element thermometer, and stable isotope partitioning thermometer. Some other techniques, such as liquid–vapor homogenization points in fluid inclusions, provide quantitative thermometry results. The best way to obtain quantitatively the T and P recorded in rocks is to combine several internally consistent thermobarometers. Various freeware programs available on the Internet calculate numerous possible equilibria with respect to an internally consistent thermodynamic database for a large number of minerals (e.g.,

TWEEQ, Berman 1991; THERMOCALC, Powell et al. 1998).

Cross-References

- [Geothermal Gradient](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Plate Tectonics](#)

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Germ

- [Microorganism](#)

German Aerospace Center

- [DLR, Germany](#)

Geyser

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Hydrothermal environments · Yellowstone National Park · Extremophiles · Cryovolcanism · Enceladus

Synonyms

Geysir

Definition

The term geyser derives from Icelandic *Geysir*, a geyser in southwestern Iceland. Its name means “spurt out”. Geyser is a type of hot spring that intermittently erupts hot water and steam, caused by the hydrothermal activity in volcanic areas. The formation of geysers is related to the uprising of pressurized water in rock conduits, at superheated conditions. Decrease of pressure close to the surface makes superheated water to rapidly change into steam (flashing) driving the hot water eruption. After the pressure decreases to a threshold value, the eruption stops and the system pressurizes again to initiate the following eruption.

Overview

On Earth, there are two types of geysers: fountain geysers and cone geysers. Fountain geysers erupt directly from a pool of water, while cone geysers erupt from a mound made of siliceous sinter (opal) called geyserite. Old Faithful, the most well-known geyser at Yellowstone National Park, USA, is a cone geyser. On Earth, geysers exist almost everywhere where there is a vigorous hydrothermal system, but a few places concentrate large amounts of them. The largest concentration of geysers in the world (300–500) is at Yellowstone National Park, followed by the Valley of Geysers in the Kamchatka Peninsula of Russia (200 geysers) and El Tatio, Chile (80 geysers), with many others in the Taupo Volcanic complex, New Zealand, and in Iceland.

On Earth, geysers have an astrobiology interest because, despite the harsh conditions of life around geyser’s mounds and pools, thermophile ($<60\text{ }^{\circ}\text{C}$) and hyperthermophile ($<110\text{ }^{\circ}\text{C}$) prokaryotes can develop. Thus, geysers are niches favorable to extremophile life and likely natural analogue of harsh conditions in the Hadean and Archean Earth.

There are other planetary bodies in the Solar System showing jet eruptions similar to geysers. Icy-cold volcanism (cryovolcanism) is also able to

reproduce geyser-like features called cryo-geysers. The Voyager 2 flyby of Neptune in 1989 showed geyser-like eruptions on its moon Triton. These eruptions are thought to be made of liquid nitrogen and dust and they were driven by solar heating. Similar solar heating-driven eruptions are believed to occur in the south pole region of Mars during spring thaw. Finally, pulsating bright plumes emanating from Enceladus’ south pole have been discovered by the Cassini flyby in 2005. These were interpreted as geysers drawing from a large body of liquid water. Tidal forces induced by Saturn’s gravity probably create sufficient friction to partially melt the ice crust of Enceladus and to create liquid water pools from which the geysers originate. Thus, cryo-geysers on icy moons could bring to their surface water and organics.

Cross-References

- [Cryovolcanism](#)
- [Enceladus](#)
- [Hydrothermal Environments](#)
- [Hyperthermophile](#)
- [Thermophile](#)

References and Further Reading

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Geysir

- [Geyser](#)

Giant Impact

Sean N. Raymond
Laboratoire d’Astrophysique de Bordeaux, CNRS,
Universite de Bordeaux, Bordeaux, France

Definition

During planetary formation, a giant impact is a collision between two planetary embryos with

masses of at least a lunar mass and often significantly larger. Planetary embryos are thought to grow by runaway and ► [oligarchic growth](#) from a swarm of small ► [planetesimals](#) primarily via embryo-planetesimal collisions. Once the local density of embryos and planetesimals is comparable, embryos can grow by embryo-embryo collisions. These so-called giant impacts are very energetic events whose consequences are not completely understood. In fact, most such impacts probably do not lead to perfect merging and probably generate significant amounts of collisional debris. The last giant impact on Earth is thought to have been a low-speed, off-center collision with a Mars-sized projectile, usually called Theia. The debris from this collision stayed in orbit around Earth and coalesced into the Moon.

Cross-References

- [Impact, Hit and Run](#)
- [Moon, Origin of](#)
- [Oligarchic Growth](#)
- [Planetary Embryo](#)
- [Planetesimals](#)
- [Runaway Growth](#)

Giant Planets

Therese Encrenaz
Observatoire de Paris – PSL – Section de
Meudon, LESIA, Meudon, France

Keywords

Planets

Synonyms

[Jovian planets](#)

Definition

The four giant planets in our solar system – ► [Jupiter](#), ► [Saturn](#), ► [Uranus](#), and ► [Neptune](#) –

are found in the outer solar system, at heliocentric distances ranging from 5 to 30 AU. Unlike the terrestrial planets – Mercury, Venus, the Earth, and Mars – located in the inner solar system, within 2 AU from the Sun, the giant planets are characterized by a large size, a large mass, and a low density. They all have a ring system and a large number of satellites. Since models show that the two largest giant planets have extensive gaseous envelopes, they are also referred to as “gas giants,” and there appear to be analogous objects in many extrasolar planetary systems. Tables 1 and 2 summarize the main orbital and physical properties of the giant planets.

History

Early Exploration

As naked-eye objects, Jupiter and Saturn have been known since antiquity. Their astronomical observation started in 1610 when ► [Galileo Galilei](#) used for the first time his new refractor to look at celestial bodies. Galileo discovered the four big satellites which orbit around Jupiter (later called Galilean satellites), the phases of Venus, the surface relief on the Moon, and the multitude of stars which populate the Milky Way. The discovery of the Galilean satellites had immense implications for the history of astronomy. It supported the heliocentric system proposed in 1543 by Nicolaus Copernicus and promoted by Johannes Kepler, but still strongly attacked by the theologians of Rome. Later, Isaac Newton elaborated the universal gravitation law, which provided the theoretical support of the heliocentric model and opened the era of celestial mechanics.

Galileo also noticed the changing aspect of Saturn as the orientation of the rings varied with respect to the Earth, but he could not provide an explanation. The answer was given by Christiaan Huygens in 1659, who also discovered ► [Titan](#), Saturn’s biggest satellite. At the end of the seventeenth century, large observatories were built and planetary observations took place on a regular basis. ► [Cassini](#) observed the zone and belt structure of Jupiter and noticed its Great Red Spot. He also discovered a gap inside Saturn’s rings, now

Giant Planets, Table 1 Orbital properties of giant planets

Name	Semimajor axis (AU)	Eccentricity	Inclination over the ecliptic plane (°)	Revolution period (years)
Jupiter	5.20	0.054	1.30	11.86
Saturn	9.54	0.047	2.48	29.42
Uranus	19.2	0.086	0.77	83.75
Neptune	30.1	0.008	1.77	163.72

Giant Planets, Table 2 Physical properties of giant planets (mass and radius relative to the Earth)

Name	Mass ($M_{\oplus}$)	Equatorial radius ($R_{\oplus}$)	Density (g/cm^3)	Rotation period (h)	Obliquity (°)
Jupiter	317.9	11.21	1.33	9.925	3.08
Saturn	95.16	9.45	0.69	10.656	26.73
Uranus	14.53	4.00	1.32	17.24	97.92
Neptune	17.14	3.88	1.64	16.11	28.80

called the Cassini Division, and he identified several icy satellites around Saturn. Cassini also used the precise timing of the Galilean satellites' mutual occultations to define a universal time and allow navigators to determine the longitude at sea. An even more spectacular result was the first measurement of the speed of light by Ole Rømer at Paris Observatory, based on the precise timing of the Galilean satellite occultations as a function of the Jupiter-Earth distance.

Thanks to improved techniques in the building of glasses and lenses, astronomical telescopes got more and more powerful. William Herschel, in particular, specialized in manufacturing a new generation of telescopes. In 1781, he discovered a new planet, which he called Uranus. The new planet was twice as far from the Sun as Saturn. At the same time, as a natural consequence of Newton's theory of universal gravitation, a new science, celestial mechanics, was developing rapidly. In 1821, the first precise calculations of the giant planets' orbits showed that the orbit of the new planet was perturbed by another more distant object. Two astronomers, John Couch Adams in England and Urbain Le Verrier in France, independently determined the position of the new object. John Adams was the first one to find the solution, but could not convince his director about the importance of his discovery. In 1846, Le Verrier sent the position of the new planet to a German astronomer, Johannes Galle, who immediately found it within 1° of its

predicted position. The planet was called Neptune; this discovery marked the triumph of the celestial mechanics.

Visual observations and drawings remained for long the only means for planetary cartography. Photographic plates were used from the beginning of the twentieth century until the apparition of the ► [CCD](#) digital cameras in the 1980s. In parallel, spectroscopic observations started to develop during the twentieth century. Spectroscopic observations are precious as they give information on the nature of the atmospheric constituents of the planets. In 1932, methane and ammonia were detected in Jupiter's atmosphere; in spite of their low relative abundance with respect to hydrogen, they were detectable because they are very active spectroscopic agents. Methane was detected also on the other giant planets. Molecular hydrogen, although by far the dominant atmospheric species on all giant planets, was not detected before the 1960s. Since the 1970s, several other minor species have been detected from ground-based observations, thanks to the development of infrared and millimeter spectroscopy.

The Space Exploration of the Giant Planets

The space exploration of the giant planets started in the 1970s with two programs, Pioneer and Voyager. Two spacecraft were first sent by NASA toward Jupiter and Saturn, Pioneer 10 and 11. Pioneer 10 was launched in 1972 and flew by Jupiter at the end of 1973; Pioneer 11 was

launched in 1973, flew by Jupiter in 1974, and took advantage of Jupiter's gravitational assistance to encounter Saturn in 1979. The Pioneer spacecraft were equipped, in particular, with a camera, ultraviolet and infrared photometers, a magnetometer, a plasma analyzer, and particle detectors. The Pioneer mission provided us with the first spectacular images of Jupiter's atmospheric structures and Saturn's rings, and they explored for the first time the planets' magnetospheres.

The first discoveries by the Voyager mission appeared soon after the success of the Pioneer spacecraft. Two identical spacecraft, Voyager 1 and 2, were launched by NASA in 1977. Flybys of Jupiter took place in 1979, and those of Saturn occurred in 1980 and 1981, respectively. Voyager 1 approached Titan for a close encounter of Saturn's satellite, while Voyager 2 used Saturn's gravitational assistance to encounter the other giant planets. Voyager 2 flew by Uranus in 1986 and by Neptune in 1989. The Voyager mission has been a spectacular success. In particular, Voyager 1 discovered the complexity of Jupiter's dynamical atmospheric structure, the active volcanism of the inner Galilean satellite Io, the possible water ocean below the surface of ► [Europa](#), the multiple structures of Saturn's rings, the magnetosphere of Saturn, and the nature of Titan's atmosphere. Voyager 2 discovered the magnetospheres of Uranus and Neptune, the unexpected tectonic activity of

Uranus' satellite ► [Miranda](#), the fascinating blue color of Neptune's atmosphere, and the active ► [cryovolcanism](#) at Triton's surface. The Voyager mission marked a major step in our understanding of the giant planets (Fig. 1).

After the flybys, a more in-depth exploration of the giant planets required the launch of additional orbiters and probes. In 1989, the Galileo mission was launched by NASA; it included an orbiter for successive flybys of the planet and the Galilean satellites and a probe for in situ measurements of the Jovian atmosphere. In spite of a technical problem which disabled the large antenna and imposed a very low telemetry rate, the Galileo mission was also a great success. On December 7, 1995, the Galileo probe entered the Jovian atmosphere and transmitted data down to a pressure level of 22 bars. The Galileo orbiter monitored the planet and the Galilean satellites until 2003. Unexpectedly, Galileo's magnetometer discovered, in particular, an intrinsic magnetic field on Ganymede.

After Jupiter, Saturn and its system also deserved an in-depth exploration. In 1997, the ambitious ► [Cassini](#) mission, jointly developed by NASA and ESA, was launched. The orbiter, led by NASA, was designed for an in-depth monitoring of Saturn, its rings, and satellites through multiple flybys. It approached Saturn's system in 2004. On January 14, 2005, the ► [Huygens](#) probe, led by ESA, successfully landed on Titan's

Giant Planets, Fig. 1 The Great *Red Spot* of Jupiter as revealed by the Voyager 1 spacecraft in 1979. (© NASA)



surface and sent to the world the first images of this new world. Among other spectacular results, the Cassini orbiter discovered lakes of hydrocarbons at the surface of Titan, cryovolcanism on Enceladus, and a very complex meteorology in the atmosphere of Saturn. The exploration continued until 2017, with two successive extensions. The next step in the space exploration of the giant planets is the Juno mission, launched by NASA in 2012, which encountered Jupiter in 2016 and is presently exploring its interior for a better understanding of its formation processes. Later, the JUICE (Jupiter and Icy moons Explorer) mission, selected by ESA for a launch in 2022, will approach the Jovian system in 2030. After a series of flybys, the spacecraft will be put in orbit around Ganymede for an exploration of possible habitability conditions in the icy satellites (Fig. 2). In parallel, the NASA probe Europa Clipper is expected to explore the Europa satellite through a series of successive flybys, also around 2030.

In addition to in situ exploration by dedicated planetary spacecraft, one should not forget the role of Earth-orbiting observatories. Both the International Ultraviolet Explorer (IUE), launched in 1978, and the Hubble Space Telescope (HST), launched in 1989, obtained UV spectra of the giant planets and Titan. The HST, in addition, gave excellent quality images of the



Giant Planets, Fig. 2 Saturn's rings, as seen by the Cassini spacecraft. (© NASA)

giant planets and the outer satellites, allowing long-term monitoring of the disk morphologies. The ► [Infrared Space Observatory](#), launched by ESA in 1995, sent infrared spectra which led, in particular, to the detection of an external oxygen source on all giant planets and Titan. ISO was followed by Spitzer, launched by NASA in 2003, and more recently by Herschel, launched by ESA in 2009, which has pursued the far-infrared and submillimeter exploration of the outer solar system.

Overview

The Formation of the Giant Planets

The striking differences between the main properties of the giant planets, as described above (Tables 1 and 2), and the terrestrial ones suggest a different formation scenario for the two types of planets. Indeed, there is presently a general agreement within the scientific community about a formation model of the solar system that does account for these specific properties.

It is now generally accepted that the solar system formed from a rotating fragment of an interstellar cloud, which collapsed into a disk perpendicular to its rotation axis. This model, called “model of the primordial nebula,” was first proposed in the eighteenth century by Immanuel Kant and later by Pierre-Simon de Laplace. Their justification for such a model was the simple observation of planetary orbits: they all rotate around the Sun on nearly coplanar and concentric orbits, in the same direction (direct, i.e., counterclockwise as seen from the north ecliptic pole), which is also the direction of the Sun's rotation. The baselines of this model are still valid today; later observations are totally consistent with this scenario. First, the chemical analysis of extraterrestrial samples (lunar samples and meteorites) has shown that all solar system bodies formed some 4.56 billion years ago, contemporaneously with the Sun itself. Second, observations of young nearby stars have revealed that the formation of a protoplanetary disk, following the collapse of an interstellar rotating cloud, is a common scenario of stellar formation. In addition,

hundreds of extrasolar planets have been discovered around nearby stars, either in these protoplanetary disks or after the dissipation of these disks.

The main lines of the solar system formation scenario can thus be summarized as follows. The protosolar disk, after the collapse of the protosolar cloud, is mostly composed of gas (hydrogen and, to a lesser extent, helium) with a small fraction of dust (metals, silicates). At the center of the disk, matter accretes to form the young Sun. The temperature is high at the center and decreases outward. The protosolar disk (see ► [“Solar Nebula”](#)) is very turbulent such that solid particles are permanently subject to mutual collisions. Because all particles revolve around the center, their relative velocities are small and collisions are not always disruptive; some of them lead to the formation of small aggregates. Following a mechanism that is not presently fully understood (possibly helped by the turbulence), some of these aggregates reach the kilometer size; they are called planetesimals. Then the biggest fragments are able to capture the surrounding particles by collisions and then by gravity. Numerical dynamical simulations show that after a few million years, a small number of big objects (of the size of terrestrial planets and satellites) are formed.

Why do we find two classes of planets, the terrestrial and the giant ones? This separation is a result of the condensation sequence that takes place within the disk as a function of the heliocentric distance. Within the disk, the element abundances follow the universal cosmic rule: the lightest one (hydrogen) is the most abundant (75% per mass), followed by helium (23%), and the 2% left is made of all heavier elements. Within these 2%, the lightest (C, N, O) are relatively more abundant than the heavier ones (Si, Mg, metals).

As planets were formed from solid material, the nature of the planet depends upon the nature of the solid material available to form the planetesimals. In the protosolar disk, the temperature decreases as the heliocentric distance increases. Two cases can be identified:

- Close to the Sun, within a few AU, the temperature (above 200 K) was such that the only

solid matter available was made of heavy atoms (metals, silicates). Because heavy elements are not abundant in the disk, the accretion process led to the formation of relatively small and dense planets: the terrestrial planets, also called the rocky planets.

- At larger heliocentric distance, the temperature (below ~ 180 K) became low enough for the small molecules (H_2O , CH_4 , NH_3 , H_2S , CO_2 , etc.) to condense. As these species were much more abundant than the heavier elements, they accreted into bigger cores, able to reach 10–15 terrestrial masses. At this point, models predict that their gravity field is sufficient for the surrounding nebula to collapse in a disk, in the equatorial plane of the planetary core. As the nebula is mostly made of hydrogen and helium, the planets formed after these collapses are very big, with a low density: they are the giant planets with their ring and satellite systems, formed within their equatorial disk.

Between the terrestrial and giant planets, the line of ice condensation is called the snow line. Water plays a special role for two reasons: first, formed from two abundant atoms, H and O, water is, among the ices, the most abundant small molecule; second, it is the first molecule to condense as the temperature decreases. Other ices (NH_3 , CO_2 , CH_4 , etc.) condense at greater heliocentric distances. Presently, water condenses at about 2 AU from the Sun, as shown by cometary activity. At the time of planets' formation, when the disk was warmer, the snow line was probably located at about 3–4 AU from the Sun.

The “core accretion model” of the giant planet's formation described above gives a natural explanation for the basic properties of the giant planets (size, mass, density, number of satellites). As will be discussed below, another observational fact supports this model: the elemental and isotopic abundances measured in the giant planets.

Gaseous Giants and Icy Giants

Table 2 shows the giant planets fall into two distinct subclasses. With masses of about 300 and 100 terrestrial masses, Jupiter and Saturn are mostly composed of protosolar gas: they are

called the gas giants. In contrast, Uranus and Neptune, with masses around 15 terrestrial masses, are mostly composed of their initial icy core; they are called the icy giants.

What can be the reason for such a difference? No definite answer can be given presently, but a plausible explanation can be proposed. Jupiter, formed just beyond the snow line, benefited from a maximum of icy material and a maximum of surrounding gas. To a lesser extent, Saturn's formation followed the same way. Jupiter and Saturn probably completed their formation within a few million years at most. In contrast, Uranus and Neptune, formed at larger heliocentric distances, needed a longer time to accrete their icy core. Possibly, they reached the critical mass of 10 terrestrial masses late enough for the protosolar disk to have dissipated, leaving little gaseous material for the planets to continue accretion. The lifetime of the protosolar disk, as inferred from the observation of protoplanetary disks around nearby stars, was probably not longer than ten million years, which may have been the time required by the icy giants to accrete their icy core.

Migration of the Giant Planets

Recent discoveries of extrasolar planets suggest that migration has been a common phenomenon in the planetary disks of nearby stars. Migration is usually generated by the interaction of the planet with the turbulent protoplanetary disk and leads the planet to move inward, from the outer stellar system to the close environment of its star. In the case of the solar system, dynamical simulations also suggest some migration might have taken place.

According to the “Nice Model” developed by Alessandro Morbidelli and his colleagues, after the dissipation of the protosolar disk, the giant planets were located on quasi-circular orbits between 5.5 and 17 AU, that is, significantly closer to the Sun than now. New numerical simulations suggest that this special configuration was the result of an earlier migration (the so-called Grand Tack) during which Jupiter came inward as close as Mars' orbit (thus interrupting the growth of Mars, which would explain the low

mass of the planet) and then migrated outward under the influence of Saturn. Later, gravitational perturbations may have induced again a moderate motion of Jupiter toward the inner solar system, while the three other giant planets moved outward. During this motion, the Jupiter-Saturn system crossed the 2:1 resonance (Saturn's revolution period being twice Jupiter's). According to dynamical simulation, this event generated a great perturbation in the inclinations and ellipticities of solar system small bodies. A clear signature would be the “► [Late Heavy Bombardment](#)” (LHB), traces of which are observed on the surfaces of all bare solar system objects, from Mercury and the Moon to the outer satellites. Crater rate counting on these objects shows that the event took place some 3.8 billion years ago, that is, about 800 million years after the planet's formation.

Comparison with other planetary systems raises a question: why was migration moderate in the solar system, while it seems to have been very efficient around nearby stars? Possibly, this was the result of the specific masses and locations of Jupiter and Saturn at the beginning of the scenario, but we have presently no firm answer to this question.

Atmospheric Composition of the Giant Planets

Because the atmospheres of the giant planets are dominated by hydrogen, atmospheric species are expected to be found in reduced form. This is the case for methane and hydrocarbons produced by its photodissociation. In addition, NH_3 , PH_3 , H_2O , GeH_4 , and AsH_3 are observed in Jupiter's and Saturn's tropospheres; these species are not observable on Uranus and Neptune because they condense below the observable atmospheric levels (at pressure levels of tens of bars). Methane also condenses on Uranus and Neptune at a level of 1 bar ($T = 80\text{ K}$), but especially on Neptune, its stratospheric content is sufficient to lead to the formation of hydrocarbons (in particular C_2H_2 and C_2H_6). The atmospheric composition of the giant planets is listed in Table 3.

Other unexpected stratospheric species have been discovered. In 1992, ground-based

Giant Planets, Table 3 Giant planets: mixing ratios of atmospheric constituents (fractional number density per unit volume relative to H₂)

Constituent	Jupiter	Saturn	Uranus	Neptune
<i>Troposphere</i>				
H ₂	1	1	1	1
He	0.157	0.13	0.18	0.23
CH ₄	2.1·10 ^{−3}	4.4·10 ^{−3}	2·10 ^{−2}	4·10 ^{−2}
NH ₃	2·10 ^{−4}	2–4·10 ^{−4}		
PH ₃	6·10 ^{−7}	1.7·10 ^{−6}		
H ₂ O	1.4·10 ^{−5}	2·10 ^{−7}		
GeH ₄	7·10 ^{−10}	2·10 ^{−9}		
AsH ₃	3·10 ^{−10}	2·10 ^{−9}		
CO	1.5·10 ^{−9}	2·10 ^{−9}	3·10 ^{−8}	10 ^{−6}
<i>Stratosphere</i>				
CH ₄	2.1·10 ^{−3}	4.4·10 ^{−3}	3·10 ^{−5} –10 ^{−4}	7·10 ^{−4}
C ₂ H ₂	3·10 ^{−8}	2·10 ^{−7}	2·10 ^{−7}	3·10 ^{−7}
C ₂ H ₄	7·10 ^{−9}	a		10 ^{−7}
C ₂ H ₆	2·10 ^{−6}	3·10 ^{−6}		2·10 ^{−6}
CH ₃		5·10 ^{−8}		5·10 ^{−8}
C ₃ H ₄	a	6·10 ^{−10}		
C ₃ H ₈	6·10 ^{−7}			
C ₄ H ₂	a	9·10 ^{−11}		
C ₆ H ₆	2·10 ^{−9}	a		
H ₂ O	3·10 ^{−9}	10 ^{−8}	7·10 ^{−9}	2·10 ^{−9}
CO	1.5·10 ^{−9}	2·10 ^{−9}	3·10 ^{−8}	10 ^{−6}
CO ₂	3·10 ^{−10}	3·10 ^{−10}		5·10 ^{−10}
HCN				3·10 ^{−10}
H ₃ ⁺	a	a	a	

NB: Isotopic species have been also detected: HD, CH₃D, ¹³CH₄, ¹⁵NH₃, ¹²C¹³CH₂

^aDetected

millimeter observations of Neptune led to the detection of stratospheric CO and HCN, in abundances much larger than the predicted ones (those predicted values were actually observed in Jupiter’s and Saturn’s stratospheres). In 1997, the ISO satellite discovered the presence of H₂O on all giant planets and Titan (as well as CO₂ in Jupiter, Saturn and Neptune). CO was detected on Uranus from ground-based infrared spectroscopy. H₂O and CO were later also studied by the Herschel satellite. Because the thermal vertical profiles of the giant planets exhibit a cold trap at the level of the minimum temperature, at a pressure level of 0.1 bar (see below), the stratospheric oxygen species had to be of external origin. The source might be either local (rings and satellites) or interplanetary (comets or flux of

micrometeorites). Following Herschel observations, the water source is believed to be the Shoemaker-Levy collision of 1994 for Jupiter and the ► [Enceladus](#) torus in the case of Saturn.

From the abundances of tropospheric species, elemental and isotopic ratios have been determined. These parameters are important as they provide precious constraints for the formation models of the giant planets. Indeed, according to the nucleation formation model described above, heavy elements are expected to be enriched with respect to protosolar values; the larger the mass fraction of the icy core, the larger the enrichment. A simple model based on an initial icy core of 12 terrestrial masses predicts enrichment in heavy elements by a factor of 4 for Jupiter, 9 for Saturn, and about 30 for Uranus and Neptune, which is in

full agreement with the carbon enrichment measured from tropospheric methane in the four giant planets. It is also fully consistent with the enrichments measured in situ by the mass spectrometer of the Galileo probe for several elements (C, N, S, Ar, Kr, Xe). These results provide a clear validation of the nucleation formation model. Still, the Galileo measurements on Jupiter raise a problem: all elements seem to have been equally trapped in ices, but N and Ar cannot be trapped unless at very low temperature (<40 K). This suggests that the planetesimals which formed Jupiter were accreted at very low temperatures, much lower than expected at Jupiter's orbit. The origin of Jupiter's planetesimals is presently an open problem. It is hoped that the Juno mission will bring new answers to this question by measuring the O/H ratio in the planet's interior.

Another additional measurement supports the nucleation model. The D/H ratio measured in the outer solar system is diagnostic of its formation temperature. Indeed, **▶ deuterium** is enriched with respect to hydrogen in ices, due to ion-molecule and molecule-molecule reactions, as observed in the laboratory and in the **▶ interstellar medium**. The observed D/H ratio increases as the temperature decreases. The D/H ratio has been measured in the giant planets by the ISO satellite from HD infrared lines. These lines were later reanalyzed on Uranus and Neptune by the Herschel satellite. In the case of Jupiter and Saturn, D/H has been found to be in agreement with the protosolar D/H value, which is consistent with the fact that they are mostly made of protosolar gas. In contrast, following Herschel's results, D/H in Uranus and Neptune is enriched by a factor of about 2–2.5, which corroborates that these planets have an icy core.

The abundance of helium in the giant planets is also diagnostic of their formation and evolution processes. The He mass fraction Y was measured by the Voyager IRIS infrared spectrometers and, in the case of Jupiter, by the Galileo probe. Results were $Y = 0.234 \pm 0.05$ for Jupiter, 0.21 ± 0.03 for Saturn, 0.26 ± 0.05 for Uranus, and 0.32 ± 0.05 for Neptune. For Uranus and Neptune, the helium abundance is consistent with the protosolar abundance ($Y = 0.275 \pm 0.01$). In the

case of Saturn and Jupiter, the apparent depletion has been interpreted as a possible condensation of helium within the liquid hydrogen ocean in the planets' interiors (see below).

Thermal Structure, Cloud Structure, and Dynamics

The atmospheres of all giant planets are characterized by several layers: (1) a convective **▶ troposphere** where the temperature decreases as the altitude increases following an adiabatic lapse rate. The minimum temperature is reached at the tropopause, at a pressure level of about 100 mbar for all giant planets. The temperature at this level is 110 K for Jupiter, 90 K for Saturn, and 50 K for Uranus and Neptune. Above the tropopause, in the **▶ stratosphere**, the temperature increases again with altitude. In the lower stratosphere, the heating mechanism is probably the absorption of the solar flux by methane and hydrocarbon aerosols formed by methane photodissociation. At higher altitudes, other heating processes must be involved, such as gravity waves and energy deposition by high-energy particles.

The cloud structure of the giant planets can be estimated on the basis of thermochemical equilibrium models. In the case of Jupiter and Saturn, a cloud of ammonia is expected at a level of 0.5–1 bar, respectively ($T = 145$ K). An NH_4SH cloud is expected at $T = 210$ K, at pressure levels of 2 bars (Jupiter) and 4 bars (Saturn). At deeper levels, an H_2O cloud should occur at 270 K, at pressure levels of 5 bar (Jupiter) and 10 bars (Saturn). In the case of Uranus and Neptune, according to the models, CH_4 is expected to condense at a level of 1 bar ($T = 80$ K). Hydrocarbon hazes (especially C_2H_6) should be present in the stratosphere. An H_2S cloud could be present at about 3 bars ($T = 120$ K). In the lower troposphere, NH_4SH and H_2O clouds could be present at temperatures of 240 K and 270 K, respectively, at pressure levels of several tens of bars.

How do the observations fit the models? The spectroscopic identification of condensates is much more ambiguous and difficult than the detection of gaseous species. Still, imaging spectroscopy at different wavelengths provides a 3D imaging of planetary disks. Typically, ultraviolet

radiation probes the stratosphere, while the visible spectrum probes the upper troposphere; the 5-micron region, known as an “atmospheric window,” probes the troposphere down to a pressure of a few bars. In the case of Jupiter, the observations performed by the Juno probe in the radio range has shown that the vertical distribution of NH_3 , at a pressure level of 10 bars or more, is by far more complex and inhomogeneous than previously thought. It is constant with altitude only near the equatorial region, where the N/H ratio is close to three times the solar value, as previously measured (see above). At higher latitudes, the N/H ratio becomes homogeneous only for pressures higher than 20 bars. This complexity makes it difficult to infer the O/H ratio in the deep troposphere of Jupiter, because NH_3 and H_2O are both strong absorbers in the radio range.

Images of Jupiter and Saturn in the visible range show the typical zone-belt structure characteristic of a Hadley-type convective circulation in a fast rotating object. Zones are cloudy regions of ascending motion, while belts are dry, cloud-free regions of subsidence. The yellow color of Jupiter’s zones is consistent with the presence of an ammonia cloud. In Saturn, the more uniform yellow color of the disk implies a thicker ammonia cloud, consistent with the colder environment of the planet. On Jupiter, dark-blue regions in the belts have been attributed to water clouds. The Great Red Spot, known for over three centuries, is believed to be a giant anticyclonic structure. Its stability over such a long time is still a puzzle. Its red color has not been unambiguously interpreted. It could be due to the presence of sulfur or phosphorus compounds or to hydrocarbon polymers formed from the irradiation of ices by high-energy particles. In Saturn, a huge storm developed in the northern hemisphere in December 2010. This phenomenon has been observed for over a century with a period of approximately 28 years near the northern summer solstice. It is attributed to a massive atmospheric upwelling generated by a seasonal insolation increase.

The Galileo and Cassini observations have shown that, on both Jupiter and Saturn, the meteorology is by far more complex than described by a simple Hadley-type convective model. In the

case of Jupiter, the Galileo probe entered a region especially dry and free of clouds. In particular, the cloud structure described above was not found, and the measured water abundance was much lower than expected. This measurement was not considered as representative of the O/H value in the deep troposphere of the planet; determining O/H in the deep interior of Jupiter, using radio measurements, was thus among the objectives of the Juno mission (see above). In the case of Saturn, near-infrared images revealed a huge cyclone at the South Pole and a complex hexagonal structure surrounding the North Pole.

In contrast with the other giant planets, the image of Uranus shows little contrast. The images taken by Voyager 2 in 1986 showed no latitudinal structure. At the time of the Voyager encounter, the rotation axis of Uranus was nearly aligned with the Sun-planet axis. Twenty years later, when Uranus came to equinox, HST images revealed more activity, with cloud features at low latitude. In spite of some possible seasonal activity, Uranus is much less dynamically active than the three other giants. Is this difference connected to the special orientation of its rotation axis, very close to the ecliptic plane, or is it connected with the absence of an internal energy source (see below)? Or are the two effects connected with each other? This is an open question.

Finally, Neptune exhibits a strong dynamical activity, which is especially remarkable in view of its large distance from the Sun. Part of the explanation may come from its strong internal source of energy (see below). Methane in Neptune is supersaturated, which induces a strong methane photochemistry. The explanation might be the continuous insolation of the South Pole over the past 40 years, which could be responsible for the temperature increase measured at the tropopause; methane would be released in the stratosphere from the South Pole and spread over the planet. An active meteorology has been observed on Neptune over the past decades. In 1989, at the time of the Voyager encounter, a large feature (the Great Dark Spot) was observed. It was interpreted as a giant anticyclone, similar to Jupiter’s Great Red Spot. However, the feature had

disappeared a few years later when Neptune was imaged by the HST. Many other variable bright and dark spots, at different altitudes, have been monitored over the years. White spots are believed to be high-altitude cirrus of methane.

Internal Structure

Our knowledge of the giant planets' internal structure relies on theoretical models, constrained by a few physical parameters (mass, diameter, density, gravitational moments). According to these models, the internal structures of Jupiter and Saturn consist of three regions: a central core of ices and rocks, an ocean of metallic hydrogen, and an envelope of molecular hydrogen. At the center, the temperature is expected to be 23,000 K (Jupiter) and 12,000 K (Saturn); the pressure is estimated to be 50–100 Mbar (Jupiter) and about 50 Mbar (Saturn). However, in the case of Jupiter, the gravimetry measurements of the Juno probe have shown that there is no clear separation between the central core and the ocean of metallic hydrogen. This “diluted” nucleus might be the result of an early collision between the proto-Jupiter and a protoplanet of about 15 terrestrial masses.

In the case of Uranus and Neptune, the models predict also a core made of ices and rocks but no metallic hydrogen. The core would be surrounded by a mixture of ices and then by an envelope of molecular hydrogen. The central temperature would be about 7000 K and the central pressure about 6 Mbar.

Other information relative to planetary interiors come from the internal energy source that has been measured by Voyager from the total infrared emission of the planets. An internal energy source has been detected on Jupiter, Saturn, and Neptune; its ratio to the absorbed solar energy amounts to 1.67 for Jupiter, 1.78 for Saturn, and 2.6 for Neptune. In the case of Uranus, the ratio was less than 1.1; no internal energy was detected. A plausible source for the internal energy is radiative adiabatic cooling, following the early accretion phase of the planet's formation. If it is indeed the case, then the absence of internal energy on Uranus is puzzling. In the case of Jupiter and Saturn, according to models, an additional

internal source might come from the condensation of helium inside the metallic ocean of hydrogen. Helium droplets would sink toward the center, releasing energy upward and contributing to the depleted helium abundance in the outer layers; no helium condensation would be expected in the case of Uranus and Neptune, as the internal pressure is not sufficient for hydrogen to be in liquid form. This process would be consistent with the helium measurements in the giant planets (see above).

Magnetospheres

Like the Earth, all giant planets have a ► [magnetosphere](#). In the case of Jupiter, its magnetic activity was first identified in 1955 by the detection of strong radio emission. In addition to the thermal emission of the planet, nonthermal emission was found at centimeter and decimeter wavelengths. It was attributed to synchrotron emission of electrons trapped in the radiation belts of a newly detected magnetic field. The magnetospheres of Jupiter and Saturn were first explored by Pioneer 10 and 11 in 1974 and 1979, respectively, and the magnetospheres of Uranus and Neptune were discovered by Voyager 2 in 1986 and 1989, respectively. The magnetic fields of the giant planets, to first order, can be approximated by a dipole, probably generated by motions within the liquid central nucleus, also activated by the fast rotation of the planets.

The magnetospheres of the giant planets show a structure comparable with the terrestrial one and result from the interaction of the magnetic field with the ionized particles of the solar wind. In the case of Jupiter, the inner magnetosphere, within 20 planetary radii, has a dipole structure, inclined by 11° with respect to the rotation axis, with radiation belts similar to the Van Allen belts on Earth, where energetic particles are trapped. The magnetic field is perturbed by Jupiter's satellites Io, Europa, and Ganymede. Aurorae are observed in the ionosphere at high latitude, in the form of localized emissions in the ultraviolet and in the near-infrared range.

The Jovian magnetic field (14 G at the North Pole, 4 G at the equator) is ten times stronger than the terrestrial magnetic field. The other giant

planets have significantly weaker magnetic fields (0.2–0.3 G). Saturn’s magnetosphere shows no radiation belts, because of the presence of the rings. As Saturn’s magnetic axis is almost aligned with its rotation axis, its magnetosphere is much more regular than the Jovian one. Repeated observations of Saturn’s gravity field by the Cassini orbiter have revealed a variation of the internal rotation period of the planet, whose origin is still a matter of debate.

Both Uranus and Neptune show a very strange configuration, as their magnetic axes are tilted with respect to their rotation axis by a large angle (59° and 47°, respectively), with an offset of 0.3 and 0.5 planetary radii with respect to the planet’s center. This configuration induces complex magnetospheric structures, modulated by the rotation period of the planets. In the case of Uranus, the situation is even more complicated due to the position of the rotation axis, close to the ecliptic plane, which leads to strong seasonal effects.

Rings and Satellites

All giant planets have a ring system (see “► [Planetary Rings](#)”) and a large number of satellites; as mentioned above, this is a direct consequence of their formation scenario. The satellites were formed within the planet’s equatorial plane, after the collapse of the surrounding nebula on the initial icy core.

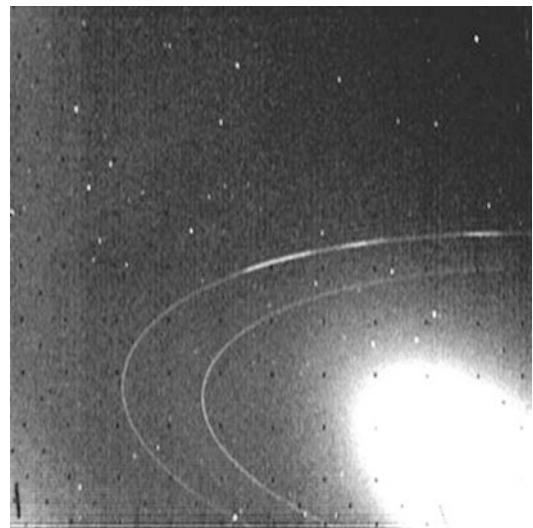
Rings are mostly found within the ► [Roche limit](#), at about two planetary radii from the planet’s center; in this region, tidal forces prevent the accretion of satellites, and dust particle revolve along circular orbits around the planet.

The giant planets show very different ring systems. Saturn’s rings have been observed over four centuries, while the three other ring systems were still undetected a few decades ago. The ring system of Jupiter, made of three tenuous components, was discovered by Voyager 1. They are made of micron-sized particles, probably ejected from the small nearby satellites (Thebe, Amalthea, Metis, and Adrastea). These particles have a very short lifetime, due to dynamical effects and erosion. Repeated observations of Saturn’s rings by the Cassini orbiter, in particular at the time of the “Grand Finale,” when the orbiter flew between

the rings and the planet in September 2017, have shown in detail the complexity of the interactions between the rings and the small nearby satellites.

The ring systems of Uranus and Neptune were both discovered by ground-based stellar ► [occultation](#) measurements. In 1977, nine very narrow rings were discovered around Uranus. The observation was made easier by the fact that the rotation axis of Uranus was almost facing the Earth at that time. The rings of Uranus were later imaged by Voyager 2 and then by the ► [HST](#). In 1984, another stellar occultation experiment was performed on Neptune. Absorption of the stellar flux was detected on one side of the planet only; it was interpreted as the presence of incomplete rings or “arcs.” In 1989, Voyager 2 confirmed this result but found that the rings were actually complete, but denser in some locations. The rings of Uranus and Neptune have a low albedo, possibly due to the presence of organic polymers resulting from the irradiation of organic ices by high-energy magnetospheric particles (Figs. 3 and 4).

The detailed structure of Saturn’s ring system has been revealed by Pioneer and Voyager and is being extensively explored by the ► [Cassini](#)



Giant Planets, Fig. 3 The rings of Neptune as observed by Voyager 2 in 1989. The denser regions correspond to the “arcs” previously identified from ground-based solar occultation observations in 1984. (© NASA)



Giant Planets, Fig. 4 The system of Uranus, observed in the near-IR range at the VLT (European Southern Observatory: ESO) in 2002. On this picture, satellites and rings are overexposed and the planet is dark because the near-IR filter (K-band) corresponds to a strong absorption band of methane. North is at the *bottom right* and east is at the *top right*. The satellites, from *left to right*, are Titania, Umbriel, Miranda, Ariel, and Oberon. (© ESO)

orbiter. Apart from the well-known A, B, and C main rings, a thin ring (D) has been found closer to the planet; other rings (A, F, G, E) have been found outside. The Cassini observations have shown that the E-ring is fed with the matter ejected by ► [Enceladus](#), which shows evidence for active ► [cryovolcanism](#).

Outer Satellites

All giant planets have many satellites, either regular (i.e., formed in the equatorial plane of the planet) or irregular (i.e., resulting from the capture of a distant asteroid or a ► [trans-Neptunian object](#)). All regular satellites are in synchronous rotation with their planet.

The outer satellites are all different, and each of them deserves a specific description. Here we will just mention some general trends. All outer satellites are made of ices. Water dominates in the case

of Jupiter (with the exception of Io, which has lost its water due to its active volcanism) and Saturn. The satellites of Uranus and Neptune, which have a lower albedo, probably contain other types of ices (N_2 , CH_4 , CO_2 , etc.) as is observed on ► [Triton](#).

The radial distribution of satellites shows large variations from one planet to another. There are some analogies between the Galilean satellites of Jupiter, which extend from 6 to 26 planetary radii, and the five big satellites of Uranus, which extend from 5 to 23 planetary radii. In contrast, Saturn's largest satellite, ► [Titan](#), is located at 20 planetary radii, beyond five midsize satellites. Titan is unique in having a dense neutral atmosphere. Neptune's system is different, because of the capture of the big satellite ► [Triton](#), located at 14 planetary radii. No midsize satellite is found at Neptune except the small Proteus at five planetary radii and the very distant Nereid. Triton's capture might have expelled other regular satellites previously formed in Neptune's equatorial plane.

Cross-References

- [Huygens](#)
- [Jupiter](#)
- [Neptune](#)
- [Planetary Rings](#)
- [Protoplanetary Disk](#)
- [Saturn](#)
- [Uranus](#)

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Giga-annum

► [Ga](#)

Gigayear

► [Ga](#)

Giotto Spacecraft

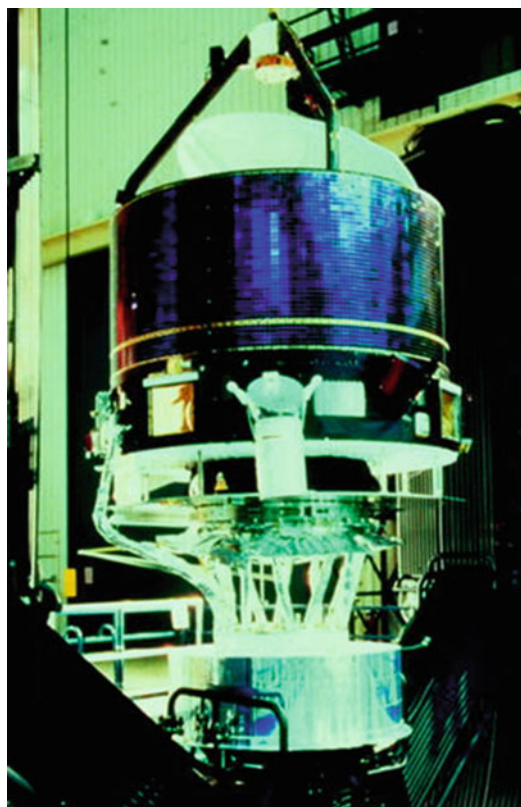
Anny-Chantal Levasseur-Regourd
Sorbonne Univ./LATMOS, Paris, France

Keywords

Comets · Nucleus · Coma · Water · Dust · Organics · CHON · Giotto · Giotto extended mission · Spacecraft · ESA · Halley · Grigg-Skjellerup

Definition

The Giotto spacecraft (Fig. 1), the first ESA (European Space Agency) interplanetary probe, was designed to flyby ► [comet Halley](#). Launched on 2 July 1985 by an Ariane-1 rocket from Kourou, Giotto succeeded in approaching the



Giotto Spacecraft, Fig. 1 Giotto spacecraft

cometary nucleus to within 600 km on 14 March 1986. Through its first accurate images of a nucleus and in situ studies of gases and dust particles within a coma, the mission has revealed the complexity of comets. Afterwards, the Giotto spacecraft was reoriented in order to study comet Grigg-Skjellerup, which was flown by on 10 July 1992, at a nucleus distance in the 150–200 km range.

History

Giotto was named after the painter Giotto di Bondone, who, in 1301, depicted a comet as the star of Bethlehem in his fresco Adoration of the Magi in Padua. The comet, easily visible from Europe at that time, was later named Halley, after Edmund Halley understood in 1705 it was periodically reappearing.

Overview

Although comets had been observed for centuries, their knowledge remained limited until the 1986 flybys of Halley by an armada of spacecraft (see below). Giotto, the first independent European mission, provided a close-up view of the cometary nucleus, afterwards described as an icy dirt ball, together with evidence for previously unsuspected properties of its dust particles, found to be under-dense and rich in refractory organics. Giotto was also the first mission to be reactivated after hibernation and to return from interplanetary space for an Earth swingby, which oriented it toward a second comet.

Basic Methodology

At the end of the 1970s, a mission to a comet was mandatory to assess the existence of the nucleus, the properties of the coma, and the solar wind interactions. The expected return in 1985–1986 of the active short-period comet 1P/Halley, the trajectory of which was well known, made it an obvious target for a ballistic flyby. Its retrograde orbit (with respect to that of the Earth and of a space probe) nevertheless implied a huge relative velocity between the comet and any spacecraft, about 70 km s^{-1} . In July 1980, once it had become clear that a sophisticated ► [NASA](#) mission with a flyby of Halley and a rendezvous with another comet would not take place, ► [ESA](#) (European Space Agency) approved a mission specifically dedicated to the study of Halley during its passage in the ecliptic at the orbital node closest to its perihelion, i.e., in March 1986.

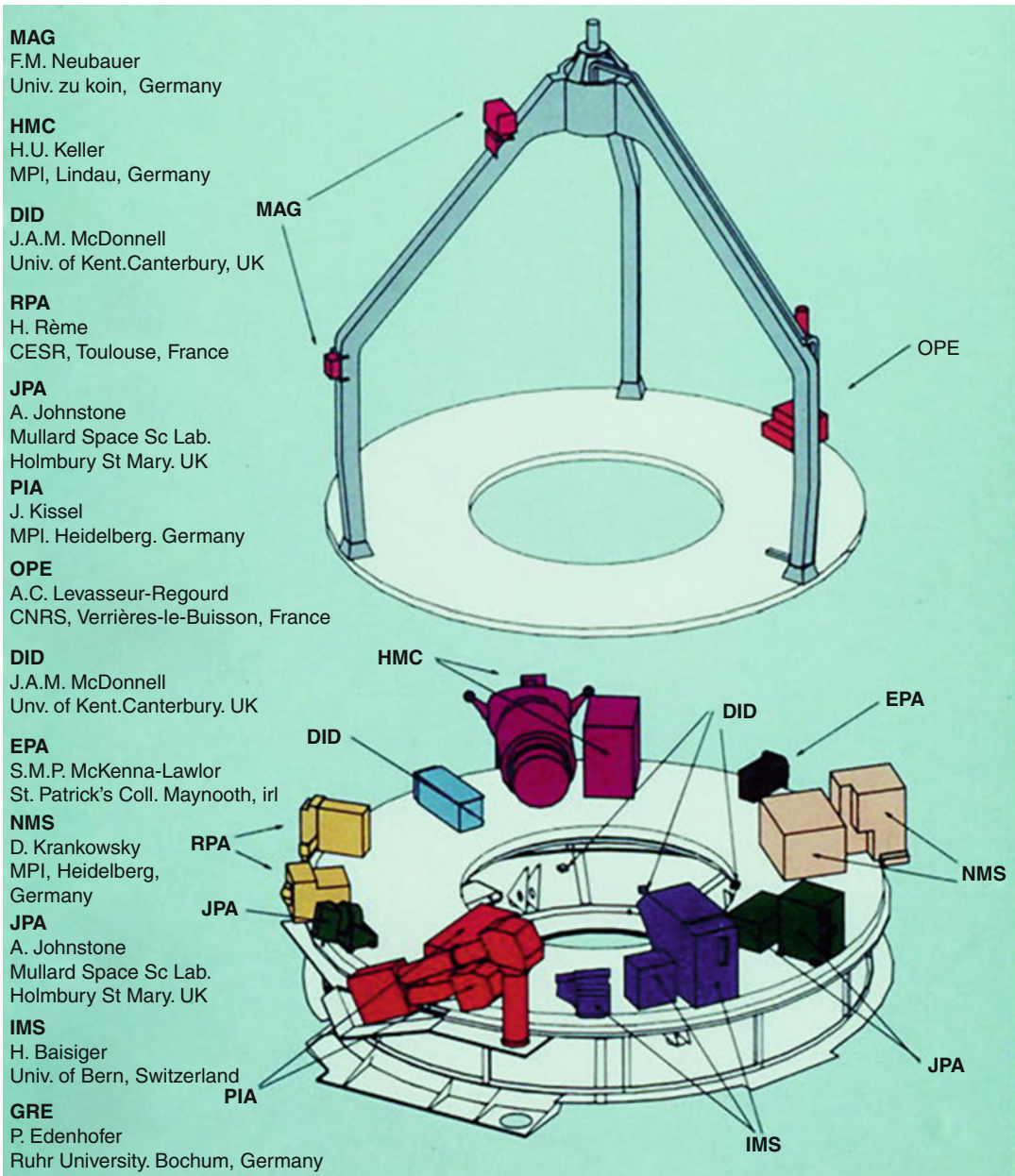
The onboard experiments (Fig. 2) were selected in January 1981. They consisted in nine instruments with a total mass of about 60 kg, i.e., one camera, three mass spectrometers (neutral, ion, dust), one dust impact detector, one optical probe, two plasma analyzers, one energetic particles analyzer, and one magnetometer, plus one radio-science experiment. The spacecraft had a cylindrical shape (diameter 1.86 m, height 2.85 m, dry mass 574 kg), with its main cylinder covered by a solar array. It was spin stabilized

(period of 4 s), with the spin axis aligned with the relative velocity vector during Halley encounter. A two-layer aluminum-kevlar dust shield, perpendicular to the spin axis, protected Giotto against high-velocity dust impacts; the despun (to counteract the effect of the spin) parabolic reflector of the high-gain antenna was mounted on a tripod at the other end, in order to be oriented toward the Earth during the flyby.

After 5 years of development and tests, Giotto was launched by an Ariane-1 rocket from Kourou, French Guyana, on July 2, 1985, into a highly eccentric geosynchronous transfer orbit. About 1 day and a half later, its solid-propellant motor was fired at perigee to inject the spacecraft into a solar ballistic orbit that allowed it, after a cruise of about 685 million kilometers, to flyby the cometary target without major trajectory adjustments. The encounter took place on March 13–14, 1986, with a relative velocity of 68.4 km s^{-1} , at 0.89 AU heliocentric distance and 0.98 AU geocentric distance and for a phase angle of 107.05° . The closest approach took place immediately after midnight UT, at $(596 \pm 2) \text{ km}$ distance from the nucleus (Fig. 3).

To allow Giotto to approach as close as possible to the nucleus without being destroyed, a unique international cooperation had been organized. An armada of spacecraft had been launched toward Halley, including besides Giotto the Japanese Suisei spacecraft with a nucleus miss distance of 151,000 km and the Russian spacecraft Vega 1 and Vega 2, respectively, at 8,890 and 8,030 km. The pathfinder concept, developed in cooperation between ESA, IKI (USSR), and NASA (USA), was used to define the photometric center (presumed to correspond to the nucleus) on the images collected by the Vega spacecraft, the positions of which were determined by the American Deep Space Network. The distance of closest approach of Giotto was accurately controlled through this unique effort, allowing the spacecraft to approach the nucleus without being totally destroyed by impacts from dust particles hitting it with a high relative velocity.

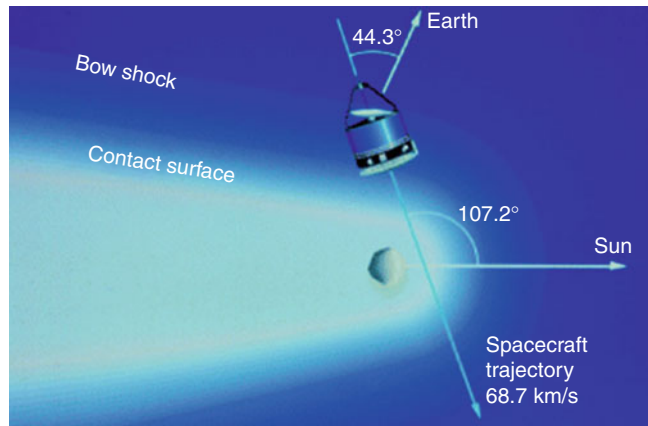
Giotto was actually hit by a rather large dust particle 14 s before closest approach, leading by



Giotto Spacecraft, Fig. 2 Giotto onboard experiments

nutatation to a shift of the spacecraft angular momentum vector of 0.9° and to an intermittent Earth data link for 32 min. Two weeks after the encounter, the spacecraft was put into hibernation. After its reactivation in February 1990, it could be established that it had survived with minor

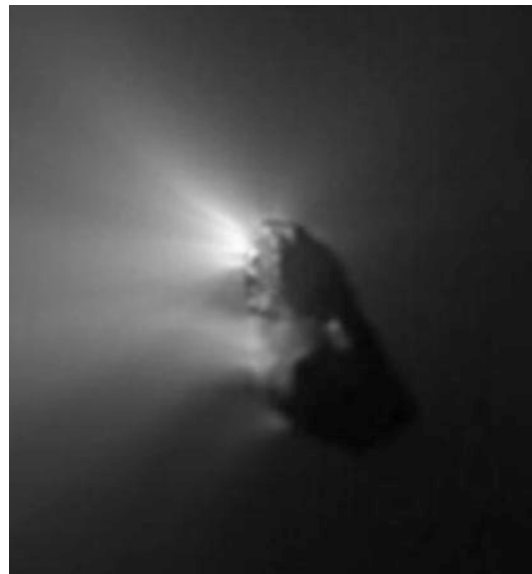
degradation of the Halley flyby. On July 2, 1992, after six orbits around the Sun, Giotto was back in the vicinity of our planet at 23,000 km altitude. The Giotto Extended Mission (GEM) to a second cometary target had already been approved by ESA, and the orbit of the spacecraft was retargeted

Giotto Spacecraft,**Fig. 3** Geometry of Comet Halley flyby

through an Earth gravity assist toward 26P/Grigg-Skjellerup, a Jupiter family comet.

This last flyby took place on July 10, 1992, with a relative velocity of 14 km s^{-1} , at 1.01 AU heliocentric distance and 1.43 AU geocentric distance. While the Giotto scientific payload was fully operational for the Halley flyby, it was only 50% operational for Grigg-Skjellerup and no images were provided by the damaged HMC camera. Nevertheless, the OPE (Optical Probe Experiment), undamaged at the rear of the spacecraft, derived a nucleus miss distance below 200 km, most likely in the 150–200 km range, from the monitoring of the evolution of the brightness under the observational geometry.

Among the huge wealth of unique results obtained by Giotto and GEM missions, many are relevant from an astrobiology perspective.

**Giotto Spacecraft, Fig. 4** Image of Comet Halley nucleus obtained by Giotto

Key Research Findings

The Giotto HMC camera provided the first accurate images of a cometary nucleus. They revealed a slightly reddish irregular object, significantly darker and bigger (about 15 km long and 7.5 km by 8 km wide) than anticipated, with various topographic features (hills, ridges, craters, cliffs, ridge, central depression). Well-defined dust structures with the appearance of narrow filaments were noticed in the inner coma, possibly originating from active regions covering 10% of the surface. The mass of the nucleus was too low

to be derived from the spacecraft trajectory perturbations near closest approach. Nevertheless, estimations of the mass from nongravitational effects (later validated through the ► [Deep Impact](#) mission) and of the shape from imaging yield a density of $550 \pm 250 \text{ kg.m}^{-3}$, typical of a highly porous object (Fig. 4).

The icy component of Comet Halley mostly consisted of water. Independent analyses of the D/H ratio from NMS and IMS (Neutral and Ion Mass Spectrometers) lead to a value in cometary

water of $(3.08 \pm 0.3) \times 10^{-4}$, i.e., twice that of seawater on Earth. However, a large dispersion among D/H ratios in both Jupiter Family comets and Oort Cloud comets was later pointed out, suggesting formations over a long period of time or solar distances. Besides, water on Earth might also have come from icy small bodies formed in the outer asteroid belt.

One of the most unexpected discoveries of Halley's missions was that the dust mass spectrometers (PIA on board Giotto, PUMA on Vega) not only detected rock-forming elements (e.g., Mg, Si, Ca, Fe) but also revealed light elements, like carbon, hydrogen, oxygen, and nitrogen, in agreement with data from one plasma analyzer. This so-called CHON material is, most likely, included in complex polymeric organic molecules. Such refractory organics, the presence of which was later confirmed, e.g., for comets Wild 2 by NASA ► [Stardust mission](#) and Churyumov-Gerasimenko by ESA ► [Rosetta mission](#), had quite likely been formed in the interstellar medium. Besides, the properties of dust particles were varying with distance to the nucleus and with time after ejection, most likely under sublimation and fragmentation processes. Comparisons between the results of OPE and DID (Dust Impact Detector) have shown that, on the average, the geometric ► [albedo](#) of the dust particles was very low (about 0.04) and their density extremely reduced (about 100 kg m^{-3}), suggesting that they mostly consisted of fluffy aggregates.

During the Giotto Extended Mission to Grigg-Skjellerup, fragmentation processes could be suspected, with one event noticed by OPE at about 1000 km distance from the nucleus, tentatively interpreted by the presence of an active fragment (10–100 m size) releasing dust in the inner coma. Altogether, discoveries of (1) porous nuclei that may suffer fragmentation processes and (2) refractory organic molecules in low-density cometary dust particles strongly suggest that the interplanetary dust cloud (also called zodiacal cloud) is permanently replenished by organics-rich fluffy particles. During the ► [Late Heavy Bombardment](#) epoch, the amount of interplanetary dust particles of cometary origin

was likely to be most significantly increased. Their highly porous structure, which leads to a significant deceleration and heat transfer in planetary atmospheres, could have contributed to extraterrestrial delivery of carbonaceous compounds, as still presently collected in the Earth and its environment, within the atmospheres of terrestrial planets.

Future Directions

Cometary flybys and, all the more, the 26-months long ► [Rosetta](#) rendezvous mission have established that the cometary dust particles are irregular aggregates of likely fractal submicron-sized grains, presenting a relative abundance of complex organics of about 50%, in volume and even in mass. Besides, similarities with the CP-IDPs presently collected in the stratosphere and the UCAMMs found in Antarctica snows have been recognized. The future ESA-JAXA ► [Comet Interceptor](#) mission should better point out differences between periodic comets and more pristine dynamically new comets. Further away in time, cryogenic samples of a cometary nucleus should lead to a better understanding of a possible contribution of comets to the origin of life on Earth.

Cross-References

- [Comet Halley](#)
- [Comet Interceptor Mission](#)
- [Comet](#)
- [Deep Impact](#)
- [Deuterium/Hydrogen Ratio](#)
- [Interplanetary Dust Particle](#)
- [Rosetta Spacecraft](#)
- [Stardust Mission](#)
- [Vega 1 and 2 Spacecraft](#)

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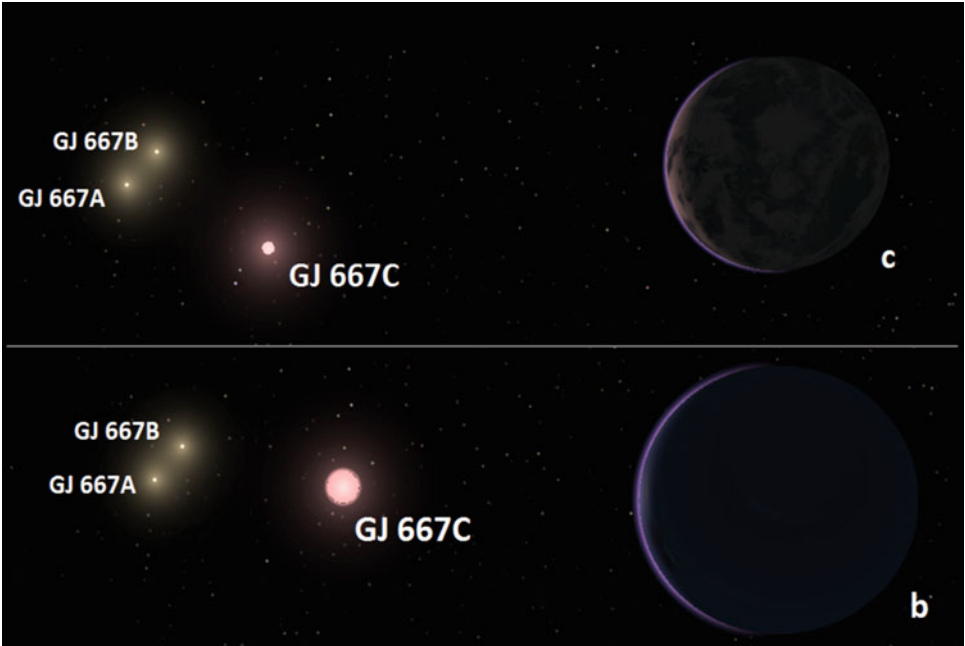
GJ 667C: First System with Multiple Super-Earth Candidates in the Habitable Zone

Nader Haghighipour

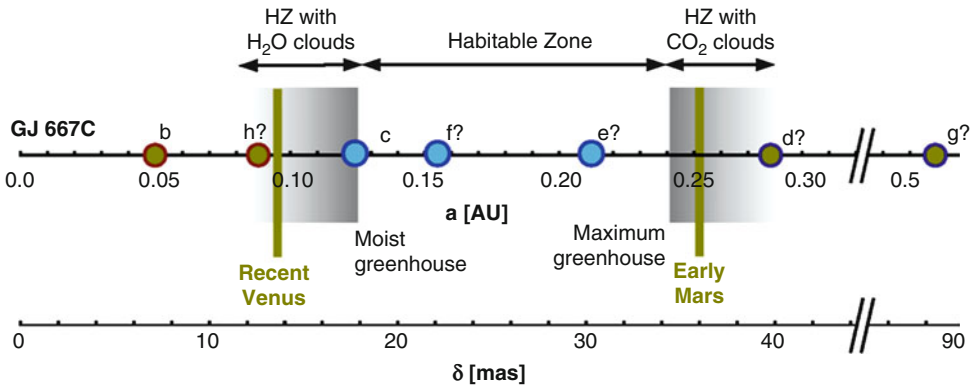
Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

The M1.5V star GJ 667C (Gliese 667C) is a faraway member of a triple star system. It orbits the central binary GJ 667AB (a K3V + K5V binary system) at a projection distance of ~230 AU. GJ 667C is known to host several super-Earth planets. In 2009, at the international ESO/CAUP exoplanet conference in Porto, the first planet candidate around this star was announced: a hot super-Earth on a 7.2 day orbit. However, it was the subsequent discovery and confirmation of a 4.5 Earth mass planet, GJ 667Cc, in the habitable zone of this star (Anglada-Escudé et al. 2012; Delfosse et al. 2013) that made this system one of the most significant planetary systems known to date. The planet GJ 667Cc is the *first* confirmed potentially habitable planet. Figure 1 shows an artist's rendering of this system.

Reanalyzing the publicly available HARPS spectra of GJ 667C using the HARPS-TERRA software (Anglada-Escudé and Butler 2012) combined with the Doppler measurements from PFS/Magellan and HIRES/Keck spectrometers (Anglada-Escudé et al. 2013) claimed that the planetary system of GJ 667C is dynamically packed and, in addition to GJ 667Cc, this system could harbor two more super-Earths in its habitable zone. Figure 2 shows a schematic of the planets of this system with respect to its habitable



GJ 667C: First System with Multiple Super-Earth Candidates in the Habitable Zone, Fig. 1 Artist’s rendering of the triple star system GJ 667 and planets GJ 667Cb and GJ 667Cc



GJ 667C: First System with Multiple Super-Earth Candidates in the Habitable Zone, Fig. 2 Habitable zone of GJ 667C and its three potentially habitable super-Earths

zone, as it is presented in Anglada-Escudé et al. (2013). As shown here, the candidate planets GJ 667Cf and GJ 667Ce, with orbital periods of 39 and 62 days and masses of 1.94 and 2.68 Earth masses, are also in the habitable zone. Note that of all the planets, only planets b and c are truly confirmed. Indeed in 2014, two studies came out that claimed that the signals previously

assigned to additional planets were actually artifacts coming from the activity of the star (Feroz and Hobson 2014; Robertson and Mahadevan 2014).

The discovery of GJ 667Cc as the first confirmed potentially habitable planet was considered as one of the top ten physics newsmakers of 2013 by the American Physical Society.

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Glacial Period

► Glaciation

Glaciation

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Carbon dioxide · Ice ages · Interglacial · Obliquity · Quaternary glaciations · Orbital eccentricity · Orbital parameters · Precession · Plate tectonics

Synonyms

Glacial period

Definition

A glaciation or glacial period is a geologically short period of time within an ice age characterized by very low surface temperatures and the advance of glaciers. The term differs from an “ice age” or more properly a “glacial age” that is defined as a long-term period of reduction in the temperature of the Earth’s surface and atmosphere, resulting in an expansion of continental and polar ice sheets.

Overview

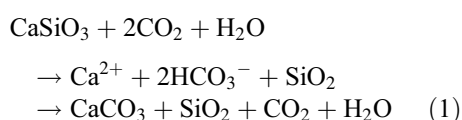
Glaciation refers to the process of glacier growth or more generally to the establishment of frigid conditions and large ice caps at a global scale. An ice age is characterized by glacial periods, when temperatures plunge and glaciers advance, and interglacial periods, when temperatures increase and glaciers retreat.

The Earth experienced at least five great ice ages. The first is the Paleoproterozoic Huronian (Melezhik et al. 2013), possibly the first recognized Snowball Earth glaciation on Earth initiated at 2450 and terminated at 2320 Ma or possibly at 2220 Ma. This first glaciation is contemporary to the Great Oxygenation Event, although it is still unclear if it is a cause or a consequence of the oxygenation. It is followed by the Neoproterozoic Cryogenian or Sturtian-Varangian (716.5–635 Ma; Macdonald et al. 2010), the most severe ice age when almost all the planet was covered with ice and “Snowball Earth” conditions prevailed (Kirschvink 1992); the Paleozoic Andean-Saharan (450–420 Ma) and the Karoo (360–260 Ma), and finally the Quaternary ice ages (2.65 Ma to present). Earth probably experienced glaciations also in Archean times with the oldest geological record of a glaciation in the 2.9 Ga Mozaan Group in South Africa (Young et al. 1998) and possible correlated rocks in the West Rand Group of the Witwatersrand Supergroup. Recently de Wit and Furnes (2016) have suggested a

glacial origin for rocks belonging to the ~3.445 Ga felsic volcanic unit at the top of the Hooggenoeg Formation, termed H6 member, but this hypothesis has been opposed by Lowe and Byerly (2020) suggesting non-glacial storm-influenced shallow water sedimentary deposits.

The Quaternary glaciations include well-known glacial periods of 41,000 and 100,000 years, which are related to oscillations in Earth's orbital parameters and subsequent variations in the amount of radiant energy of the Sun which is received by the Earth surface, hypotheses that are summarized in the well-known theory of the Milankovitch Cycles.

Several causes have been proposed to explain planetary glaciations on Earth (the so-called ► [Snowball Earth](#) or Snowball episodes). Huronian glaciations could have been triggered by the rise of the oxygen in the atmosphere and the contemporary loss by oxidation of the greenhouse gas CH₄ (Pavlov et al. 2000). Some of the larger glaciations could have been caused by major tectonic re-arrangements of the continental plates and their effect as a sink of atmospheric CO₂, one of the greenhouse gases able to stabilize the atmospheric temperature (Kasting 1993). This is caused by the well-known Urey reaction (Urey 1952), which combines atmospheric CO₂ with calcium silicate to generate calcium carbonate plus silica:



The tectonic episodes of continental plate re-arrangements could be related to accelerated rifting which increased the burial of organic C and thus the decrease of the CO₂ in the atmosphere (Hoffman et al. 1998) or the clustering of continents at low latitudes (Marshall et al. 1988) enhancing weathering of calcium silicates by acid rains with production of carbonates which worked as a sink for CO₂.

In the past 65 million years, the Earth's climate has undergone significant evolution, including alternating trends of warming and cooling driven by plate tectonic processes (rifting, orogenesis, and

continental drift causing the increase of carbon burial and consequent decrease of pCO₂ in the atmosphere), on timescales of 10⁵–10⁷ years, and higher-frequency change in climate (10⁴–10⁵ years) generated by periodic and quasiperiodic oscillations in Earth's orbital parameters (eccentricity, obliquity, and precession) that affected the distribution and amount of incident solar energy (Milankovitch cycles; Zachos et al. 2001). The drifting of continental masses at higher latitudes (Antarctica and Greenland) and the formation of permanent ice sheets in the last 35 Ma probably amplified the orbital effects on the climate and the generation of high-frequency Quaternary climates.

Glaciations are likely not precluded to Earth, and evidence of glacial phases on planetary surfaces could be indirect evidence of chemical atmospheric evolution and/or active plate tectonics. Morphological features that could have been caused by retreating or advancing glaciers have been observed on the surface of Mars and have been attributed to multiple episodes of glaciation (Kargel and Strom 1992; Dickson et al. 2008). In contrast to Earth's ice ages, those on Mars wax when the poles warm up and water vapor is transported toward lower latitudes and wane when the poles cool and lock water into polar icecaps. NASA's Mars Global Surveyor and Mars Odyssey missions have revealed that a covering of water ice mixed with dust mantled the surface of Mars to latitudes as low as 30° and is now degrading and retreating, indicating that the Red Planet is coming out from an ice age started likely between 2.1 Ma and 400,000 years ago (Head et al. 2003).

Cross-References

- [Antarctica, Natural Analogue Site](#)
- [Huronian Glaciation](#)
- [Mars](#)
- [Snowball Earth](#)

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Glassy Carbon

- [Amorphous Carbon](#)

Global Circulation

- [Atmospheric Circulation](#)

Global Climate Model

- [GCM](#)

Globular Cluster

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

A globular cluster is a dense spherical collection of 10^5 – 10^6 stars orbiting a galaxy. Their origin is poorly understood. About 160 globular clusters are known in the ► [Milky Way](#), while the giant elliptical galaxy M87 may have up to 10,000. In the case of the Milky Way, they are composed of old (~ 12 Gyr) and thus low-mass stars, with low abundances of elements heavier than He, similar to those of field halo stars. Their high internal density (up to 1,000 stars per pc³ in the cluster core) favors dynamical interactions between stars and makes the survival of any planetary system problematic.

Cross-References

- [Galaxy](#)
 ► [Milky Way](#)
 ► [Stars](#)

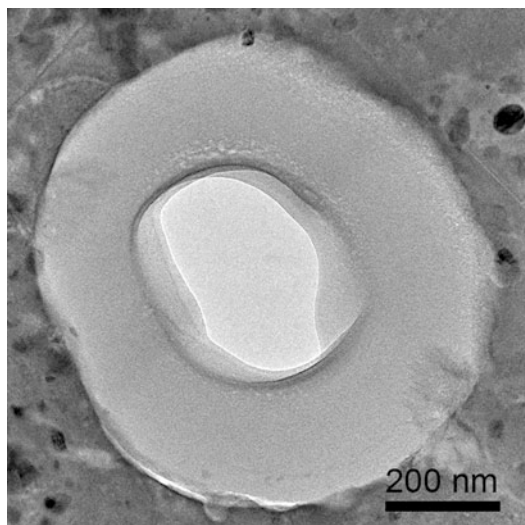
Globule, Nanoglobule

Bradley De Gregorio

Materials Science and Technology Division,
 U.S. Naval Research Laboratory, Washington,
 DC, USA

Definition

In meteoritic chemistry, globules or nanoglobules are microscopic, hollow (but sometimes solid),



Globule, Nanoglobule, Fig. 1 Transmission electron microscopy image of an organic nanoglobule within fine-grained silicate matrix of ordinary chondrite QUE 97008

spherical to irregular organic grains present in the fine-grained matrix of carbonaceous chondrites (Fig. 1). Organic globules have also been reported in ordinary chondrites, Antarctic micrometeorites, interplanetary dust particles, and comets. Globule diameters range from less than 100 up to 2 μm . Many are enriched in [▶ deuterium](#) and/or nitrogen-15 relative to the surrounding bulk [▶ insoluble organic matter](#) (De Gregorio et al. 2013), suggesting formation in extremely cold (less than 20 K) [▶ molecular cloud](#) or [▶ solar nebula](#) environments where such isotopic enrichments of organic matter are theorized to occur (Nakamura-Messenger et al. 2006). Some organic globules may also have formed on asteroid and/or planetesimal parent bodies through organic polymerization, such as the [▶ formose reaction](#), during aqueous processing (Cody et al. 2011).

History

Originally discovered in 1961 in crushed samples of the Orgueil and Ivuna meteorites by George Claus and Bartholomew Nagy (Claus and Nagy 1961), organic globules were initially interpreted as [▶ microfossils](#) indigenous to their host

meteorites. They were “rediscovered” independently by Keiko Nakamura-Messenger in 2002 (Nakamura et al. 2002) and Lawrence Garvie in 2004 (Garvie and Buseck 2004).

Cross-References

- ▶ [Carbonaceous Chondrites, Organic Chemistry of](#)
- ▶ [Nitrogen Isotopes](#)

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Glove Box

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A glove box is a sealed container that is designed to manipulate objects in a different atmosphere. Built into the front of the glovebox are gloves arranged in such a way that the user can place their hands into the gloves and perform tasks inside the box without breaking containment. Two types of glove boxes exist: one manipulates hazardous substances, such as infectious disease agents; the other allows manipulation of

substances in an oxygen-free or a high-purity inert atmosphere. It is very useful for the manipulation of strict anaerobic microorganisms.

Glucogenesis

► Gluconeogenesis

Gluconeogenesis

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

Glucogenesis

Definition

Gluconeogenesis refers to the biosynthetic pathway of hexoses from noncarbohydrate substrates such as acetate, glycerol, pyruvate, etc. This can be achieved by conversion of the precursor into an intermediate of ► [glycolysis](#) and the reverse of this pathway (with the appropriate bypass of three irreversible enzymatic steps). The phylogenetic distribution of the gluconeogenetic enzymes suggests an early origin of this anabolic pathway, before the emergence of the different glycolytic pathways.

Cross-References

- [Anabolism](#)
- [Embden-Meyerhof-Parnas Pathway](#)
- [Entner-Doudoroff Pathway](#)
- [Glycolysis](#)
- [Metabolism](#)

Glutamic Acid

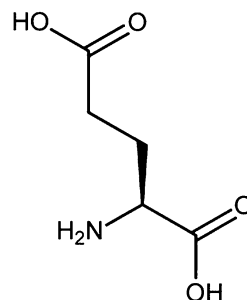
Kensei Kobayashi

Yokohama National University,
Yokohama, Japan

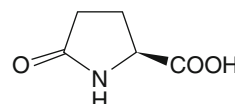
Definition

Glutamic acid (Fig. 1) is one of the 20 ► [protein](#) amino acids, whose three-letter symbol is Glu and one-letter symbol is E. Its compositional structure is $C_5H_9N_4$, and its molecular weight is 147.13. It is a monoaminodicarboxylic acid and is classified as an acidic ► [amino acid](#), whose isoelectric point (pI) is 3.22. Its salt is referred to as glutamate: monosodium glutamate is a popular condiment. When it is heated, intramolecular condensation occurs to give pyroglutamic acid (Fig. 2). It is found in extracts from carbonaceous chondrites and is easily produced in a number of prebiotic synthesis experiments such as electric discharge experiments.

Glutamic Acid,
Fig. 1 Glutamic acid



Glutamic Acid,
Fig. 2 Pyroglutamic acid



Cross-References

- ▶ [Amino Acid](#)
- ▶ [Protein](#)

Glutamine

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Glutamine is one of the 20 protein ▶ [amino acids](#), whose three-letter symbol is Gln and one-letter symbol is Q. Its side chain has a terminal amide group ($-\text{CONH}_2$). The chemical formula for glutamine is $\text{C}_5\text{H}_{10}\text{N}_2\text{O}_3$, which gives a molecular weight of 146.14. It has an isoelectric point (pI) of 5.65. It is easily hydrolyzed to give the amino acid ▶ [glutamic acid](#) (Glu) and ammonia. Both glutamic acid and glutamine are determined as glutamic acid in the hydrolysate of ▶ [proteins](#). After acid hydrolysis, it is thus unknown whether the original species was Glu or Gln, and thus it is reported as Glx.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Glutamic Acid](#)
- ▶ [Protein](#)

Glyceraldehyde

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Glyceraldehyde is a one of the simplest ▶ [carbohydrates](#) (also called sugars); its chemical

structure is $\text{CH}_2\text{OH}-\text{CH}_2\text{OH}-\text{CHO}$. It is an aldo-triose (three carbon sugar with an aldehyde group). Since the middle carbon atom is stereogenic (connected to four different groups: H, OH, CHO, and CH_2OH), it is a chiral compound and two enantiomeric forms are possible: D-glyceraldehyde and L-glyceraldehyde. Terrestrial organisms largely use only D-glyceraldehyde. D-Glyceraldehyde (as its phosphate ester) plays important roles in sugar metabolism, such as in the Benson-Calvin cycle of photosynthesis and in glycolysis. It can be synthesized by mild oxidation of ▶ [glycerol](#). It is formed in the formose reaction, i.e., the polymerization of ▶ [formaldehyde](#) with a catalyst in basic aqueous solution. It has not been detected in carbonaceous chondrites nor in interstellar space, although the related triose, dihydroxyacetone ($\text{CH}_2\text{OH}-\text{CO}-\text{CH}_2\text{OH}$), has been reported in both. However these interstellar identifications have recently been questioned.

Cross-References

- ▶ [Carbohydrate](#)
- ▶ [Formaldehyde](#)
- ▶ [Formose Reaction](#)
- ▶ [Homochirality](#)

Glycerin

- ▶ [Glycerol](#)

Glycerine

- ▶ [Glycerol](#)

Glycerol

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

1, 2, 3-Propantriol; Glycerin; Glycerine

Definition

Glycerol is a three-carbon organic compound with a hydroxyl group on each carbon atom. It is viscous colorless liquid at room temperature. It is extremely soluble in water and is a component of many lipids, either as part of fatty acid esters or phytanyl ethers. Dissolved aqueous glycerol lowers the freezing point of water. Glycerol, like its phosphate ester, is generally metabolically derived from the reduction of glyceraldehyde 3-phosphate or dihydroxyacetone phosphate.

Glycine

Bernd Michael Rode
Institute for General, Inorganic and Theoretical
Chemistry, Leopold-Franzens University,
Universität Innsbruck, Innsbruck, Austria

Keywords

Amino acids · Chemical evolution · Glycine ·
Origin of life · Peptides · Proteins

Synonyms

Aminoacetic acid; Aminoethanoic acid;
Glycocoll; $\text{NH}_2\text{CH}_2\text{COOH}$

Definition

Glycine is the simplest ► [amino acid](#). It is achiral (see ► [Chirality](#)) and found in ► [meteorites](#) and ► [comets](#), indicating the ease of its abiotic formation. It is catalytic in some peptide formation reactions and can be readily oligomerized under some geochemically plausible conditions.

History

Glycine was first isolated by Henri Braconnot in 1820. Its formation under prebiotic conditions was proven by Miller-Urey type experiments using various types of primitive atmospheric gas mixtures and energy sources.

Overview

Glycine is the simplest amino acid and is formed readily and apparently ubiquitously under various natural conditions. Its pK_a values are 2.35 and 9.78 at 25 °C; in neutral solution, it exists therefore predominantly as its ► [zwitterion](#), $^+\text{H}_3\text{NCH}_2\text{CO}_2^-$.

Glycine has been identified in meteorites and comets (Elsila et al. 2009). Although the detection of interstellar glycine remains controversial (see ► [“Molecules in Space”](#)), the glycine precursor aminoacetonitrile was discovered in SgrB2, a giant gas cloud near the galactic center (Belloche et al. 2008). Glycine could also have formed easily from reactions in the primitive atmosphere under various conditions, such as the classical Miller-Urey setting via electrical discharges acting on an atmosphere of hydrogen, methane, ammonia, and water (Miller 1953), or a carbon dioxide – N_2 – water atmosphere (Plankensteiner et al. 2004), now assumed to have predominated on Earth 3.8 billion years ago. A number of other experiments have also demonstrated the formation of glycine from basic chemicals under the influence of various energy sources. It can be derived via Strecker synthesis from NH_4CN and formaldehyde, as well as directly from the self-condensation of HCN.

Starting from glycine, numerous plausibly prebiotic chemical reactions lead to more complex amino acids which are also important in biochemistry, such as serine and alanine (Choughuley et al. 1975). Hence, glycine may have enabled the formation of complex peptides even before the advent of RNA.

Cross-References

- [Amino Acid](#)
- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Protein](#)
- [Strecker Synthesis](#)

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Glycine Anhydride

- [Diketopiperazine](#)

Glycinonitrile

- [Aminoacetonitrile \(NH₂CH₂CN\)](#)

Glycocoll

- [Glycine](#)

Glycol

- [Ethylene Glycol \(HOCH₂CH₂OH\)](#)

Glycolaldehyde (HOCH₂CHO)

Didier Despois
Laboratoire d’Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

HOCH₂CHO; [Hydroxyacetaldehyde](#)

Definition

Glycolaldehyde (IUPAC name hydroxyacetaldehyde) is the simplest molecule that is both an alcohol and an aldehyde. It shares with ► [monosaccharides](#) (“sugars”) a formula (H₂CO)_n so that it can be considered formally to be a polymer of ► [formaldehyde](#) H₂CO and to be a carbohydrate. It is an intermediate in the ► [formose reaction](#). Monosaccharides have $n \geq 3$, so that glycolaldehyde is a “pre-sugar” rather than a sugar. Glycolaldehyde has been identified in the interstellar medium.

History

Hollis et al. (2000) identified glycolaldehyde for the first time in the interstellar medium, toward the Galactic center.

Cross-References

- ▶ [Carbohydrate](#)
- ▶ [Formaldehyde](#)
- ▶ [Formose Reaction](#)
- ▶ [Molecules in Space](#)
- ▶ [Monosaccharide](#)

References and Further Reading

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Glycolic Acid

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[2-Hydroxyethanoic acid](#)

Definition

Glycolic acid, HOCH₂COOH, is the smallest α-hydroxy acid. It is an odorless and colorless hygroscopic crystalline solid at room temperature, and it is highly soluble in water. It plays a minor role in biochemistry and has been found in carbonaceous chondrites and in electric discharge experiments. The hydrolysis of cyanohydrin formed from HCN and formaldehyde yields glycolamide and finally glycolic acid, which may be the source of this compound in meteorites and certain types of prebiotic syntheses.

Cross-References

- ▶ [Carbonaceous Chondrite](#)
- ▶ [Hydroxy Acid](#)

Glycolysis

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València, Spain

Definition

Glycolysis refers to the metabolic pathways using carbohydrates as a source of carbon, energy, and electrons. In anaerobic conditions, glycolysis can be the only source of ▶ [ATP](#) through the substrate-level phosphorylation mechanism. The diversity of glycolytic pathways includes the ▶ [Embden-Meyerhof-Parnas pathway](#) (the canonical version of glycolysis) present in bacteria and eukaryotes, the variants of the ▶ [Entner-Doudoroff pathway](#) found in bacteria and archaea, and the hexose monophosphate pathway (or pentose phosphate pathway). Different redox balance mechanisms under anaerobic conditions allow the operation of a diversity of ▶ [fermentation](#) pathways in microorganisms.

Cross-References

- ▶ [Embden-Meyerhof-Parnas Pathway](#)
- ▶ [Entner-Doudoroff Pathway](#)
- ▶ [Fermentation](#)
- ▶ [Metabolism](#)

Glycolyurea

- ▶ [Hydantoin](#)

Gneiss

Daniele L. Pinti
GEOTOP Research Center for the Dynamics of
the Earth System, Université du Québec à
Montréal, Montréal, QC, Canada

Definition

Gneiss is a ▶ [metamorphic rock](#) composed of quartz, mica, and feldspathoids. It is the most

characteristic metamorphic rock formed during deep or “regional” ► [metamorphism](#), which means at high temperature and pressure. Typically, gneisses are formed at temperatures higher than 500 °C and at pressures between 2 and 12 kbars which corresponds to the *amphibolite* and *granulite* facies (*metamorphic facies* corresponds to mineral assemblages in metamorphic rocks formed under similar pressures and temperatures). The protolith rock can be felsic ► [igneous rocks](#) (*orthogneiss*) or sedimentary siliceous rocks as sandstone (*paragneiss*). The texture of gneiss is easily identifiable for its *foliation*, i.e., the minerals are aligned and flattened forming typical layers of alternate colors corresponding to quartz (white) and micas (dark). This primary layering can be successively deformed by tectonic stresses creating micro-folding. Because of the high temperatures and pressures, gneisses are normally found at the core of mountain chains (orogens). In Archean terranes, gneisses are common and they testify of the presence of early ► [continental crust](#) sequences such as the ► [Amitsoq gneiss](#) (McGregor 1979). Most famous gneiss sequence is the ► [Acasta gneiss](#) with an age of 4.01 Ga, the oldest preserved rock on Earth.

Cross-References

- [Acasta Gneiss](#)
- [Amitsoq Gneisses](#)
- [Archean Eon](#)
- [Mafic and Felsic](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Plate Tectonics](#)
- [Quartz](#)

References and Further Reading

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Goethite

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Limonite](#); [Needle ironstone](#)

Chemical Formula

$\text{FeO}(\text{OH})$

Definition

Goethite is a hydrated iron oxide, or iron oxyhydroxide of the orthorhombic crystal system. Goethite forms by weathering of iron-rich minerals and it is commonly found in soils. It may also be precipitated by groundwater in low-temperature environments (authigenic goethite in marine and lacustrine sediments). Silica-associated goethite has been found in hydrothermal deposits. The occurrence of goethite on planetary surfaces could be used as an indicator of low-temperature weathering with the involvement of liquid water. On Mars, experimental studies (Fish Jr. 1966) have shown that hematite (Fe_2O_3) rather than goethite should be stable on its surface.

Cross-References

- [Banded Iron Formation](#)
- [Hematite](#)
- [Iron](#)
- [Iron Cycle](#)
- [Iron Oxidation](#)
- [Iron Reduction](#)
- [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- [Mars](#)
- [Weathering](#)

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Goldschmidt, Viktor Moritz

Pierre Savaton

Université de Caen Basse-Normandie, Caen, France

History

Victor Moritz Goldschmidt (1888–1947) is considered the founder of modern geochemistry, establishing its general laws and principles and making it a new discipline in earth sciences. Among his works, there are researches about mineral metamorphic associations and thermodynamic equilibrium; the laws which determine distribution of the chemical elements on the Earth and their classification as litho- (rock-loving), sidero- (iron-loving), and chalcophile (sulfur-loving); the ionic substitution in mineral; the process of fractional crystallization; and the substitution laws of ions of rare elements. He systematized the use of X-rays in study of composition and structure of crystals. Goldschmidt wrote a manuscript about geochemical aspects of the origin of complex organic molecules on the Earth.

Cross-References

- ▶ [Chalcophile Elements](#)
- ▶ [Lithophile Elements](#)
- ▶ [Rare Earth Elements](#)
- ▶ [Siderophile Elements](#)

Gondwana

Nicholas Arndt

Maison des Géosciences, LGCA, Université

J. Fourier, St-Martin d'Hères, France

Synonyms

[Gondwanaland](#)

Definition

Gondwana (originally *Gondwanaland*) is the ▶ [supercontinent](#) composed of the landmasses of the present-day southern hemisphere (Africa, South America, Australia, and Antarctica, together with India and Arabia). Along with its northern counterpart, ▶ [Laurasia](#), Gondwana comprised almost all of present-day continental crust. Between about 500 and 200 Ma, Gondwana and Laurasia together formed part of a single supercontinent called ▶ [Pangea](#). Breakup started 180–200 Ma ago when Gondwana split from Laurasia. This mechanism accelerated about 170 Ma ago when Antarctica, Madagascar, India, and Australia began to separate from Africa, and that the Atlantic Ocean progressively opened to separate South America from Africa. The correlation of geological features and fossils on both sides of the Atlantic provides convincing evidence of continental drift and eventually ▶ [plate tectonics](#).

History

Austrian geologist Eduard Suess named Gondwana after a region in northern India (from Sanskrit गोण्डवन = *gondavana* which means “forest of Gond”).

Cross-References

- ▶ [Laurasia](#)
- ▶ [Pangea](#)
- ▶ [Plate Tectonics](#)
- ▶ [Supercontinent](#)

Gondwanaland

- ▶ [Gondwana](#)

Graben

- ▶ [Rille](#)
- ▶ [Rima, Rimae](#)
- ▶ [Vallis, Valles](#)

Gram-Negative Bacteria

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A Gram-negative bacterium is a prokaryotic cell with a ► [cell wall](#) containing small amounts of ► [peptidoglycan](#) and an ► [outer membrane](#) containing lipopolysaccharides, proteins, and other complex macromolecules. The distinction between Gram-positive and Gram-negative bacteria is based on a differential stain, the Gram stain, which depends on the structure of the cell wall (see ► [“Cell Wall”](#)). After Gram staining, Gram-positive bacteria appear purple and Gram-negative bacteria appear red. This difference in reaction to the Gram stain arises because of differences in the cell wall structure which promote the retention of the purple dye, crystal violet, in the Gram-positive bacteria after decoloring with ethanol, while in the Gram-negative bacteria, the stain is not retained. The Gram stain is one of the most useful staining procedures in microbiology. In addition to the peptidoglycan, Gram-negative bacteria contain an additional wall layer, the outer membrane. This layer is effectively a second lipid bilayer, but in addition to phospholipids and proteins as in the cytoplasmic membrane, it contains polysaccharides. The lipid and polysaccharide are linked to form a lipopolysaccharide complex known as LPS. Unlike the cytoplasmic membrane, the outer membrane of Gram-negative bacteria is relatively permeable to small molecules due to the presence of porins, proteins that function as channels that facilitate the transit of low-molecular-weight substances. The outer membrane is not permeable to proteins and other large molecules. The space between the outer and the cytoplasmic membranes is known as ► [periplasm](#). In the periplasm, important functional proteins like hydrolytic enzymes or binding proteins for transport acting as chemoreceptors can be found.

Cross-References

- [Bacteria](#)
- [Cell Wall](#)
- [Chemotaxis](#)
- [Cytoplasmic Membrane](#)
- [Outer Membrane](#)
- [Peptidoglycan](#)
- [Periplasm](#)

Gram-Positive Bacteria

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A Gram-positive bacterium is a prokaryotic cell whose ► [cell wall](#) consists of mainly ► [peptidoglycan](#) and lacks the outer membrane characteristic of the Gram-negative cells. Bacteria can be divided into two major groups, called Gram positive and Gram negative. The original distinction between both groups was based on the Gram stain, which depends on differences in the structure of the cell wall (see ► [“Cell Wall”](#)). The Gram-negative cell wall is a multilayered structure and quite complex, whereas the Gram-positive cell wall consists of a single type of molecule, the peptidoglycan, which is often much thicker. In Gram-positive bacteria, as much as 90% of the cell wall consists of peptidoglycan, although another molecule, teichoic acid, is usually present in small amounts. The phylogenetic analysis of bacteria has demonstrated that the cell wall structure is phylogenetically consistent: all Gram-positive bacteria form a coherent phylogenetic group. The Gram-positive bacteria are a large group of chemoorganotrophic bacteria. The Gram-positive bacteria can be separated into two subgroups, according to the GC content of their genome. Among the different Gram-positive, low-GC bacteria of industrial interest can be found, including lactic acid bacteria, endospore-forming bacteria (like those belonging to the

Bacillus and *Clostridium* genus), and cell-wall-less bacteria, like the *Mycoplasma*. The high-GC, Gram-positive bacteria group corresponds to the phylum Actinobacteria, some of them producers of antibiotics, secondary metabolites of pharmacologic interest.

Cross-References

- Antibiotic
- Bacteria
- Cell Wall
- Gram-Negative Bacteria
- Peptidoglycan
- Phylogeny

Granite

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

Granite is a coarse-grained intrusive (i.e., crystallized at depth) ► [felsic igneous rock](#) composed mainly of Si- and Al-rich minerals (quartz and feldspars), with minor amounts of biotite, muscovite, and amphibole. Granitic rocks are the dominant component of the ► [continental crust](#). A granite cannot be a primary melt of the mantle ► [peridotite](#). Its formation (and implicitly that of the continental crust) involves the fractional crystallization of mafic magmas or more commonly, remelting of basaltic or sedimentary precursors (anatexis). Granite has not been reported on planets other than Earth, except as rare and disseminated veinlets in a few lunar rocks. Most granite forms in a two-stage process: The first stage involves partial melting of the lower crust and sometimes of subducted oceanic material (of basaltic composition) to form magmas of intermediate andesitic composition. Andesite, in turn, partially melts to form magmas

of granitic composition. The so-called S-granites are intrusive rocks formed by the partial melting of metasedimentary and metavolcanic rocks within orogenic belts through the process of anatexis.

Cross-References

- Basalt
- Continental Crust
- Igneous Rock
- Mafic and Felsic
- Peridotite

Graphite

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale
Supérieure de Lyon, Lyon Cedex 7, France

Definition

Graphite is a mineral composed of carbon arranged in graphene sheets of six-atom hexagonal rings and stacked in layers. It is the stable form of crystalline ► [carbon](#) at the Earth's surface and shallow pressure and with increasing pressure converts to diamond, which in the Earth is stable at depths in excess of 150 km. Graphite is a widespread accessory mineral in both terrestrial rocks and meteorites. It may result from the inorganic reduction of carbon dioxide and carbonate, notably by hydrogen, or from the dehydrogenation of organic materials at temperatures in excess of 300 °C. Typically, it crystallizes during metamorphism from precursor carbonaceous material or forms from fluid deposition as a precipitate of $\text{CO}_2\text{--CH}_4\text{--H}_2\text{O}$. It coexists with methane-rich gases over a broad range of temperatures. The discovery of ^{13}C -depleted graphite in 3.8 Ga-old rocks from West Greenland triggered a controversy over whether they represent carbon from early organic remains or inorganic precipitates.

Cross-References

- Carbon
- Kerogen

Gravitation

Jérôme Perez
Applied Mathematics Laboratory, ENSTA
ParisTech, Paris, Cedex 15, France

Keywords

Fundamental interaction · Mass

Synonyms

Gravity

Definition

Gravitation is one of the four fundamental forces of physics. It causes an attraction between any two massive bodies which is proportional to their masses.

Overview

Gravitation is a property of space which modifies the velocity of massive bodies under its influence. Then, by using Newton's definition, it is a force.

In the context of classical (i.e., nonrelativistic) physics, this same Newton gave a formula for gravity as a fundamental example of his theoretical work between 1666 and 1687. This is the

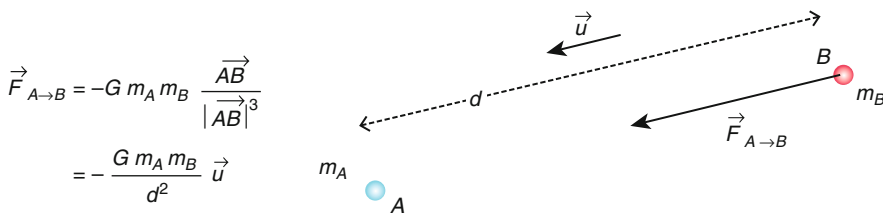
famous inverse-square law: the force produced by a point-like body of mass m_A located at the position A on another point mass m_B located at the position B is given by Fig. 1.

The second formulation, in which the squared distance d^2 appears, is the more popular but needs to introduce the unit vector $\vec{u}$ in the direction from one mass toward the other.

If an apple falls, its velocity changes: from zero when it leaves the tree to a certain value when it reaches the ground. This apple is thus subject to a force.

If the Moon orbits around the Earth, it is also because its velocity is slightly modified at each instant, by changing its direction in order to close its orbit. As the apple, the Moon is thus subject to a force. Newton had the idea to consider that these two forces are of the same nature: they are of gravitational origin.

On one hand, situated on the surface of the Earth and at one Earth radius ($\sim 6,400$ km) from its center, the apple falls 5 m in 1 s. On the other hand, each second, the orbit of the Moon moves away from a straight line by 1.4 mm. Finally, Newton knew that the Moon was located at a distance representing 60 times the radius of the Earth. The apple, which is then nearer to the Earth by this same factor, feels an effect which is $5/0.0014 \sim 60^2$ stronger, hence the inverse-square law! The other quantities which appear in the formula are the respective masses of the interacting bodies and Newton's universal gravitational constant G , needed to fix the intensity of the force. Newton didn't precisely know the value of this constant; its measure requires precise and refined experiments. One of the first values, $G = 6.7 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, was obtained by using a torsion balance and was proposed by



Gravitation, Fig. 1 Definition of the geometrical quantities in the Newtonian gravitational force

Cavendish in 1798. This is why some texts refer to Cavendish's constant. The modern value, $G = (6.67428 \pm 0.00067) \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$, was recommended in 2006 by the CODATA (see Mohr et al. 2006).

The more complete description of gravitation is Einstein's theory of general relativity. This formulation confirms the deep relation between gravitation and space, including its temporal dimension, which is absent in the Newtonian theory. The refinements introduced by Einstein are fundamental for theoretical physics, but in most astrophysical cases, the Newtonian formulation of gravity allows a correct description of the general properties of the system (the Newtonian theory breaks down, e.g., in the vicinity of a black hole).

The form of the gravitational force equation is equivalent to the electrostatic one (Coulomb's law), but in the latter case, the masses are replaced by electric charges and Newton's constant is replaced by $(4\pi\epsilon_0)^{-1}$ where $\epsilon_0 = 8.854 \times 10^{-12} \text{A}^2 \text{s}^4 \text{kg}^{-1} \text{m}^{-3}$. Due to their same spatial dependency, the ratio of the electrostatic force to the gravitational one between protons and electrons depends only on fundamental constants and is independent of the distance. Its magnitude, of order 10^{40} in favor of electrostatics, makes gravity irrelevant for most chemical problems. Nevertheless, as masses are always of the same sign, gravity is always attractive, whereas the electrostatic force can be repulsive. It must be noted at this point that in general relativity, repulsive gravity can appear; it is caused by the so-called dark energy and could be relevant for dynamics at a very large scale, such as in galaxy clusters or in the context of the primordial universe.

This purely attractive behavior of the classical gravitational force represents the main characteristic of gravity; although it is the weakest fundamental interaction, it cannot be screened. This feature allows gravity to build and shape objects on very large spatial and temporal scales.

Pure gravitational problems are generally classified according to the number of interacting bodies. On one hand, two-body problems and their perturbations are the domain of celestial mechanics. On the other hand, when the number of

interacting bodies is more than, say, several thousands, like in star clusters or cluster of galaxies, one deals with a sort of self-gravitating gas and thermodynamics law may be used. There also exist systems for which gravity is only one among the fundamental interactions that must be considered. That is especially the case for stars or large gaseous planets on which gravity acts to keep the matter confined, whereas internal pressure pushes it outward. The balance between these opposite forces produces, at equilibrium, a star or a planet. The different states in which we observe stars correspond to the different types of pressure (thermodynamical, degeneracy) that must be considered to balance the gravity associated to their respective masses. The isotropic character of gravity is at the basis of the spherical aspect of large gaseous planets or stars. In the case of telluric planets, the situation is more complicated: gravity produces a sphere as soon as the body's radius exceeds some hundreds of kilometers.

The Two-Body Problem and Its Perturbations

The academic two-body problem deals with two point masses A and B evolving in empty space and interacting only through their reciprocal Newton force (see Fig. 1). This problem was solved by Newton in 1687. The defining equation is

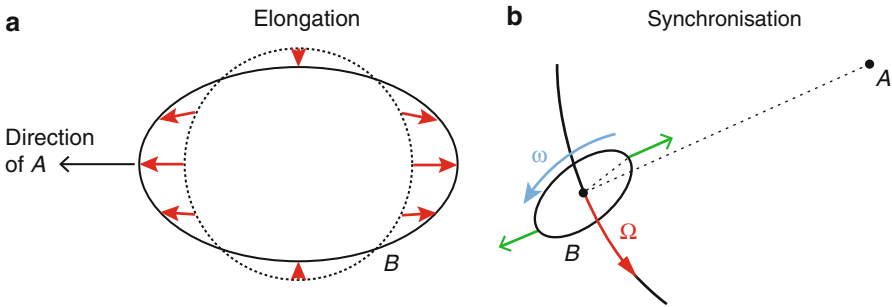
$$\frac{d^2 \vec{r}}{dt^2} = -\mu \frac{\vec{r}}{|\vec{r}|^3}$$

where $\vec{r}$ is the vector distance between the masses (the distance AB in Fig. 1) and μ depends on the chosen reference frame. In celestial mechanics, one of the two bodies (say A) is generally much heavier than the other. If we consider the reference frame in which A is at rest, one has $\vec{r} = \vec{AB}$ and $\mu = G(m_A + m_B)$. The solution $\vec{r}(t)$ of this problem is a conic curve, the nature of which depends on B 's total energy E_B . This energy is the sum of B 's kinetic energy which is positive and of B 's potential gravitational energy which is by definition negative. If $E_B \geq 0$, the conic is a

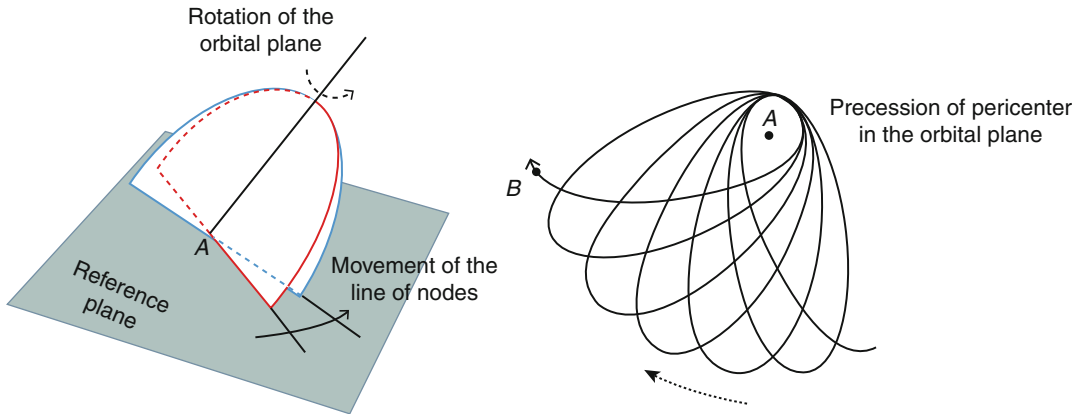
hyperbola or a parabola with focus A and the curve is open. If $E_B < 0$, the conic is an ellipse with A at one focus (this case includes the circle), and the curve is closed. Open trajectories are quite exceptional; ellipsoidal is the rule. In the solar system, all the planets lie on such orbits, as do satellites around planets. This configuration provides an equilibrium state between the central force imposed by gravity and the centrifugal one due to this kind of orbit. This last remark explains why the velocity of B is not uniform: Near the focus (planet at perihelion for motion around the Sun), gravity is strong and must be balanced by a large velocity; on the contrary, at aphelion, the velocity reaches a minimum. Such elliptic orbits are periodic with a period $T = 2\pi(a^3/\mu)^{1/2}$ where a is the semimajor axis of the ellipse. This relation is the well-known Kepler's third law.

When B is not a point mass and if its extension is large enough with respect to the gradient of the gravity field, tidal effects can occur. The principal tidal effect is an elongation produced by the stretching (see the entry “► [Roche Limit](#)”). This elongation, combined with B 's own spin at an angular velocity ω , produces a torque (in green on Fig. 2b). This torque accelerates or decelerates the spin of B until ω reaches the value of B 's angular velocity of revolution Ω around A .

This is the reason why the Moon always shows the same face to the Earth: Because of the tidal effect from the Earth, the Moon takes the same time to rotate around its axis as it does to revolve around the Earth. This phenomenon is called synchronisation. The reciprocal effect (from Moon to Earth) makes Earth rotate more slowly on itself: The length of the day actually increases by 2 m per



Gravitation, Fig. 2 Cartoon describing the two major tidal effects



Gravitation, Fig. 3 Principal effects of a radial perturbation on the elliptical two-body problem

century. For instance, at the end of the Neoproterozoic (~900 million years ago), each year on Earth was lasting 481 days, 18 h. Tidal effects can also circularize the orbit of planets or satellites that were initially in an eccentric orbit. This last phenomenon is generally less effective than the previous one and only takes place for planets or satellites in the inner solar system. It does seem to occur for short-period exoplanets.

Perturbations of the two-body problem occur when the source of the potential (essentially A) cannot be considered as a point mass or when other bodies must be considered. Generally, small perturbations produce a precession of the perihelion and a rotation of the orbital plane. The intersection, called line of nodes, between a reference plane (the ecliptic for planets moving around the Sun) and the orbital plane then generally rotates (Fig. 3).

For example, the Sun produces a precession of the Moon's perigee (closest approach to Earth) and a regression of this orbit's line of nodes around the Earth. These two motions have the same period of about 18 years. Most of the motions in solar or stellar systems can be explained using Newton's theory coupled with perturbations and tidal effects. The only "remarkable" exception is the 42 arcsec per century motion of Mercury's perihelion, which has been explained by Einstein's theory of gravity.

Cross-References

- ▶ [Keplerian Orbits](#)
- ▶ [Orbital Resonance](#)
- ▶ [Roche Limit](#)
- ▶ [Surface Gravity](#)

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Gravitational Biology

Ruth Hemmersbach¹, Ralf H. Anken¹ and Michael Lebert²

¹Gravitational Biology, German Aerospace Center, Institute of Aerospace Medicine, Cologne, Germany

²Biology Department, Cell Biology, Friedrich-Alexander-University Erlangen/Nuremberg, Erlangen, Germany

Keywords

Gravity · Microgravity · Weightlessness · Hypergravity · Centrifuge · Clinostat · Gravitaxis · Gravitropism · Gravisensor · Statolith · Signal transduction chain · Development · Evolution

Definition

The main scope of gravitational biology is the identification understanding of the effects of gravity on organisms. Main emphases are the identification of gravity sensing systems as well as the analysis of gravity-sensitive responses on all biological organizational levels. This includes the clarification of the role of gravity during evolution and also during individual development, in the course of which gravity has shaped life and provides an essential cue for spatial orientation and the development of polarities.

History

The origin of the discipline "Gravitational Biology" might be set at the nineteenth century, when Julius Sachs (1868), Charles Darwin (1880), and Wilhelm Pfeffer (1904) started to investigate the influence of gravity on plants by demonstrating the role of the root cap in downward growing

plants (gravitropism: growth response in relation to the gravity vector). Sachs and Pfeffer already constructed machines (centrifuges and clinostats, see “[Basic Methodology](#)”) in order to change the influence of gravity and observed the resulting gravity-dependent responses.

Overview

Gravity is one of the most important environmental factors which organisms use for orientation and adaptation to their environment to optimize exploitation of resources. In contrast to all other environmental factors such as light/radiation, temperature, and humidity, gravity has always been constant in direction and strength during evolution of life. Gravity sensing mechanisms have evolved early in the phylogenesis of organisms. By studying the influence of altered gravity by increasing or decreasing Earth gravity (see “[Basic Methodology](#)”), obvious effects such as gravitaxis (orientation of free-moving organisms with respect to gravity), gravitropism (orientation and growth direction of sessile organisms), and general physiological changes (see “[Key Research Findings](#)”) have been identified. However, much remains to be learned about the impact of gravity on basic mechanisms and about possible countermeasures against effects which occur during the absence of gravity under ► [microgravity \(weightlessness\)](#) conditions.

Basic Methodology

Ground-based studies under conditions of hypergravity (by the use of centrifuges) or simulated microgravity (weightlessness) (by, e.g., the use of 2-D and 3-D clinostats/random positioning machines) have identified and brought deeper insights into gravity-induced biological effects. Subsequently, these studies have to be verified in real microgravity (free fall, near weightlessness). Exposure time ranging from seconds to several minutes are achieved, e.g., in a drop tower, parabolic aircraft, and during ballistic rocket flights. Long-term studies (weeks to months) require the

use of orbiting spacecraft such as satellites (e.g., Foton, Bion, or Compact Satellites) or space stations (e.g., MIR, ISS). The methodology for analyses depends on the issue under investigation and ranges from qualitative video observation via (high-end) microscopy to quantitative molecular biology and high-throughput technologies (Omics). Control experiments are necessary to identify microgravity-related effects and exclude potential non-gravitational responses, e.g., due to launch conditions (hypergravity and vibration).

Key Research Findings

Studies to identify the influence of gravity on living matter cover all organizational levels including isolated proteins, single cells, tissues, and whole organisms. While the primary receptors and mechanisms of graviperception are remarkably similar in evolutionary very diverse biosystems, they differ in their gravitational responses. Visible reactions range from movement reorientation to directed growth responses and from physiological reactions to gene regulation.

Cellular and Molecular Biology

The observation that already unicellular organisms (protists, protozoa) can swim to the top of a completely filled and sealed tube by means of gravitaxis has been made more than a century ago. A real breakthrough in understanding the underlying mechanisms came with technologies designed in order to alter the influence of gravity and methodological advances such as image analysis of cellular behavior as well as biochemical approaches.

Due to current knowledge, the principle of cellular graviperception is sedimentation of a mass, which may either be a heavy statolith or the whole content of the cell heavier than the surrounding medium to operate on a gravireceptor either by exerting pressure and contact or by pulling on cytoskeletal elements. In many cases, the receptor seems to be a mechanosensitive ion

channel activated by the gravitational force followed by gated ion flux across the membrane and in turn activation of a sensory transduction chain. The subsequent responses to the gravity stimulus differ widely, ranging from the activation of enzymes or gene expression to physiological reactions, orientation movements, and directed growth.

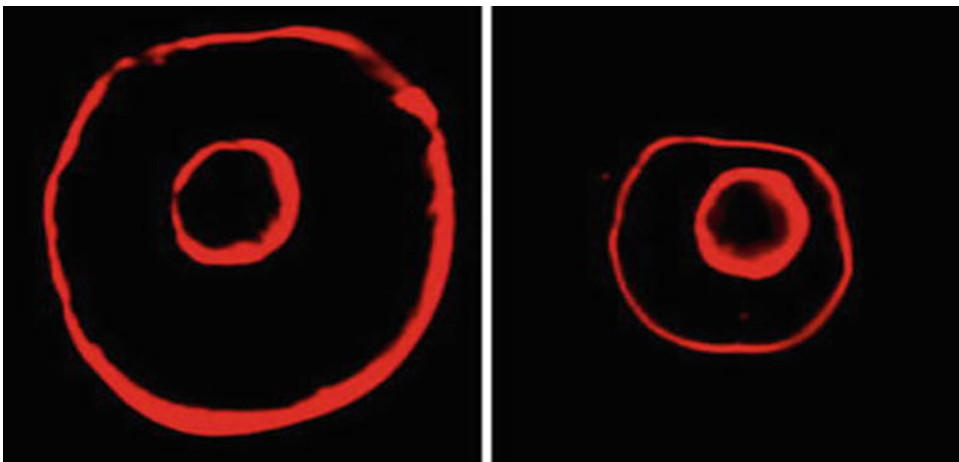
Animal Biology

Spatial orientation and development of animals requires the complex processing of a variety of stimulus inputs by means of specific receptors. Thus it seems likely that altered gravity impairs the physiology of organisms on numerous levels. Microgravity affects early developmental processes; however, regulatory capabilities are able to correct and compensate at least some of these modifications via more or less unknown mechanisms, resulting in an apparently “normal” adult animal compared to the Earth-grown control. Experiments employing aquatic vertebrates yielded critical periods for the development of the vestibular system. Multiple adaptive effects of altered gravity on the development of the neuro-vestibular system in aquatic vertebrates

have been found, especially regarding the neural control of inner ear otolith mineralization in fish (Fig. 1). A closer understanding of the reasons for (human) motion sickness susceptibility was gained by these experiments. In general, the findings support the “otolith asymmetry hypothesis” which relates motion sickness to differential sensory input from the left and the right inner ear. Thus, numerous experiments on fish as model system have shown that particular neuroscientific issues can be transferred to human physiology.

Plant Biology

Plants demonstrate in a fascinating and easily detectable way the impact of gravity on biological systems (Fig. 2). Considerable progress on the basic knowledge of plant gravity sensing and gravitropism has been achieved regarding especially the basic knowledge on the effects of altered gravity (gravitational stress) on essential cellular functions related to plant growth and development. Experiments performed in microgravity have greatly contributed to the understanding of how plants sense the direction of gravity and respond to it. As a simple unicellular system the green alga *Chara* shows a very pronounced gravitropism,



Gravitational Biology, Fig. 1 Otolith mineralization is affected by gravity. Note that a fish otolith grown 3 weeks at 3xg hypergravity (right image, hg) has a core (indicating the begin of the experiment) as small as in a control reared

at Earth gravity (left image, 1xg), but did not grow that large under hypergravity (1xg, left: 175 μm ; hg, right: 115 μm). (Photo: Marion Beier)



Gravitational Biology, Fig. 2 Gravity as a reliable stimulus for the orientation of plants resulting in gravitropism. (Photo: Vanessa Berghoff)

which is based on the directional growth of the opposite flanks to the cell tip. The tip growth of the cell is controlled by the gravity-dependent displacement of statoliths (small grains of barium sulfate), which get into contact with gravireceptor proteins in the lower cell membrane. Gravireceptor activation in gravistimulated rhizoids induces a local reduction of cytosolic calcium at that area where the statoliths sediment. This causes a local inhibition of exocytosis, which results in a differential extension of the opposite cell flanks and the gravitropic response of the rhizoid, namely, the correction of the growth direction.

Arabidopsis thaliana has become the model system of choice to examine gravity-related responses and regulation in higher plants due to the availability of genomic information. While the gravitropism of roots and shoots of higher plants has been well known for over a century, a detailed understanding of the signal perception and transduction has not yet been achieved. Already Charles Darwin identified the root cap as well as

starch containing particles (amyloplasts which serve as statoliths in the root cap) as important for gravitropism. Another line of evidence showed that a phytohormone, auxin, is involved, too. A differential displacement of auxin was identified as main cause for the reorientation growth of plant organs in respect to gravity (but also to other stimuli like light). The current model of gravitropism is based on the differential transport of auxin due to specific membrane proteins (PIN proteins). In roots, auxin is transported in the direction of root caps by the combined action of several PIN proteins. The location of one of the PIN proteins in the membrane changes according to the orientation of the root. As a result the concentration of the auxin increases in the lower half of a gravistimulated root. However, this model includes many unproven hypotheses and the current view might well change in the future.

Applications

Application of gravitational biology aims at the solution of terrestrial and space-related challenges. Assuming that gravisensation is a general capacity of each type of cell, translational research from the cellular level to a medical application provides new aspects of research. Identified issues include the progressive atrophy of bones and muscles as well as the reduced stimulation of immune cells. The recent attempts to understand the microgravity-induced alterations on the molecular and cellular level increase our knowledge in basic life science and might well contribute to human health considerations. Development of countermeasures against, e.g., depression of the immune system, induction of cancer, muscle atrophy, and osteoporosis is relevant for health problems on Earth as well as for long-term crewed space flight.

Furthermore, exploration demands life support systems, for which gravitational biologists take over severe parts of research by studying the physiology and performance of the biological components under altered gravity conditions. Waste management (which means biodegradation of waste into food production), closing of element cycles, as well as optimization of plant growing in

space bear new technologies for agriculture on Earth in extreme environments.

Future Directions

In recent years, research directions changed from descriptive observations to a deeper molecular understanding of the underlying mechanisms. New research directions are fostered by the availability of whole genomes and high-throughput technologies (Omics). This includes the long-term influence of altered gravity (microgravity and hypergravity) on the development of cells, animals, and plants by means of multi-generation experiments. These experiments require biological life-support systems which allow the analysis of the complex interaction of different species in artificial habitats with the direct application in the future of food production, waste removal (solid, liquid, and gaseous), and recycling. Knowing how biological systems manage the absence of gravity is mandatory for long-term orbital and interplanetary missions and will have an impact on health and plant breeding issues on Earth.

Cross-References

- [Gravitation](#)
- [International Space Station](#)
- [Microgravity](#)
- [Microorganism](#)
- [Organelle](#)
- [Planetary and Space Simulation Facilities](#)
- [Radiation Biology](#)
- [Space Biology](#)

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Gravitational Collapse, Planetary

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Gravitational collapse is the collapse of a region of material under its own gravity, for example, of the dense core of an interstellar cloud on its way to becoming a star. Gravitational collapse occurs when the local self-gravity (i.e., the inward-directed force) exceeds the restoring force, which is often in the form of thermal gas pressure or turbulent stirring.

Overview

In astrophysics and planet formation, gravitational collapse is extremely important, and the process is thought to occur in a variety of settings and on a range of different size scales. For example, stars are thought to form from clumps of gas that are gravitationally unstable within ► [molecular clouds](#). In addition, an alternate to the core accretion model for giant planet formation is the top-down, disk instability model. This model proposes that giant planets may form within the very short span of a few thousand years in the outer regions of gravitationally unstable

► [protoplanetary disks](#). Finally, models for the formation of ► [planetesimals](#) suggest that they may form via the gravitational collapse of aggregates of pebble- to boulder-sized bodies that are concentrated within turbulent structures in protoplanetary disks.

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Protoplanetary Disk Instability](#)
- [Star Formation, Theory](#)
- [Star Formation, Triggering](#)

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Gravitational Collapse, Stellar

Steven W. Stahler
Department of Astronomy, University of California, Berkeley, CA, USA

Definition

The rapid contraction of a fluid mass because of the mutual gravitational attraction of its component particles is called gravitational collapse. If the forces supporting the object are weak, then its internal elements freely fall toward one another, leading to a highly condensed final configuration. As a consequence of the inverse-square nature of the gravitational force, the duration of collapse (known as the ► [free-fall time](#)) depends mainly on the object's initial density. In practice, only the very large masses found in astronomical bodies are susceptible to this process. Examples are

dense cores within molecular clouds, which collapse to form stars, and the interiors of massive stars, prior to supernova explosion.

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Free-Fall Time](#)
- [Protostars](#)
- [Protostellar Envelope](#)
- [Star Formation, Theory](#)

Gravitational Focusing

Rory Barnes
Astronomy Department, University of Washington, Seattle, WA, USA

Definition

Gravitational focusing refers to the enhancement in the likelihood that two particles will collide, due to their mutual gravitational attraction. Without gravity, the probability of a collision scales with the cross-sectional area of the two particles, but with gravity, some particles that would have missed each other can still collide. In other words, the particles have effective cross sections larger than their physical cross sections. In the presence of only two bodies (two-body approximation), the gravitational enhancement factor is given by $1 + (v_{esc}/v_{rel})^2$, where v_{esc} is the particle's escape speed and v_{rel} is the relative velocity of the two particles. Gravitational focusing is important during planet formation, as it leads to faster growth.

Cross-References

- [Escape Velocity](#)

Gravitational Instability

- [Protoplanetary Disk Instability](#)

Gravitational Instability (Model for Giant Planet Formation)

► [Disk Instability, Model for Giant Planet Formation](#)

Gravity

► [Gravitation](#)

Great Chain of Being

David Dunér
Lund University, Lund, Sweden

Keywords

History of Biology · History of Science ·
Philosophy of Science

Synonyms

[Chain of being](#); [Ladder of nature](#); [Scala naturae](#)

Definition

The Great Chain of Being suggests that all things in existence are connected in an unbroken, hierarchical chain, from the simplest forms to the most complex ones.

Overview

A prevailing idea through the ages is that of the Great Chain of Being, understanding the universe as a hierarchy of beings, an unbroken chain of existence, from the simplest forms to the most complex ones, from non-living matter to the most rational creatures (Lovejoy 1936). In his *History of Animals* from the fourth century BCE, Aristotle arranged all beings in a ladder of nature,

a *scala naturae*, a gradation of natural things from minerals, through plants and animals, to the human being. The chain of being got biological significance with, among others, Gottfried Wilhelm Leibniz, Carl Linnaeus, Georges-Louis Leclerc de Buffon, and Charles Bonnet. Nature does not make jumps, *Natura non-facit saltus*, as Carl Linnaeus formulated it in *Philosophia Botanica* (1751). There is continuity in nature. In that respect, the Great Chain of Being is connected to the Principle of Plenitude, the fullness of being. The principle suggests that every possible form of creature exists. This could also be understood in a temporal sense that every possible form of creature, even though not existing right now, might have existed before or could be realized at some stage in the future. Continuity is an idea implicit in that of plenitude. In the early nineteenth century, this continuity of nature became understood in temporal meaning. Jean-Baptiste de Lamarck went from a static concept of the series of life-forms to a theory of species transformation that life had developed over time from simpler to more complex forms. During the nineteenth century, the Great Chain of Being was replaced by another metaphor, the Tree of Life, which also stressed on the continuity of nature, but took into account the genealogy and evolution of life-forms, as in Lamarck's *Philosophie zoologique* (1809) and Darwin's *Origin of Species* (1859).

Cross-References

- [Buffon's Conception of Origins of Life](#)
- [Copernican Principle](#)
- [Principle of Plenitude](#)

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Great Oxidation Episode

► Great Oxidation Event

Great Oxidation Event

Andrey Bekker

Department of Earth Sciences, University of California, Riverside, CA, USA

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Keywords

Paleoproterozoic · Lomagundi carbon isotope excursion · Huronian glaciation · Rise of atmospheric oxygen · Great Oxidation Event · Great Oxidation Transition · Great Oxidation Episode

Synonyms

Great Oxidation Episode; Great Oxidation transition; Oxyatmversion; Rise of atmospheric oxygen

Definition

The Great Oxidation Event (GOE) refers to the transition from the mildly reducing Archean atmosphere-ocean system to the oxygenated atmosphere and shallow oceans of the early Paleoproterozoic that started at ~2.4 and ended between 2.1 and 2.0 Ga (Holland 2002). The beginning and the end of the GOE were never explicitly defined. In general terms, the beginning of the GOE is marked by the disappearance of mass-independent fractionation of S isotopes and

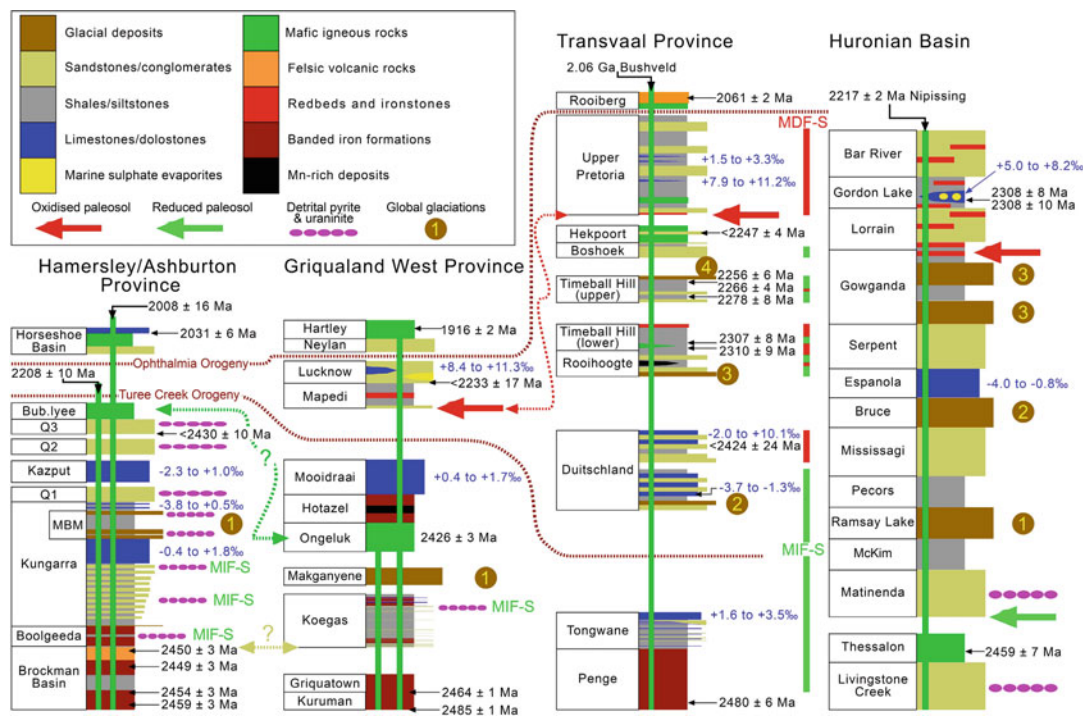
an increased range of mass-dependent fractionation of sulfur isotopes in association with highly variable carbon isotope record, Huronian glaciations, and the final stage in the assembly of the supercraton Superia (Bekker et al. 2004; Holland 2006; Bekker and Holland 2012; Gumsley et al. 2017). Although the term implies a relatively short duration, as that of phenomena used in event stratigraphy, the GOE is originally defined to last more than 200 Ma and finish at the end of the >2.22–2.06 Ga Lomagundi carbon isotope excursion during which between ~12 and 22 times the oxygen content of the present-day atmosphere was released to surface environments (Karhu and Holland 1996). While the internal texture of the GOE is still unresolved and remains to be a topic of further work (see Poulton et al. 2021), during these 200 Ma, atmospheric oxygen likely fluctuated across the level of 10^{-5} PAL (present atmospheric level) to a magnitude of fully oxygenated atmosphere (well below the modern level) before rapidly falling to much lower atmospheric and ocean oxygen concentrations in the immediate aftermath of the Lomagundi carbon isotope excursion (Ossa Ossa et al. 2018a). The GOE ended up with the ocean deoxygenation in association with the supercraton Superia breakup, sea-level rise, and deposition of Mn- and P-rich sediments (Bekker et al. 2003).

History

The notion that the early Earth's atmosphere did not contain oxygen is deeply rooted in studies of biology and chemistry in the eighteenth and nineteenth centuries (Priestley 1781; Phipson 1893). The first detailed discussion, founded on geological evidence that atmospheric oxygen was low and then rose in the Middle Precambrian, was presented by MacGregor (1927), a director of the Rhodesia Geological Survey, based on his observations on sedimentary successions preserved in the Archean ► [greenstone belts](#) and the Paleoproterozoic Magondi Mobile Belt of Rhodesia (Zimbabwe). This interpretation remained largely unnoticed since poor age constraints limited correlation of Precambrian sedimentary

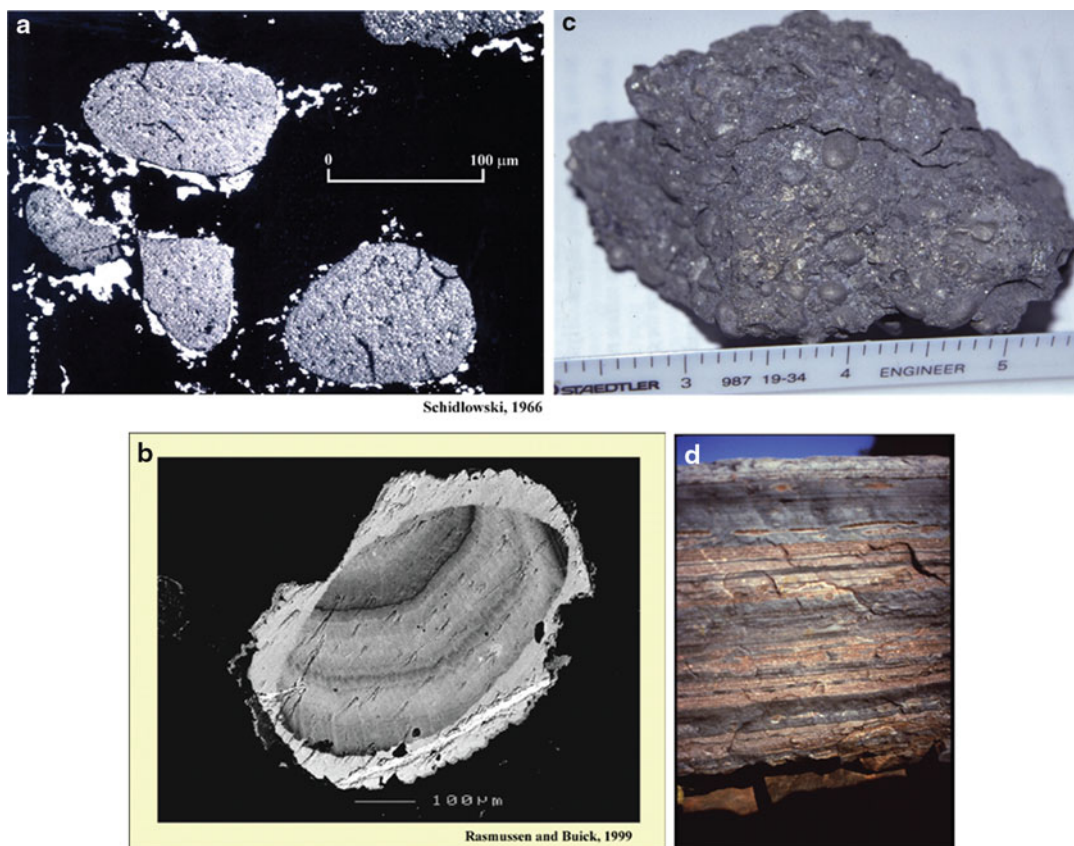
successions, making it difficult to constrain the age and stratigraphic position of this event. By the 1960s, several independent lines of evidence were employed to provide a strong support for atmospheric oxygenation in the Middle Precambrian. S.M. Roscoe (1969, 1973) working for the Geological Survey of Canada in the Huronian basin of Southern Ontario observed that the lower part of the Huronian succession contains detrital pyrite and uraninite and reduced paleosols, while the upper part has red beds and oxidized paleosols; sandwiched between these levels, the middle part recorded three glacial events (Fig. 1). Similar rounded grains of pyrite, uraninite, and siderite (Fig. 2), which are not stable in contact with oxidized waters and

oxygenated atmosphere, were also observed worldwide in fluvial conglomerates from sedimentary successions of similar and older age (e.g., Schidlowski 1966; Rasmussen and Buick 1999). Roscoe (1973) named this transition at ~ 2.3 Ga “oxyatmoverison.” Interestingly, as shown on Fig. 1, more than 40 years later, our geochronological and stratigraphical estimates for this transition did not change significantly. Preston E. Cloud Jr. of the University of California, Los Angeles (UCLA), linked biological evolution and environmental changes suggesting that once efficient oxygen- and peroxide-mediating enzymes developed, oceans became oxygenated and banded iron formations were replaced by red beds in the rock record by ~ 1.8 – 2.0 Ga (Cloud



Great Oxidation Event, Fig. 1 Generalized stratigraphic sections of the Pilbara, Griqualand West/Transvaal and Huronian successions, highlighting the stratigraphic position of Paleoproterozoic global glaciations, C- and S-isotope chemostratigraphy, and published geochronology (after Bekker et al. 2020 and 2021 with additional information on mass-independent fractionation of sulfur (MIF-S) and mass-dependent fractionation of sulfur (MDF-S) from Poulton et al. 2021). Neither stratigraphic

thickness nor absolute age are implied by the thickness of units in stratigraphic columns, whereas gaps along stratigraphic sections are hiatuses on unconformities. Bub.lyee is the Bubbawalyee Formation; Q1, Q2, and Q3 are respectively Quartzite 1, 2, and 3; MBM is the Meteorite Bore Member. The exact stratigraphic position of the transition from MIF-S to MDF-S is uncertain for the Huronian Supergroup and therefore not shown



Great Oxidation Event, Fig. 2 Mineralogical and lithological proxies for Archean anoxic atmosphere and ocean: (a) detrital, muffin-shaped grains of uraninite with galena overgrowths from Archean fluvial conglomerates of South Africa (From Schidlowski 1966); (b) detrital,

rounded siderite grain, with core of compositionally banded siderite and syntaxial overgrowth (From Rasmussen and Buick 1999); (c) detrital, rounded pyrite grains from the ~2.64 Ga Black Reef Quartzite, South Africa; and (d) ~2.45 Ga banded iron formation, Western Australia

1968). Heinrich D. Holland of Princeton University, on the basis of geochemical arguments and the presence of detrital uraninite in siliciclastic fluvial and shallow-marine successions, inferred the occurrence of a largely anoxic atmosphere before ~1.8 Ga (Holland 1962). These interpretations were not universally accepted and they were contested on various occasions (e.g., Dimroth and Kimberley 1976; Ohmoto 2004 and references therein). Arguments of the 1970s–1990s helped to deepen our understanding of timing and different geochemical and geological proxies for the rise of atmospheric oxygen as well as to quantify atmospheric and seawater oxygen levels implied by these proxies. Most of these arguments were

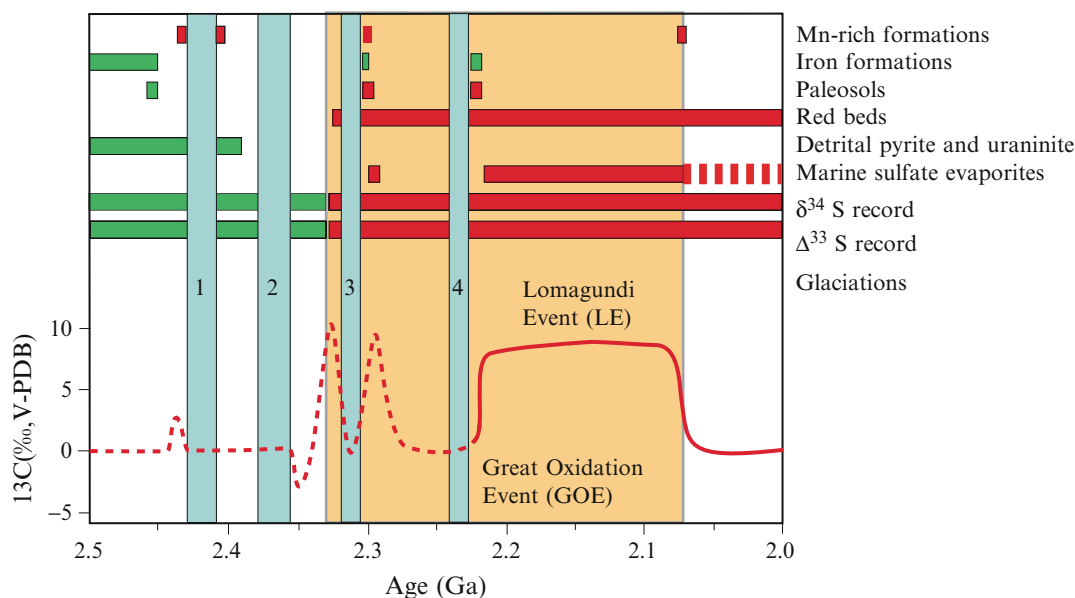
put to rest by 2000, when James Farquhar of the University of Maryland (Farquhar et al. 2000) discovered mass-independent fractionation of sulfur isotopes in Archean sedimentary sulfides and sulfates, which can only be explained by photochemical processes in the atmosphere with low levels of oxygen ($<10^{-5}$ PAL). This approach was subsequently applied to infer that the rise of atmospheric oxygen started at ~2.45 Ga (Bekker et al. 2004; Hannah et al. 2004; Guo et al. 2009; Warke et al. 2020) and that atmospheric oxygen fluctuated across the 10^{-5} PAL level until ~2.22 Ga (Poulton et al. 2021). In the last decade, a number of studies were published, which suggested transient, low-level oxygenation events

before the GOE, of either global or local extents (e.g., Anbar et al. 2007; Crowe et al. 2013; Planavsky et al. 2014). The current and future research is now faced with a challenge: how to reconcile the notion of the long-lasting (>1 Ga) period with transient or low-level oxygenation with a geologically rapid transition to the oxygenated atmosphere at ~ 2.4 Ga.

Overview

Evidence is growing for supporting oxygenic photosynthesis as early as ~ 3.0 Ga ago and for transiently, globally or locally, oxygenated environments since that time (Anbar et al. 2007; Crowe et al. 2013; Planavsky et al. 2014). However, it is clear that mass-independent fractionation of sulfur isotopes persisted in the sedimentary record until ~ 2.22 Ga, indicating that oxygen was not a stable component of the

atmosphere at concentrations higher than 10^{-5} PAL, until more than half billion years later (Farquhar et al. 2000; Bekker et al. 2004; Poulton et al. 2021) and that large-scale fluctuations in atmospheric oxygen across the 10^{-5} PAL level continued after the GOE started. This is somewhat disconcerting considering a relatively small size of atmospheric oxygen reservoir and theoretical modeling indicating bistability of oxygen in the atmosphere at either very low ($<10^{-5}$ PAL) or substantial ($>5 \times 10^{-3}$ PAL) steady-state concentrations (Goldblatt et al. 2006). The rise of atmospheric oxygen in the early Paleoproterozoic is associated with the Huronian ice ages, when the Earth experienced four, potentially low-latitude glaciations between ~ 2.45 and 2.22 Ga ago (Fig. 3; Rasmussen et al. 2013). Association between the rise of atmospheric oxygen and global glaciations in the Paleoproterozoic has been explained by high (>1000 ppm) concentrations of methane in the Archean anoxic



Great Oxidation Event, Fig. 3 Secular carbon isotope variations in seawater and redox indicators for the oxidation state of the early Paleoproterozoic atmosphere-ocean system (Modified from Bekker and Holland 2012). Four blue vertical bars mark Paleoproterozoic glacial events; the dashed secular carbon isotope curve between 2.5 and 2.22 Ga emphasizes the uncertainty in this part of the curve; the dashed bar for marine sulfate evaporites after

ca. 2.07 Ga indicates that sulfate evaporites again became rare in the Paleoproterozoic and Mesoproterozoic records after that time. Deposition of iron formations and Mn-rich deposits indicates anoxic conditions in deep-waters. While deposition of iron formations does not necessarily require atmospheric oxygen and can be mediated by anoxygenic photosynthetic bacteria, Mn oxidation requires significant levels of atmospheric oxygen (e.g., Ossa Ossa et al. 2018b)

atmosphere, contributing to greenhouse conditions (Pavlov et al. 2000). The rise of atmospheric oxygen would decrease methane residence time and its concentration in the atmosphere, resulting in loss of greenhouse conditions; the Huronian ice ages in this scenario could reflect a transition from the anoxic, methane-rich Archean atmosphere to the oxygenated atmosphere with much lower levels of methane and sufficient concentrations of CO₂ to maintain greenhouse conditions (Bekker and Kaufman 2007).

The rise of atmospheric oxygen is also associated with dramatic fluctuations, with escalating magnitudes, in biogeochemical carbon cycle following the long-term stability of the Archean carbon cycle (Fig. 3; for notation, see ► [Delta, Isotopic](#)); their development immediately before and during the Huronian ice ages argues for a dynamic state of carbon cycle. The carbon isotope values of carbonates are mostly at around +8‰ for the duration of the >2.22–2.06 Ga Lomagundi carbon isotope excursion (Bekker et al. 2003; Fig. 3). Since positive C-isotope values in carbonates are thought to reflect high relative burial rate of organic carbon, between 12 and 22 times, the present atmospheric oxygen inventory could have been released to the surface environments during the Lomagundi carbon isotope excursion (Karhu and Holland 1996), with oxidation of reduced iron and sulfur in the continental crust consuming most of it. Indeed, red beds, sulfate evaporites, and high concentrations of redox-sensitive trace metals such as U, Mo, and Re in organic-matter-rich shales appear at that time, indicating expansion of oxidized environments. The end of the Lomagundi carbon isotope excursion is bracketed between 2.11 and 2.06 Ga (Karhu and Holland 1996) and marked by deposition of organic-matter-rich shales with highly ¹³C-depleted isotope values and Mn- and P-rich sediments (Bekker et al. 2003), whereas sulfate evaporites became again scarce, and proxies for ocean oxidation state indicate expansion of anoxia at the end of the GOE (e.g., Scott et al. 2014; Ossa Ossa et al. 2018a).

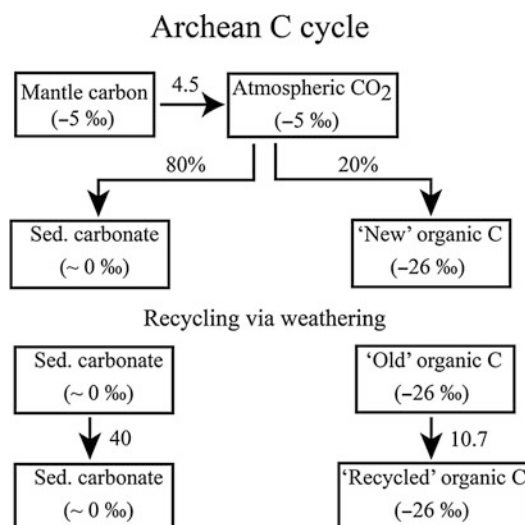
The beginning of the Lomagundi carbon isotope excursion has been related to high continental nutrient (e.g., phosphorus) flux linked to acidic

groundwaters during the GOE (Konhauser et al. 2011; Bekker and Holland 2012). The high acidity in terrestrial waters was related to extensive oxidation of sulfides for the first time in Earth's history during continental weathering. Acidic conditions in continental runoff promoted dissolution of phosphates and higher P delivery to the ocean resulting in higher relative burial rate of organic carbon and associated oxygen release. Another contributing factor could have been increased seawater sulfate content, resulting in sulfurization of organic matter and higher preservation/burial of sulfurized labile organic matter (Bekker et al. 2020). The duration of the Lomagundi carbon isotope excursion is comparable to the half-life of sedimentary rocks in the continental crust suggesting that groundwater acidity could have been largely titrated by the end of the excursion. This, by itself, could have resulted in decreased nutrient flux to the ocean ending the GOE (cf., Bekker and Holland 2012). Alternatively, weathering of organic-matter-rich shales deposited during the Lomagundi carbon isotope excursion and uplifted during the ~2.1 Ga orogenic events or submarine hydrothermal activity associated with the breakup of the supercraton Superia or emplacement of Large Igneous Provinces could have contributed reduced carbon, iron, and manganese to the atmosphere-ocean system and resulted in expansion of anoxic settings (cf., Kump et al. 2011; Bekker and Holland 2012; Ossa Ossa et al. 2018a). Although it remains unclear which of these scenarios (or a combination of them) ended the GOE, the largest and longest-lived carbon isotope excursion in Earth's history ended up with the return to low-oxygen levels in the atmosphere-ocean system.

While the timing and texture of the GOE is progressively better understood (e.g., Gumsley et al., 2017; Warke et al. 2020; Poulton et al. 2021), mechanisms for delayed oxygenation remain highly speculative. The proposed diverse mechanisms can be broadly grouped into three categories relying on (1) changes in mantle properties, (2) continental crustal growth, and (3) progressive oxidation of continental or oceanic crust. Inferred changes in mantle properties, bearing on

the surface redox state, include oxidation of the mantle by crustal subduction and mantle overturn (Kump et al. 2000; Holland 2002) and progressive cooling of the upper mantle (Konhauser et al. 2009). Continental crustal growth is held responsible for sea-level fall (emergence of landmasses; Bindeman et al. 2018) and increased subaerial volcanism during the Archean to Paleoproterozoic transition (Kump and Barley 2007; Gaillard et al. 2011), which resulted in delivery of more oxidized volcanic gases with respect to predominantly submarine volcanism in the Archean. Progressive oxidation of oceanic or continental crust by either hydrogen escape from the atmosphere or oxygenic photosynthesis is inferred in a number of models to either decrease oxygen sinks in the surface environments or increase oxidation potential of volcanic gases generated via crustal subduction and recycling (Holland 2009; Claire et al. 2006; Catling et al. 2001; Kasting 2013; Zahnle et al. 2013). All these models are concerned with the changes in the size of oxygen sinks and assume that the oxygen source did not change in size since oxygenic photosynthesis evolved.

An alternative could be that oxygenic photosynthesis was limited by low continental flux of nutrients (e.g., Mo and V; important for nitrogen fixation) into the Archean ocean or high removal potential of phosphorous in ferruginous ocean with green rust, iron oxyhydroxides, iron phosphates (Stüeken et al. 2021), resulting in limited net primary productivity and organic carbon burial. This suggestion is generally dismissed since it would have significant repercussions for the biogeochemical carbon cycle, which are not apparent in the carbon isotope record of Archean carbonates (e.g., Kasting 2013). However, continental weathering of sedimentary rocks would not return buried organic carbon to biogeochemical cycling under the Archean anoxic atmosphere; rather it would be buried again as recycled organic matter with sediments. Similarly, carbon isotope mass balance requires that carbon released by dissolution of sedimentary carbonates was also excluded from biogeochemical carbon cycle to satisfy carbon isotope values of Archean carbonates near to 0‰. Consequently, carbon isotope



Great Oxidation Event, Fig. 4 Archean biogeochemical carbon cycle; fluxes for the Neoproterozoic are in 10^{12} mol/year from Bekker and Holland (2012). Isotopic composition of Archean carbonates and organic matter is based on the geological records. It is proposed that organic and carbonate carbon contents of the Archean crust have been growing, resulting in a progressively increasing subduction flux of carbon to the mantle. Both carbonate and organic carbon were recycled during continental weathering, but did not pass through biogeochemical carbon cycle due to the lack of oxygen in the Archean atmosphere and low flux of nutrients to the oceans (see text for more details)

records could be potentially consistent with limited net primary productivity and organic-carbon burial under the Archean anoxic atmosphere-ocean conditions (Fig. 4).

The critical gap in our understanding of the GOE is why it started at ~2.45 Ga. Association with the supercontinent assembly and 2.45–2.5 Ga mantle plume events has been previously recognized (e.g., Barley et al. 2005; Kump and Barley 2007), but was not satisfactorily explained. In view of the above discussed limited net primary productivity and nutrient limitation in the Archean oceans, it is worth considering enhanced continental nutrient flux under highly acidic groundwater conditions during mantle plume events, when large amounts of CO_2 and, especially, SO_2 were released to the anoxic atmosphere and precipitated as acidic aerosols on the continents. Similar scenario could potentially explain Archean transient oxidation events, but in

contrast to these short-lived events, the 2.45–2.5 Ga time interval is marked by multiple mantle plume events that affected all continents. This period was previously singled out in the Earth's history and was linked to a fundamental change in heat flux at the core-mantle boundary (Heaman 1997).

The recent model for recycling mass independently fractionated sulfur from the continental crust to the oceans allows for as much as 100 Ma delay for the disappearance of MIF-S from the sedimentary record after the GOE started (Reinhard et al. 2013). In this model, atmosphere could have had significant level of oxygen resulting in continental weathering under anoxic conditions, while seawater sulfate and sedimentary sulfur would still carry MIF. However, the relationships among the demise of MIF in the sedimentary S isotope records, evidence for atmospheric and ocean oxygenation, ice ages, and dynamic state of biogeochemical carbon cycle clearly argue against this delay (Fig. 1; see also Poulton et al. 2021; Bekker et al. 2021). As our understanding of Earth's history evolves and as we answer some of our questions, more complex puzzles surface and motivate us to search for a deeper grasp. We are reasonably certain now when the GOE happened and what were other events associated with it. The questions that we will be likely faced for another decade or two are these: Why was the GOE delayed? Why did it happen when it happened? Why biogeochemical carbon cycle did not change after the GOE? To answer these questions, a combination of theoretical modeling with field and laboratory studies will be required. The prospective of full understanding of the Earth system is as ever a tantalizing goal to reach.

Cross-References

- [Cap Carbonates](#)
- [Carbon Cycle, Biological](#)
- [Diamictite/Diamicton](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Glaciation](#)
- [Isotope Biosignatures](#)
- [Oxygenation of the Earth's Atmosphere](#)

- [Paleosols](#)
- [Precambrian](#)
- [Proterozoic Eon](#)
- [Pyrite](#)
- [Red Beds](#)
- [Sedimentary Rock](#)
- [Snowball Earth](#)
- [Stable Isotopes](#)
- [Stratigraphy](#)
- [Sulfur](#)
- [Sulfur Cycle](#)
- [Transvaal Supergroup, South Africa](#)
- [Weathering](#)

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Great Oxidation Transition

► Great Oxidation Event

Green Bacteria

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

Green nonsulfur bacteria; Green sulfur bacteria

Definition

Green bacteria denote strict anoxygenic phototrophic bacteria containing chlorosomes as light-harvesting system. Chlorosomes are very efficient light-harvesting structures. This structure is a giant antenna in which bacteriochlorophyll molecules are not bound to proteins and functions instead like a solid-state circuit. Chlorosome bacteriochlorophylls absorb light and transfer the energy to the bacteriochlorophyll located in the reaction center on the cytoplasmatic membrane. This arrangement is highly efficient for absorbing light at low intensities. Chlorosomes allow green bacteria to grow at the lowest light intensities of all known phototrophs. The green photosynthetic bacteria are divided into two distinct phylogenetic groups: the green sulfur bacteria and the green nonsulfur bacteria. The green sulfur bacteria utilize H_2S as an electron donor, so they can tolerate this toxic molecule. Most of the species are photoheterotrophs so they can assimilate few organic compounds as carbon sources. The autotrophic species of this phylum use the reverse citric cycle to fix CO_2 . The green nonsulfur bacteria only tolerate low concentrations of H_2S . Although the few species known have a chlorosome structure, their reaction center differs from the green sulfur bacteria and is more similar to the reaction center of the purple phototrophic bacteria (*Proteobacteria*). The strict autotrophic species of the green nonsulfur bacteria use the hydroxypropionate pathway to fix CO_2 , which is unique to other phylogenically ancient organisms.

Cross-References

- Anoxygenic Photosynthesis
- Carbon Dioxide
- Citric Acid Cycle
- Photoautotroph

Green Bank Equation

- Drake Equation

Green Nonsulfur Bacteria

- [Green Bacteria](#)

Green Sulfur Bacteria

- [Green Bacteria](#)

Greenhouse Effect

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Definition

The warming of a planet by the “greenhouse effect” is caused by atmospheric gases that are very efficient absorbers in the infrared but not in the visible. Symmetric, nonpolar molecules such as H₂, N₂, and O₂ have no electric dipole and cannot absorb or emit photons. They are therefore not greenhouse gases. The visible light of the parent star reaches and heats the planetary surface and is reemitted in the infrared, where part of the energy is absorbed by the atmospheric greenhouse gases with some radiated back toward the surface. Water, carbon dioxide, and methane are the greenhouse gases that raise the surface temperature on Earth to an average of +15 °C instead of −17 °C. The “runaway greenhouse” occurs when greenhouse conditions vaporize part of a water reservoir, the resulting water vapor increases the greenhouse effect, and this feedback cycle leads to loss of the entire surface water and, as a secondary effect, to the photodissociation of the atmospheric water vapor and the loss of hydrogen to space (e.g., a possible scenario for Venus, if it had a similar water reservoir as the Earth).

Cross-References

- [Absorption Cross Section](#)
- [Atmospheric Modeling, Gray Gas Model](#)

- [Atmospheric Modeling, Non-gray Gas Model](#)
- [Climates, Diversity in the Solar System](#)
- [Climates, Terrestrial Planets](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)

Greenschist Facies

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Greenschist facies is one of the major subdivisions of the classification scheme of metamorphic rocks. Greenschist facies refers to rocks which were affected by low- to medium-grade metamorphic conditions corresponding to temperatures of about 300–500 °C and pressures of 3–20 kbar, conditions equivalent to crustal depths of about 8–50 km. The name is derived from the green color of its characteristic minerals (chlorite) and the schistose fabric, consisting of thin and abundant layers of minerals that are naturally flat or long (foliation). This fabric is induced by recrystallization and deformation. Characteristic minerals are chlorite, actinolite, and albite ± epidote in metabasalt; chlorite, serpentine ± talc, tremolite, and brucite in meta-ultramafic rocks; and muscovite, garnet, and andalusite in metapelitic sediments. Greenschist facies prevails in the middle levels of oceanic crust and in the upper levels of orogenic belts. Many supracrustal rocks in Archean terranes are metamorphosed at greenschist facies, hence the name “greenstone belts.”

Cross-References

- [Archean Eon](#)
- [Greenstone Belt](#)
- [Metamorphic Rock](#)
- [Oceanic Crust](#)

Greenstone Belt

Nicholas Arndt

Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

A greenstone belt is a usually elongate structure composed dominantly of metamorphosed supra-crustal rocks (rocks formed at or near the Earth's surface, i.e., volcanics and sediments). Together with granite and gneiss, greenstone belts are the main constituents of Archean and Proterozoic cratons.

The volcanic rocks range in composition from komatiite to rhyolite but are dominated by basalt; sedimentary rock types are diverse and include shale, siltstone, sandstone, conglomerate, rare carbonates and evaporites, and (bio)chemical precipitates such as banded-iron formation and chert. The elongated shape and the vertical structures of greenstone belts are generally considered as the result of sagduction mechanisms.

The geochemical composition of the basaltic rocks shows that some formed as oceanic crust, perhaps as part of oceanic plateaus, and that others formed in island arcs. The sedimentary rocks usually document the evolution of greenstone belts from deep marine, open-oceanic settings through marginal basins filled with voluminous turbidites and chemical sediments. Very few greenstone belts include a sedimentary cap of shallow-water and quartz-rich sediments.

Although the metamorphic grade of most greenstone belts ranges from sub-greenschist to amphibolite facies, greenschist-facies metamorphism dominates. Metamorphic grade typically increases toward the plutonic or gneiss terranes bordering the greenstone belts and toward internal ductile shear zones. Abundant chlorite and actinolite in greenschist-facies basalts and serpentinite formed from ultramafic rocks impart a green color that gives rise to the name.

Because greenstone belts can be considered the down-sagged "keels" of deformed sedimentary basins, most units in greenstone belts dip steeply, are tightly folded, and are cut in places by large shear zones. These developed as parts or all of the volcano-sedimentary sequence were accreted to a continent or deformed in a continental collision zone.

Archean greenstone belts represent the oldest record of Earth's surface conditions, including the evolution and spreading of life on Earth. They host important ore deposits of metals such as gold, Cu-Zn, Ni, and Fe. Well-known examples include the Abitibi and Flin Flon belts in Canada, the Norseman-Wiluna belt in Australia, and the Barberton, Sutherland, and Murchison belts in South Africa.

Cross-References

- ▶ [Barberton Greenstone Belt](#)
- ▶ [Canadian Precambrian Shield](#)
- ▶ [Greenschist Facies](#)
- ▶ [Metamorphic Rock](#)
- ▶ [Metasediment](#)
- ▶ [Pilbara Craton](#)

Grey Body

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A grey body is a hypothetical source of electromagnetic radiation that would emit as a ▶ [black body](#) but with an ▶ [emissivity](#) lower than 1 and constant with wavelength. The grey body assumption is often more useful as a first approximation to the actual emission of a real object or medium than is the ideal black body radiation. It is used in ▶ [radiative transfer](#) problems, for instance, in planetary atmospheres.

Cross-References

- ▶ [Blackbody](#)
- ▶ [Emissivity](#)
- ▶ [Radiative Processes](#)
- ▶ [Radiative Transfer](#)

Groove

- ▶ [Rille](#)
- ▶ [Rima, Rimae](#)
- ▶ [Sulcus, Sulci](#)

Guanine

Shin Miyakawa
Kamagaya, Chiba, Japan

Definition

C₅H₅N₅O. MW: 151.13. Guanine is one of four nucleic acid bases found in DNA and ▶ [RNA](#). In double-stranded DNA, guanine base pairs with cytosine. It is hydrolyzed to xanthine. The half-life to hydrolysis in solution is 0.8 years at 100 °C and 1.3×10^6 years at 0 °C at pH 7. It has a UV absorption maximum at 246 and 276 nm (pH 7). It has been found in the Murchison meteorite and can be synthesized in HCN polymerizations, Fischer-Tropsch type reactions, and electric discharges acting on gas mixtures such as CO-N₂-H₂O.

Cross-References

- ▶ [Cytosine](#)
- ▶ [DNA](#)
- ▶ [Fischer-Tropsch-Type Reaction](#)
- ▶ [HCN Polymer](#)
- ▶ [Hydrogen Cyanide](#)
- ▶ [Murchison](#)
- ▶ [Nucleic Acid Base](#)
- ▶ [RNA](#)

Gullies

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Keywords

Erosion · Flooding · Groundwater · Ice · Water

Definition

On Earth, the term gully refers to a small and narrow but relatively deeply incised stream course. On ▶ [Mars](#), the term is used somewhat differently to denote a landform consisting of – from top to bottom – (1) a catchment area or erosional alcove, (2) one or several transport channels, and (3) a depositional fan or apron.

Overview

Gullies were first unambiguously identified on Mars in images taken by the Mars Orbiter Camera (MOC) (Malin and Edgett 2000). Gullies are relatively small landforms, with common lengths of a few kilometers only. Close morphological analogues to Martian gullies exist in the Arctic regions on Earth (e.g., Greenland, Svalbard), but also in hot arid environments. On Earth, gullies typically form by the action of liquid ▶ [water](#). The gullies on Mars are very young and could have formed in the past several million years or even more recently (Reiss et al. 2004). Most of the gullies have been found in midlatitudes, where liquid surface water is physically not stable with the current Martian climate. Most of the present-day activity in gullies appears to be by mass wasting associated with CO₂ frost/ice (Dundas et al. 2012). Many hypotheses have been put forward to solve this conundrum, including a formation by groundwater (Malin and Edgett 2000), liquid CO₂ (Musselwhite et al. 2001), or dry granular flows (Treiman 2003). While these models avoid the problem of forming midlatitude liquid

surface water in the recent past, they have been challenged on the basis of physical and morphological arguments (e.g., see the discussion in Dickson and Head 2009). On the other hand, scenarios involving liquid water as a result of near-surface ground ice or snow melting (Costard et al. 2002; Christensen 2003) would imply precipitation (most probably snow) and, therefore, a recent climate change on Mars. The climate of Mars is susceptible to astronomical forcing (i.e., the effect on climate of changes in the tilt of the rotational axis of a ► [planet](#) and of orbital parameters such as ► [eccentricity](#)) (Jakosky et al. 1995), and it is plausible that periodic variations of the obliquity of the planet's spin axis in the past 10^5 – 10^6 years (Laskar et al. 2004) allowed the deposition of snow and ice in midlatitudes (Mischna et al. 2003). The possible existence of liquid water or water ice at or near the surface classifies some gullies as potential special regions that are banned from being investigated in situ due to ► [planetary protection](#) rules.

Cross-References

- [Eccentricity](#)
- [Mars](#)
- [Obliquity and Obliquity Variations](#)
- [Planet](#)
- [Planetary Protection](#)
- [Water](#)

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Gunflint Formation

Takeshi Kakegawa, Akizumi Ishida and Kohei Sasaki
Graduate School of Science, Tohoku University,
Sendai, Japan

Keywords

Gunflint Formation · Microfossils · Rove formation · Stromatolites · Sudbury impact · Traces of life

Definition

The Gunflint Formation of the late Paleoproterozoic Animiki Group comprises chemical, clastic, and volcanoclastic sedimentary rocks that are 100–160 m thick and which extend for 175 km along the Gunflint Range from northeastern Minnesota to the Thunder Bay area of Ontario, Canada. The Gunflint Formation is known for the occurrence of various ► [microfossils](#), including *Gunflintia*, *Huroniospora*, and *Eoastrian* (e.g., Tyler and Barghoorn 1954; Awramik and

Barghoorn 1977). Fossilized primitive fauna in Gunflint Formation is one of the best preserved in the geological record. For this reason, the biogenicity of older microfossils and dubiofossils is often tested by comparison with the Gunflint Formation fossil record.

Overview

The Gunflint Formation was deposited on an Archean basement at the southwestern margin of the Superior Province (see ► [“Canadian Precambrian Shield”](#)). The occurrence of granular peloidal and oolitic iron formations or taconite (an iron-bearing, high-silica, chert-like rock) characterizes the Gunflint Formation. Previous investigators subdivided the Gunflint Formation into two members based on their respective lithologies (Fralick and Barrett 1995). The lower member typically has a basal conglomerate with algal chert, covered by cherty calcareous rocks, changing into jaspilitic grainstone facies (see ► [“Jaspilite”](#)). The upper member has a stratigraphy resembling that of the lower member: algal chert is followed by a succession of cherty calcareous rocks and banded chert carbonate that passes westward into jaspilitic facies. Those facies suggest that the sediments of the Gunflint Formation were deposited under wave-dominated and tide-dominated inter-shelf environments (Fralick and Barrett 1995). The carbonaceous shales of the Rove Formation overlie the upper member of the Gunflint Formation. The occurrence of various microfossils and ► [stromatolites](#) together with kerogenous sediments makes the Gunflint and Rove Formations attractive for astrobiologists to constrain the course of the Paleoproterozoic ecological evolution (Tyler and Barghoorn 1954). Accretionary lapilli were reported from near the Gunflint-Rove boundary. These accretionary lapilli are often interpreted as impact-related ► [ejecta](#) (Addison et al. 2005). Such occurrence of accretionary lapilli creates another research interest for astrobiologists, related to whether or not a Paleoproterozoic meteoritic impact might have affected the microbial ecosystem.

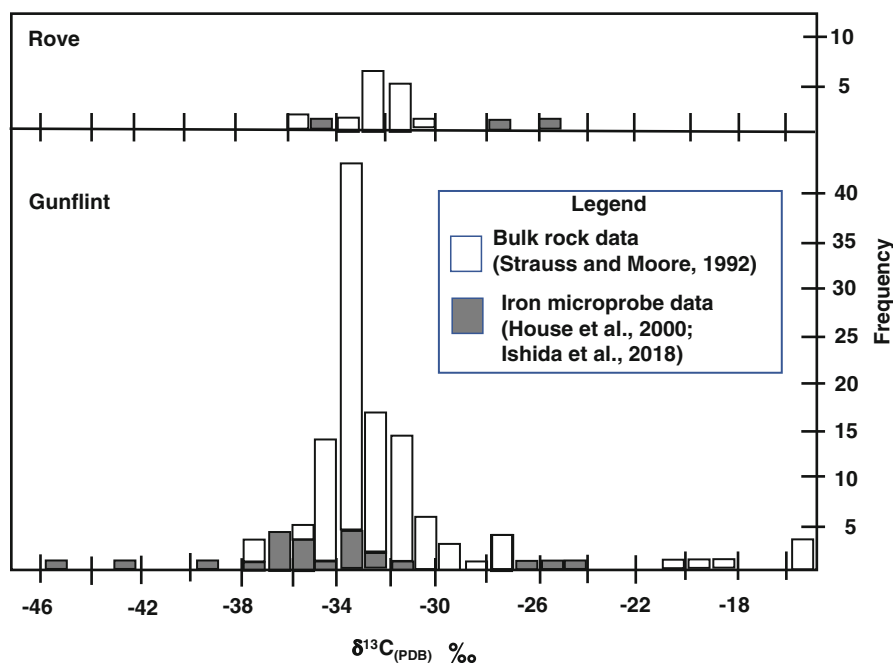
Basic Methodology

The morphology of the microfossils in the Gunflint Formation can be identified and classified based on microscopic observations of multiple of thin sections. Individual microfossils were often extracted from rock chips by the maceration method to examine their morphologies. The detailed textures or morphologies of individual microfossils are observed by the secondary electron microscopy (SEM). Stable carbon isotope compositions of organic matter can be analyzed either by the standard gas mass spectroscopy or secondary ionization mass spectroscopy (SIMS). The carbon isotope compositions are expressed as the delta notation ($\delta^{13}\text{C}$) compared to the international reference of V-PDB (Vienna Pee Dee Belemnite).

Key Research Findings

A Redox-Sensitive Ecosystem

Banded iron formations (BIFs) disappeared after ca. 1.7 Ga. The BIFs of the Gunflint Formation are thus among the most recent BIFs on Earth. It is generally accepted that hydrothermal vent waters were the dominant source of dissolved iron to form BIFs. The deep ocean becomes ferruginous by an enhanced hydrothermal Fe flux, leading to Fe-rich deep-water upwelling onto oxidized shelves. Previous studies also indicate the presence of stratified ocean to form BIFs during deposition of the Gunflint Formation. Large quantities of carbon isotope compositions of organic matter and kerogen are available for the Gunflint and Rove Formations (Strauss and Moore 1992). Most organic matter has $\delta^{13}\text{C}_{\text{(PDB)}}$ values of -36 to -31‰ (Fig. 1). Such values are consistent with carbon fixation via the Calvin cycle. They are therefore consistent with earlier studies that assigned some of the Gunflint microfossils to the ► [cyanobacteria](#) phyla based on their morphology (Barghoorn and Tyler 1965). Therefore, it appears certain that oxygenic environments were widespread on the surface of the Gunflint Ocean as supported by the occurrence of banded iron formations.



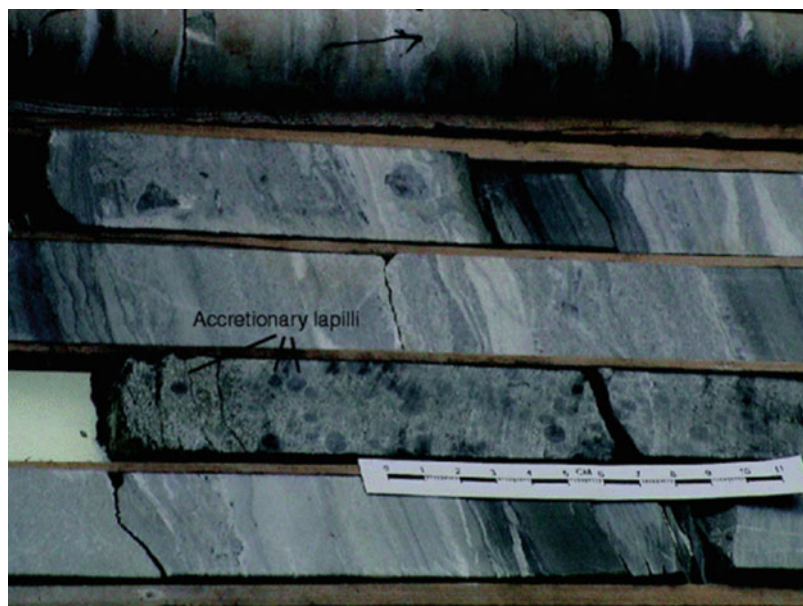
Gunflint Formation, Fig. 1 Carbon isotope compositions of organic matter and kerogen in Gunflint and Rove Formations

Siliceous stromatolites in the Gunflint Formation contain abundant microfossils and hematite. Current Fe-isotope studies of hematite suggest that such siliceous stromatolites formed in low oxygen conditions or near the redoxcline (Marine-Carbonne et al. 2011). This engenders the possibility that a redoxcline was present at shallow water depth, implying that reducing environments were more widespread among surface areas than was previously thought. The Fe-isotope studies suggest that chemoautotrophic iron-oxidizing microbial ecosystems are potential primary producers at around the redoxcline. Such geochemical data are consistent with some paleontological observations (Knoll 2003).

Disagreement persists among researchers (1) whether cyanobacteria were the major primary producers and (2) how deep the oxygenated waters developed. Chemoautotrophic Fe-oxidizing bacteria might be the alternative primary producers to cyanobacteria (Planavsky et al. 2009). On the other hand, the activity of chemoautotrophic Fe-oxidizing bacteria is dependent on cyanobacterial activity because of their

necessity of dissolved O_2 , which further suggests that biomass production of chemoautotrophic Fe-oxidizing bacteria cannot exceed that of cyanobacteria. Black shales of the Rove Formation are rich in organic carbon (up to 6 wt%), suggesting high microbial productivity during sedimentation. The absence of hematite deposition implies less influence of chemoautotrophic Fe-oxidizing bacteria in the Rove Formation than in Gunflint. In this situation, cyanobacteria are the only reliable primary producers. ► Carbon isotope compositions of organic matter of the Rove Formation are compared to those of the Gunflint Formation (Fig. 1). It is noteworthy that no carbon isotope difference was found between organic matter of the Rove and Gunflint Formations, which suggests that the dominant primary producers for both formations were most likely cyanobacteria.

Ion microprobe analyses were also performed on individual microfossils and microscale organic matter (House et al. 2000; Ishida et al. 2018). The Gunflint microfossils analyzed using an ion microprobe show a range of $\delta^{13}\text{C}_{\text{(PDB)}}$ values

Gunflint Formation,**Fig. 2** Accretionary lapilli in Gunflint Formation

of -45 to -32% . Extremely ^{13}C -depleted compositions down to -45% were not consistent with carbon fixation via the Calvin cycle, and they were explained by involvement of methanogens and methanotrophs in the ecosystem (House et al. 2000). On the other hand, such ^{13}C -depleted values were found only in micro-scale analysis implying that activities of methanogens and methanotrophs were limited in space. Therefore, the possibility exists that ^{13}C -depleted organic matter and heavy Fe-isotope in hematite might represent local environmental effects rather than widespread characteristics in the surface ocean. Nitrogen isotope compositions or organic matter were analyzed by ion-microprobe or stepwise combustion methods (Ishida et al. 2012, 2017, 2018). $\delta^{15}\text{N}_{(\text{air})}$ values of organic matter, ranged from $+2.9$ to $+8.0\%$, are within a reasonable range explained by the N_2 -fixation by cyanobacteria and biological nitrogen recycling under the oxic condition. Sedimentary organic matter in the Gunflint Formation generated large quantities of petroleum (Rasmussen and Muhling 2019). Those petroleum were migrated and disseminated in the Gunflint Formation, although the timing of petroleum generation is still uncertain.

Sudbury Impact Record

The Sudbury Structure in Ontario (Canada) was most likely generated by a hypervelocity impact at 1850 ± 1 Ma. Previous investigators searched for “evidence” of the Sudbury impact in the Gunflint Formation. The potential impact-related bed appears in the recrystallized and silicified carbonate sequence in the uppermost Gunflint Formation. The proposed ejecta layer ranges from a few tens of centimeters thick (Fig. 2). Accretionary lapilli appear near the middle of this specific layer. They are considered as ejecta products. Planar deformation features (PDFs) were also found in quartz and feldspar grains. Most grains with PDFs are located within accretionary lapilli. Tsunami-like deposits, associated with tektite and glassy materials, also appear at the top of the Gunflint Formation, for which the depositional age is consistent with the time of the Sudbury impact (Addison et al. 2005). Those features suggest that the Sudbury impact event was most likely recorded in the Gunflint Formation and that accretionary lapilli might represent impact ejecta, although the alternative origins, such as volcanic ashes, are not excluded (Schumacher and Schmincke 1995; Addison et al. 2010). Earlier reports described the difference

between the fossil-rich Gunflint Formation and the fossil-absent Rove Formation and discussed the possibility of impact-induced extinction (Addison et al. 2005).

Future Directions

The late Paleoproterozoic represents a unique period in the evolution of the redox conditions of the atmosphere and oceans because very localized oxic and anoxic conditions were present. During the transition from Gunflint to Rove oceans, the deep-water conditions became Fe poor because of either euxinic or suboxic deep-water conditions (Poulton et al. 2004; Slack et al. 2007). Dynamics of redox changes and/or Fe-flux changes are important for the astrobiology community to evaluate the tolerance and/or adjustability of anaerobic microorganisms to oxic and metal-poor conditions. The Gunflint and Rove Formations will provide good opportunities to examine the survival of microbial ecosystems to impact events. Furthermore, current experiments and theoretical studies suggest that impact events can convert atmospheric CO₂ and N₂ into CH₄ and NH₃. Therefore, C and N isotope compositions of ancient kerogens might be used to evaluate the effect of an impact event on contemporary microbial ecosystem. In brief, no marked change was observed in carbon isotope compositions of organic matter from the Gunflint Formation to the Rove Formation (Fig. 1), which implies that either (1) the Sudbury impact event did not considerably affect the microbial communities or (2) the impact event affected it, but the microbial ecosystem recovered quickly enough that the influence was not recorded in rocks. To evaluate the effect in greater detail, high-resolution geochemical data will be necessary. Recent developments of analytical techniques will allow a more detailed examination of microfossils, and new data will be obtained to constrain how they lived and how they coexisted with other communities and adjusted to radically changing environments (Maldanis et al. 2020).

Cross-References

- ▶ [Banded Iron Formation](#)
- ▶ [Cyanobacteria](#)
- ▶ [Ejecta](#)
- ▶ [Impactite](#)
- ▶ [Iron Isotopes](#)
- ▶ [Microfossils](#)
- ▶ [Stromatolites](#)

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Gunflint Microbiota

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

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Gunflint formation · Microfossils ·
Paleoproterozoic · Stromatolites · Traces of life

Definition

The Late Proterozoic ► **Gunflint Formation** comprises 100–160 m thick iron-rich chemical, clastic, and volcanoclastic sedimentary rocks

extending for 175 km along the Gunflint Range from northeastern Minnesota, USA, to the Thunder Bay area of Ontario, Canada. The iron formation is well dated at $1,878 \pm 1.3$ Ma by U-Pb on zircons (Fralick et al. 2002). The microfossil assemblage of the Gunflint Formation is renowned among astrobiologists for its excellent preservation in stromatolitic and non-stromatolitic cherts and for its abundance and diversity of filamentous, coccoidal fossils and problematic forms that are reported only in iron formations between 2.1 and 1.7 Ga.

Overview

The Paleoproterozoic (2.5–1.6 Ga) era is a crucial and unique time of changing ocean and atmosphere's chemistries. During this period, the atmosphere and surface ocean waters were likely moderately oxygenated (1–10% PAL; present atmospheric level of oxygen). Traces of this changing redox conditions are globally detected in the geological record since the GOE (Great Oxidation Event, around 2.4 Ga), but local oxygenation probably occurred earlier. The deeper bottom waters might have been euxinic (anoxic and sulfidic; Canfield 1998) or only anoxic or dysoxic (i.e., having low oxygen levels between anoxic and hypoxic levels) (Johnston et al. 2009), with a transient return to a ferruginous ocean possibly around Gunflint times, at 1.9 Ga (see review in Lyons et al. 2009).

The Paleoproterozoic rocks host the oldest ► **microfossils** diagnostic of modern ► **cyanobacteria** in carbonate formations, for example, the Belcher Fm, Canada, and the Franceville Fm, Gabon (Amard and Bertrand-Safarti 1997; Hofmann 1976; review in Knoll and Golubic 1992), contemporaneous of the Gunflint Fm, and the oldest microfossils of stem-group eukaryotes, in 1.8 Ga shales from China and 1.65 Ga shales from Australia (reviews in Knoll 2003; Knoll et al. 2006). Diverse microfossils of unknown biological affinities are reported from iron formations around the world, including the Gunflint Fm. The Paleoproterozoic record of biological activities also includes ► **stromatolites** and

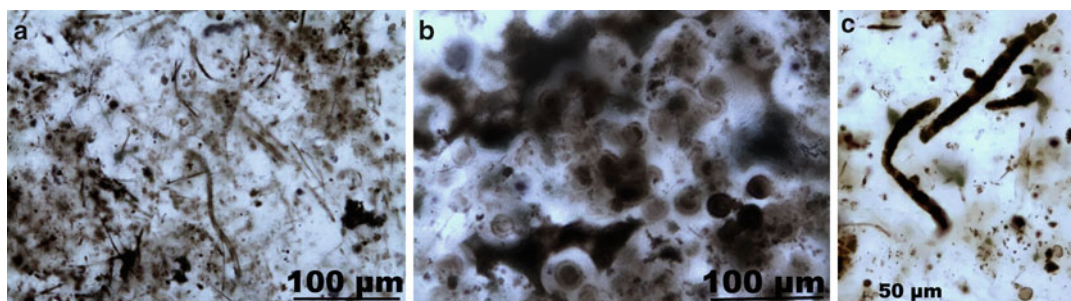
► **biomarkers** (discussed elsewhere in this volume), macroscopic carbonaceous compressions and possible pyritic fossils, mat rip-ups, and putative fossil or trail impressions.

Gunflint Microbiota

The stromatolitic and nonstromatolitic cherts of the Gunflint Formation have been first investigated in the classical work of Barghoorn and Tyler (1965), Awramik and Barghorn (1977), Cloud (1965), and Strother and Tobin (1987). The stromatolites have variable chemical composition (iron rich, siliceous, calcitic) and morphologies (from small – sometimes branching – centimeter-scale columns to large domes up to 1 m in diameter) (Planavsky et al. 2009). The assemblage includes prokaryotic taxa difficult to relate to extant organisms. No eukaryotes are unambiguously recognized, although some taxa found in nonstromatolitic cherts like *Eosphaera* (vesicles surrounded by a layer of smaller coccoids in an envelope) and *Leptotrichos* (5–30 μm solitary coccoids) could be prokaryotic or eukaryotic (Knoll 1996). In the stromatolitic cherts (Fig. 1), the assemblage contains star-like forms (*Eoastrion*), coccoids (*Hurioniospora*), problematic forms (*Kakabekia umbellata*), filaments (*Gunflintia*), and budding tubular forms (*Archaeorestis*). *Gunflintia* filaments are coated by iron oxides and have been compared to modern iron bacteria *Leptothrix* (Knoll and Simonson 1981), and geochemical analyses have evidenced the activities of Fe-oxidizing bacteria (Planavsky

et al. 2009). *Gunflintia* and *Hurioniospora* can also be preserved by pyrite, some fossils showing the presence of small hollow, sometimes C-filled vesicles interpreted as cells of heterotrophs degrading them (Wacey et al. 2013). In situ sulfur isotope analyses of individual microfossils showed that pyritization resulted from the activity of sulfate-reducing bacteria within anoxic, sulfate-poor sediment pore waters (Wacey et al. 2013). Carbon isotopic analyses performed on individual Gunflint microfossils (*Gunflintia* and *Hurioniospora*) (House et al. 2000) showed $\delta^{13}\text{C}$ values of –31‰ to –37‰ consistent with carbon fixation via the Calvin cycle, except for two badly preserved specimens of *Hurioniospora* which had extremely ^{13}C -depleted compositions down to –45‰. Most microfossils do not show a preferred orientation and are probably planktonic, but *Gunflintia* filaments are sometimes densely intertwined and coat convex surfaces, suggesting benthic lifestyle (Hofmann 1969; Strother and Tobin 1987).

Similar associations are known in the coeval Franceville biota, Gabon (Amard and Bertrand-Sarfati 1997); the Balbirini Dolomite, Australia (Oehler 1977); the 1.8 Ga Duck Creek Dolomite, Western Australia (Knoll and Barghoorn 1976; Knoll et al. 1988); the Tyler Fm, Michigan (Cloud and Morrison 1980); the 1.7 Ga Frere Fm, Australia (Walter et al. 1976); and in other coeval iron formations and subtidal carbonates worldwide. These assemblages were widely distributed in shallow habitats where iron-rich deep waters mixed with oxygenated surface waters,



Gunflint Microbiota, Fig. 1 Gunflint microfossils in thin section through stromatolitic chert. (Pictures courtesy of K. Lepot), showing in (a) thin filamentous sheaths *Gunflintia* and coccoids; (b) double-walled coccoids; (c)

one star-like specimen of *Eoastrion* (upper left corner), filamentous sheath *Gunflintia*, coccoidal *Hurioniospora* (bottom right corner), and two large tapering, cellular filaments of possible cyanobacteria

before the late Paleoproterozoic expansion of sulfidic subsurface waters. Recent investigations of the 1.9 Ga Gunflint Formation (Planavsky et al. 2009) and another slightly younger iron formation, the 1.8 Ga Duck Creek Formation, Western Australia (Wilson et al. 2010), confirmed previous micropaleontological investigations and provided geochemical evidence supporting the presence of iron-oxidizing bacteria in these early ecosystems.

In most Proterozoic microbial mat assemblages, empty filamentous sheaths (e.g., species of the genera *Oscillatoria*, *Siphonophycus*, *Eomycetopsis*, *Tenuofilum*, *Taeniatum*, *Gunflintia*) are abundant and range from >10 μm (or >100 μm) to <1 μm in diameter (Knoll and Golubic 1992). Because of their nondiagnostic morphology, their biological affinity is difficult to determine in the absence of paleoenvironmental interpretations or fossilized behavior. The large sheaths are possibly attributed to cyanobacteria, especially when they occur in shallow-water sediments deposited in the photic zone and when their distribution shows phototaxis (movement induced by a rapid light flashing). They could also represent *Beggiatoa*-like sulfur-oxidizing bacteria forming mats at the sediment-water interface with steep redox gradient. The narrow sheaths could also represent the remains of *Chloroflexus*-type photosynthetic bacteria or of *Leptothrix*-type iron bacteria (as for *Gunflintia minuta*, which grew in an iron-rich stromatolitic environment of the Gunflint Formation) (Knoll and Golubic 1992). Similar uncertainty applies to colonies of microfossils such as the possibly heterotrophic rod-shaped *Eosynechococcus* or the coccoidal *Myxococcoides*, in the absence of paleoenvironmental information (Knoll and Golubic 1992).

Gunflint Paleoenvironmental Conditions

Geochemical proxies combined with paleontological investigations may help to constrain the metabolisms and biological affinities of the filaments and isolated cells of the Gunflint Fm. ► **Iron isotopes** and REE (rare earth element) analyses on hematite-rich stromatolites of the Gunflint Fm permitted to suggest the presence of a shallow redoxcline in the ocean, separating fully oxygenated shallow waters from iron-rich deep

waters (Planavsky et al. 2009). In the redoxcline, microaerophilic chemolithotrophic microbial ecosystems could proliferate. Cyanobacteria lived in the surface-oxygenated waters, as suggested by paleontological investigations (review in Knoll and Golubic 1992) and C-isotope analyses (Strauss and Moore 1992), and provided dissolved oxygen used by chemoautotrophic Fe-oxidizing bacteria just below. This new model could explain the presence of cyanobacteria microfossils in some Paleoproterozoic carbonate successions and the presence of iron-coated filaments and other unusual microfossils in coeval iron-rich formations.

In shallow habitats of the Gunflint Formation, iron-rich deep waters mixed locally with oxygenated surface waters (Planavsky et al. 2009). A recent study based on S-isotopes analyses, and tectonic and sedimentologic models, suggests that the shift to sulfidic conditions in the Paleoproterozoic Animikie Basin (where the Gunflint Fm was deposited) approximately coincided with the onset of restricted circulation. Therefore, the basin may record an evolving basin with restricted water circulation and thus may not reflect the open-ocean structure and composition during the global onset of sulfidic conditions (Pufahl et al. 2010).

Further detailed studies of contemporaneous iron formations are required to clarify the global extent of the chemical stratification, changing from a redoxcline between oxygenated surface waters and iron-rich deep waters to a redoxcline between oxygenated surface waters and sulfidic deep waters in the late Paleoproterozoic when iron formations disappear, and the possible implications on ecosystem evolution. The occurrence of ferruginous waters and iron formation in younger Paleoproterozoic successions (e.g., 1.8 Ga Duck Creek Fm, Western Australia) may suggest that the Late Paleoproterozoic expansion of sulfidic subsurface waters was globally asynchronous (Wilson et al. 2010).

Future Directions

The late Paleoproterozoic represents a unique period in the evolution of the redox conditions of

the atmosphere and ocean, with locally stratified waters and the development of a redoxcline. The Gunflint Formation recorded life and fossilization processes in iron-rich oxygen-poor conditions. Study of past extremophile life and iron-rich habitats is relevant for astrobiology. Such interdisciplinary investigations, combining micropaleontology with geochemistry, sedimentology, and mineralogy, are good examples of what needs to be done to improve our understanding of past ecosystems and the characterization of traces of life.

Cross-References

- [Banded Iron Formation](#)
- [Biomarkers](#)
- [Biom mineralization](#)
- [Cyanobacteria](#)
- [Fossilization, Process of](#)
- [Gunflint Formation](#)
- [Iron Isotopes](#)
- [Microfossils](#)
- [Redox Zonation](#)
- [Stromatolites](#)

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H

H Bond

- ▶ [Hydrogen Bond](#)

H⁺ Region

- ▶ [HII Region](#)

H₂Cl⁺

- ▶ [Chlorine Hydrides in the Interstellar Medium](#)

H₂CS

- ▶ [Thioformaldehyde \(H₂CS\)](#)

H₂NCN

- ▶ [Cyanamide](#)

H₂O

- ▶ [Water in the Solar System](#)
- ▶ [Water in the Universe](#)
- ▶ [Water, Delivery to Earth](#)
- ▶ [Water, Formation and Photodissociation](#)
- ▶ [Water, Solvent of Life](#)
- ▶ [Water, Vibrational and Rotational Transitions](#)

H₂O⁺

- ▶ [Water, Related Interstellar Radicals and Ions](#)

H₂S

- ▶ [Sulfur Hydrides in the Interstellar Medium](#)

H₃O⁺

- ▶ [Water, Related Interstellar Radicals and Ions](#)

Habitability of the Solar System

Lilia Montoya¹ and Antígona Segura²

¹Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

²Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Keywords

Earth · Exoplanets · Habitability · Icy satellites · Life · Mars · Solar System

Definition

Habitability refers to the capability to sustain life or for the origin of life and its potential can be constrained to a period or a planetary environment. Basic elements to determine the potential for habitability of a member of the Solar System are: availability of liquid water, energy sources, physicochemical conditions for the origin and sustenance of life, and presence of organics. Assessment of habitability depends on the tools available to study a particular planetary body that may be: observational data from telescopes, images and data from spacecraft, terrestrial analog sites, meteorites, in situ measurements by landers and rovers, and experimental and theoretical models.

History

Venus and Mars were the first bodies in the Solar System considered habitable based on empirical evidence. Clouds on Venus were evidence of a warm and habitable climate until 1958 when radio observations pointed to a surface temperature of 600 K (Lewis 2004). Venera missions in the 1970s returned photographs and data from Venus' surface that showed a dry, hot planet with a 92 bar atmosphere where life was not possible,

but clouds were and are still considered a likely habitat for Venusian life (e.g., Morowitz and Sagan 1967; Seager et al. 2020).

During the end of the XIX century, drawings based on telescope observations portrayed lines crossing the Martian surface that were later interpreted as canals built by a civilization. As telescopes technology improved and photography were used to capture astronomical images, those lines faded as well as the idea of such civilization (Lewis 2004). Even so the idea that Mars was habitable continued, color variations in its surface were interpreted as vegetation responding to seasonal changes. In 1947, Gavriil Tikhov, a soviet scientist, funded the Sector for Astrobotany of the Kazakhstan Academy of Science to study the spectroscopic properties of plants to identify the ones that matched the spectral signatures of the Martian surface (Tejfel 2009). The work by Tikhov and his collaborators was published in a series of proceedings and the first astrobiology book (Tejfel 2009). Salisbury (1962) deduced that “earthly organisms could not account for the markings on Mars”; however, he was still supporting the idea that those markings were best explained by the presence of life. Viking mission in 1975 performed the first experiments to detect life in Martian soil without finding it (Klein 1979).

In 1983, Europa, the smallest of the Galilean satellites, became the first icy satellite included in the list of habitable worlds (Reynolds et al. 1983) as a feedback between three main findings: (1) the flybys of Voyager 2 (launched in 1977) which retrieved images showing an astonishing young Europa surface; (2) the first observations of hydrothermal communities thriving in the absence of sunlight and sustained by mantle derived fluids at the Galapagos Spreading Center in 1977 (Humphris and Klein 2018); and (3) the discovery of lakes beneath the Antarctic ice sheet, e.g., Vostok Lake, during the same decade.

The habitability of Europa is partly interchangeable to Enceladus. With the discovery of the whitish E-ring at Enceladus orbit by Walter Feibelman in 1966 it was suggested that the ring was composed of water ice originated from this satellite. However, the scarce knowledge about

the energy supplied by tidal dissipation on icy satellites at the time could not envisage a heat source, besides radioactive decay, and accretion, to justify that the E-ring was a consequence of material ejected from the active satellite (Henin 2018; Hendrix et al. 2018). Studies about the orbital properties of icy satellites and psychrophilic extremophiles performed since the end of the 1970s enriched the understanding of habitability in the Solar System bodies.

The discovery of organics in Titan's atmosphere generated by the reactions of N_2 and CH_4 led to models and experiments focused on understanding the nature of the hazes that cover the satellite. The Cassini-Huygens mission displayed a geologically complex satellite whose potential for habitability we are just starting to explore. Some authors have proposed that Titan's organic chemistry may be like Earth's conditions before the appearance of life (Raulin et al. 2010), but this view has been challenged by experimental results that show that atmospheres with CO and CO_2 – such as the one expected for prebiotic Earth – produce organic compounds different to those

produced in reduced Titan-like atmospheres (Trainer 2013). Margulis et al. (1977) analyzed the Titan habitability using extremophiles as models concluding that terrestrial organisms could hardly survive on this satellite.

Overview

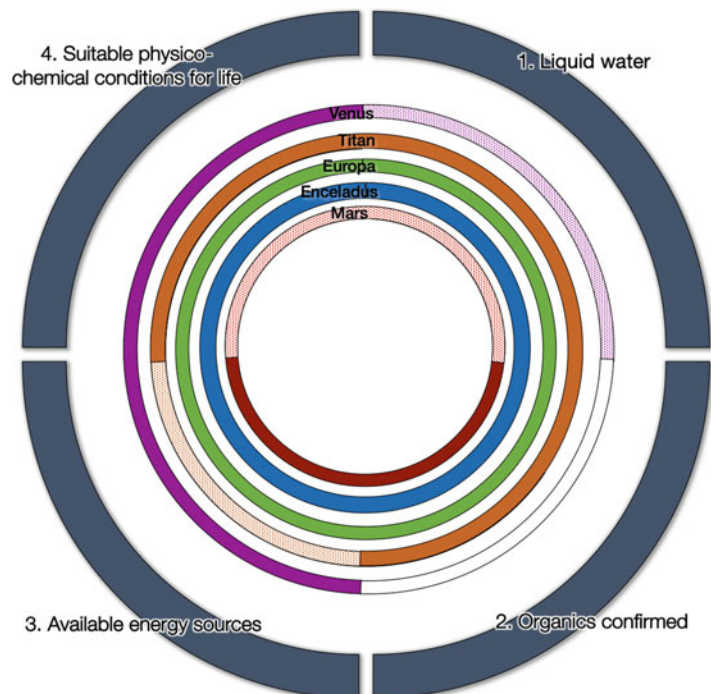
The potentially habitable environments can be limited to a region or time for a given planetary body (satellite, dwarf planet, or planet). The main characteristics to assess the habitability potential of a planetary body in the Solar System are (Fig. 1):

1. Liquid water: considered the best and most abundant solvent for carbon-based life, its properties and relevance for life on Earth resulted in the strategy “Follow the water” (Mottl et al. 2007).
2. Organics: indicate the potential for the origins of life or the presence of life either in the past or present.

H

Habitability of the Solar System,

Fig. 1 Representation of the knowledge state of habitability in selected Solar System bodies. The habitability potential comprises four categories: (1) liquid water, (2) organics, (3) energy sources for life, and (4) suitable physicochemical conditions for life. Discontinuous regions represent uncertainty either for present or past conditions and the white ones lack of information or conditions for that category



3. Energy sources: organisms harvest redox reactions to promote cellular processes.
4. Physicochemical conditions for life: environmental characteristics such as the presence of bioelements (sulfur, potassium, calcium, etc.), temperature, pH, and pressure that are favorable to carbon-based life.

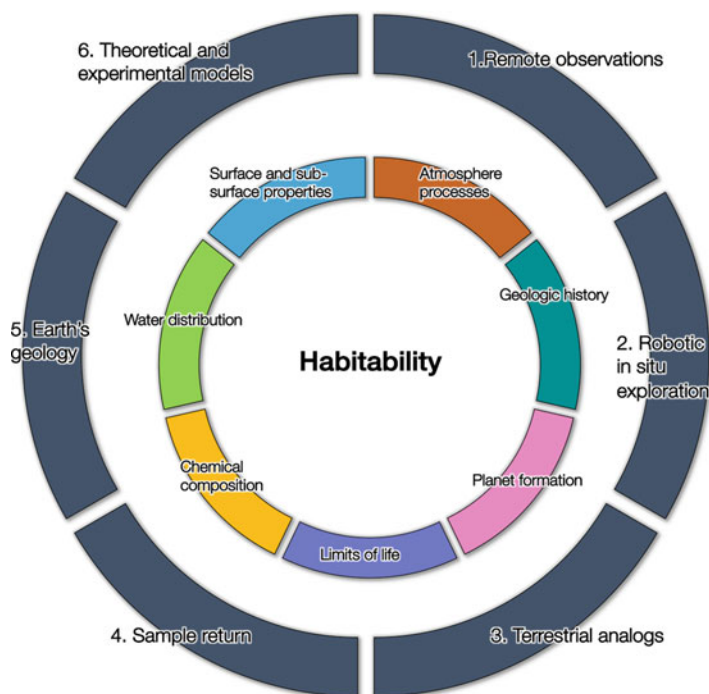
Basic Methodology

Assessment of habitability in the Solar System requires to identify places and times where a planetary environment was suitable for the origins or sustenance of life. The tools to constrain which elements for habitability were or are available in a Solar System body are (Fig. 2):

1. Remote observations: Telescopes and spacecraft (flybys and orbiters) provide data about the surface and atmospheric composition, global processes such as atmospheric escape, volcanism, and other characteristics like magnetic fields and presence of water. Also,
2. Robotic in situ exploration: Landers, rovers, and other robotic explorers (e.g., Dragonfly for Titan) give a closer knowledge of planetary characteristics by directly analyzing the physical and chemical properties of the subsurface, surface, and atmosphere. Along with remote observations provide constraints to the geologic history, structure of planetary bodies, and the initial properties of the Solar System.
3. Terrestrial analog sites: Sites on Earth that share chemical (e.g., pH, composition) or physical (e.g., temperature, humidity) conditions with a given environment of a Solar System planetary body. For example: hydrothermal fields, hypersaline lakes, permafrost, and experiments with extremophiles.
4. Sample return: Lunar and Martian meteorites are samples available on Earth that help to constrain the characteristics of the Moon and

Habitability of the Solar System, Fig. 2

Diagram of the main tools used in astrobiology (outer circle) to build the concepts (inner circle) required for evaluating the habitability of the Solar System



Mars, while other meteorites constrain the initial history of the Solar System. In situ analysis by robots is limited to a suite of instruments and experiments while sample return missions provide the opportunity to apply a wider variety of techniques that can reveal more details about a given planetary environment (National Academies of Sciences et al. 2018).

5. Earth's geologic history and present characteristics: As the only inhabited planet we know of, the study of the origins of life and our planet geologic changes provide the first clues to understand the characteristics of habitable environments.
6. Theoretical and experimental models: Models simulate a given set of planetary characteristics to understand the processes that lead to the origins of life, set the limits of life, and to evaluate the chemical and/or physical conditions of a present or past planetary environment, or to provide clues of the origin of the solar system and the initial water inventory.

Key Research Findings

Venus exploration is limited due to the harsh atmospheric and surface conditions; landers have not visited the planet since the 1980s and the last Venus orbiter ESA Venus Express, finished operations in 2014. In 2020, radio observations claimed the detection of phosphine (PH_3), a chemical compound that has no known source in Venus and is produced by life on Earth (Greaves et al. 2020). This claim remains under debate by the scientific community (e.g., Akins et al. 2021) and shows how much we ignore our closest neighbor planet.

Mars has been continuously visited by orbiters, landers, and rovers since 1994. In 2021, three missions are expected to study the Red Planet: Tianwen-1 (China), Hope (the United Arab Emirates), and Perseverance (the United States). Geologic evidence and in situ sample analysis have provided strong evidence of liquid water in the surface and other characteristics such as volcanic activity, chemical elements relevant for life,

and presence of organic matter that indicates that Mars was a habitable planet about 3.5 billion years ago (Cockell 2014; Eigenbrode et al. 2018).

The Galileo spacecraft (1989–2003) images of Europa captured by the Solid-State Imaging (SSI) experiments revealed surface features like lenticulae, bands, cryovolcanic structures, chaos regions, and ridges whose interpretations are consistent with a geologically active satellite (Siddiqui 2018). The uncertainty about water distribution was dissipated after the detection of inductive currents that describe a salty global ocean beneath the ice crust. More recently, a survey performed with the Hubble Space Telescope (HST) at infrared and ultraviolet has provided evidence of water vapor plumes at Europa leading hemisphere (Paganini et al. 2020). Also, the perception of the endogenous salts evolved from entirely sulfates to sulfates and chlorides (Hibbitts et al. 2019). Several answers will be provided by the NASA Europa Clipper mission (launch date 2024) and the ESA JUperiter ICy moons Explorer (JUICE) mission (launch date 2022) (Hendrix et al. 2018).

The understanding of Saturn system has several chapters of advancement thanks to Cassini spacecraft (1997–2017) and the Enceladus water plume is located among the major discoveries. Enceladus' south pole comprises extensive crater-free regions and high temperature levels, measured by the Cassini mid-IR interferometer correspond closely with the active tectonic fractures known as "tiger stripes" which may feed water plumes. The finding of silicon-rich nanometer-sized dust particles by the Cassini Cosmic Dust Analyzer (CDA) has added a hint of hydrothermal activity which was reinforced by the detection of hydrogen and hydrocarbons in the plume. The convergence of these discoveries has guided thinking about a liquid media as an energy source for chemotrophs (Waite et al. 2017; Hendrix et al. 2018).

Titan has a geologically active surface and methane lakes with ethane and other organic compounds (Henin 2018) and poses the opportunity to test liquid methane as a solvent for life under low temperature (-180°C). Acrylonitrile has been

proposed as the molecule that can build vesicles for life compartmentalization because membranes made of lipids would lose its elasticity under cryogenic temperatures (Stevenson et al. 2015). Titan's interior is potentially habitable starting from the silicate core boundary with the water mantle up to the ammonia and water ocean below the water ice crust (Norman and Fortes 2011).

Future Directions

Solar System exploration although not always focused on habitability, provides information relevant to understanding the habitability potential of the Solar System. Thus, all future missions aimed to study a member of our planetary system are relevant for the assessment of the past and present habitability of the Solar System.

Planets and satellites of the Solar System are the nearest experimental bench to explore how planets evolve and how habitability may change with time to infer the characteristics of exoplanets and constrain their habitability potential.

Cross-References

- [Asteroid](#)
- [Cassini-Huygens Space Mission](#)
- [Comet](#)
- [Enceladus](#)
- [Europa](#)
- [Europa Analogues](#)
- [Extremophiles](#)
- [Galileo Mission](#)
- [HST](#)
- [Mars](#)
- [Mars Analogues](#)
- [Meteorites](#)
- [SNC Meteorites](#)
- [Terrestrial Analog](#)
- [Titan](#)
- [Venus](#)
- [Viking](#)
- [Water, Solvent of Life](#)

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Habitability on Mars

Alessandro Airo¹, Ernst Hauber² and Stephan van Gassel³

¹Fachbereich Geowissenschaften, Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Berlin, Germany

²Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

³Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Berlin, Germany

Definition

Habitability has been defined as “the potential of an environment (past or present) to support life of any kind” (Steele et al. 2005). Consequently, the concept of habitability depends on the conditions life requires, which commonly are described as complex chemistry taking place within a liquid solvent and with access to energy. It is reasonable to assume that putative life on Mars would be physically implemented on the basis of organic chemistry and liquid water (Benner et al. 2004).

Beyond the conceptual requirements for habitability (water, organics, energy), life can only exist in physicochemical settings (e.g., temperature, radiation, pH) that do not cause a lethal degradation of the organisms. Consequently, habitability greatly depends on the type of biochemistry, which makes it challenging to predict the physicochemical boundaries of habitability with respect to alien life of unknown molecular composition.

Although this difficulty cannot be overcome, the discovery of extremophiles over the past few decades has greatly expanded our knowledge of the range of habitable environments for “life as we know it”. Based on these known boundaries of life on Earth, it can be conservatively estimated that habitable environments on Mars are those where liquid water is stable at temperatures below ~120 °C.

Early Mars

Among the first to scientifically discuss the putative habitability of Mars was Alfred Russel Wallace (Wallace 1907). Although Wallace largely argued against Mars being habitable, high hopes for this not being the case persisted until the 1970s when the Viking landers reported Mars to be a cold desert.

Since then, Mars exploration efforts were guided by the slogan “follow the water” and yielded a profound understanding of Mars’ watery past and the current water-ice-rich cryosphere (e.g., Lasue et al. 2013). As a result of this successful search, it symbolically transitioned to “follow the habitability.” The recent discovery of clay-rich sediments at Gale Crater by the Curiosity rover suggests that these deposits formed within a shallow-water environment of neutral pH and therefore would indicate the former existence of a habitable lacustrine environment on Early Mars (Grotzinger et al. 2014).

However, the frequency, duration, and chemistry of such habitable paleoenvironments remain largely unknown, and the degree of similarity between Early Mars’ and Earth’s habitable environments continues to be debated. Furthermore, the length of time needed and exact

physicochemical conditions required for an origin of Earth-like life remain in the realm of speculation. Therefore, any estimate on the suitability of Martian paleoenvironments for an origin of life is highly speculative as well. However, even if life never originated on Mars itself, it could have been transferred from Earth to Mars through the process of ► [panspermia](#) and continued to thrive on Mars until today.

Mars Today

Although Mars might have been habitable at the surface in the past, today the Martian surface conditions (low temperatures and pressures) usually do not allow liquid water to be stable. Only at very low-lying areas (higher atmospheric pressure) and/or if the water is very saline (reduced melting point temperature) can water remain liquid at the surface today. Local melting of ground ice and the formation of cold brines are hypothesized to be responsible for the seasonal appearance of recurring slope lineae (McEwen et al. 2011). However, such environments would only be habitable for halophilic and psychrophilic organisms that are known to thrive in arctic environments on Earth. Alternatively, in the event of a large impact into water-ice-bearing terrain, crater lakes could form and be considered to represent transitional habitable surface environments (McKay and Davis 1991).

In contrast to surface environments, it could well be that putative subsurface aquifers are the largest, most stable, and longest-lasting habitable environments on Mars. Furthermore, it can be argued that if microbial life did exist on Early Mars, it is more likely that it has adapted to the deep subsurface conditions, as life has done on Earth, than it having gone extinct entirely.

Cross-References

- [Aquifer \(Mars\)](#)
- [Crater Lakes \(Mars\)](#)
- [Extremophiles](#)
- [Mars](#)

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Habitability, Effect of Eccentricity

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Definition

Variations in the ► [eccentricity](#) of a planet's orbit can lead to climate changes, including possible phase transitions of liquids on a planet's surface and therefore different climate feedback mechanisms due to ► [albedo](#) changes. A more eccentric orbit both intensifies the ratio of stellar irradiation at ► [periastron](#) to that at apoastron and increases the annually averaged irradiation, proportional to $(1 - e^2)^{-1/2}$, where e is eccentricity.

Periodic oscillations of eccentricity cause oscillations of the total amount of starlight incident on a planet in each annual cycle. These oscillations depend on gravitational perturbations from other companion objects.

Cross-References

- [Albedo](#)
- [Atmosphere, Structure](#)
- [Eccentricity](#)
- [Habitability of the Solar System](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)
- [Periastron](#)

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Habitability, Effects of Stellar Irradiation

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Keywords

Biomarkers · Earth geological evolution of · Habitability · Biomarkers remote detectability thereof

Definition

Stellar irradiation refers in this context to the wavelength-dependent incoming flux of photons into the planetary atmosphere from the central star. This in turn will influence e.g. the planet's atmospheric photochemistry, climate, and potential biomarkers.

Overview

The range of characteristics of planets is likely to exceed our experience with the planets and

satellites in our own Solar System by far. Models of planets more massive than our Earth need to consider the changing atmosphere structure, as well as the interior structure of the planet (see, e.g., Seager et al. 2007; Valencia et al. 2006). Earthlike planets orbiting stars of different spectral type might evolve differently (Selsis 2000; Segura et al. 2003, 2005). Modeling these influences will help to optimize the design of the proposed instruments to search for Earthlike planets. The spectral resolution required for optimal detection of habitability and biosignatures has to be able to detect those features for different stellar types as well as over the evolution of a planet (► [Biomarkers](#), ► [Spectral](#); Biomarkers, Atmospheric; ► [Habitable Planet](#), Characterization). Using a numerical code that simulates the photochemistry of a wide range of planetary atmospheres, several groups (Selsis 2000; Segura et al. 2003, 2005; Grenfell et al. 2007) have simulated a replica of our planet orbiting different types of star: an F-type star (more massive and hotter than the Sun) and a K-type star (smaller and cooler than the Sun). The models assume the same background composition of the atmosphere as well as the strength of biogenic sources. A planet orbiting a K star has a thin O₃ layer, compared to Earth's, but still exhibits a deep O₃ absorption at ultraviolet (UV) wavelengths: indeed, the low UV flux is absorbed at lower altitudes than on Earth, which results in a less efficient warming (because of the higher heat capacity of the dense atmospheric layers). Therefore, the ozone layer is much colder than the surface, and this temperature contrast produces a strong feature in the thermal emission. The process works the other way around in the case of an F-type host star. Here, the ozone layer is denser and warmer than the terrestrial one, exhibiting temperatures about as high as the surface temperature. Thus, the resulting low-temperature contrast produces only a weak and barely detectable feature in the infrared spectrum. This comparison shows that planets orbiting G- (solar) and K-type stars may be better candidates for the search for the O₃ signature than planets orbiting F-type stars. This result is promising, since G- and K-type stars are much more

numerous than F-type stars, the latter being rare and affected by a short lifetime (less than 1 Gyr).

Cross-References

- [Atmosphere, Structure](#)
- [Biomarkers Atmospheric, Evolution Over Geological Time](#)
- [Biomarkers, Spectral](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)
- [Spectral Type](#)

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Habitability, Role of the Atmosphere

John Lee Grenfell

Institut für Planetenforschung, Extrasolare Planeten und Atmosphären, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany

Keywords

Habitable · Habitable zone · Life · Atmospheric

Definition

“Habitability” is classically defined as the (past or present) existence of surface conditions that support life. This in turn leads to the requirement for the presence of liquid water, which is needed by all known life. “Atmosphere” refers to the envelope of gas trapped within a planet’s gravitational field and for a terrestrial planet extends from the surface up to the exosphere. This entry discusses the critical importance of atmospheres for habitability.

Overview

“Habitable” is derived from the Latin *habitabilis* meaning “to inhabit.” “Habitable” denotes environmental conditions that could support life (Steele et al. 2005) but does not necessarily imply that life is present. In simple terms one can imagine a house that is habitable but may be unlivable in. In its simplest terms habitability is classically defined as the requirement for liquid water. However, “conditions which could support

life” can be rather many more and varied. Broadly speaking, one can define three central criteria, namely, the access to (i) energy, (ii) a suitable solvent (e.g., water), and (iii) molecular complexity (e.g., via carbon chain molecules). Other factors such as the availability of nutrients and protected conditions (e.g., shelter from UV, cosmic rays, climate excesses, strong impacts, etc.) also play a role. The distribution of habitability in the Universe depends, therefore, on how well we understand the limits and occurrences of these various criteria and on how sensitively life responds to them. In this entry we will focus on the central role for habitability played by planetary atmospheres in and beyond the Solar System.

Atmospheres are essential for habitable conditions for several reasons. First, liquid water (needed for habitability) is thermodynamically unstable at low pressures. Second, (in addition to a magnetosphere) atmospheres protect the planetary surface, e.g., from harmful radiation and cosmic rays. Third, atmospheres transport heat from warm to cool regions, which helps to maintain stable conditions favored by life. Fourth, atmospheres may interact with biological and geochemical processes via feedback cycles such as the “carbonate-silicate” cycle, which stabilizes the (Earth’s) climate. Fifth, (on Earth) the atmosphere supplies CO₂ for autotrophic life and O₂ needed for aerobic respiration and hence directly supports higher life on our planet. Finally, atmospheric spectral signatures on rocky exoplanets may provide indications of surface habitability and even biosignature signals.

Key Research Findings

Huang (1960) investigated the key requirements a star should meet to maintain life in its habitable zone (HZ). Dole (1964) introduced the “complex life habitable zone (HZ)” – the region where a planet could have surface temperatures between 0 and 30 °C (for >10 % of its surface with an oxygen (O₂)-rich atmosphere and <1.5 Earth gravity). Early climate modeling by Hart (1978) suggested a narrow HZ from 0.95 to 1.01

astronomical units (AU) for a solar-type star. Kasting et al. (1988) subsequently suggested that including negative (i.e., opposing the original change) feedback mechanisms such as the carbonate-silicate cycle could significantly expand the HZ. Kasting et al. (1993) calculated the HZ boundaries for different main sequence stars.

Modern Solar System

The (classical) HZ in the Solar System lies somewhere between Venus and Mars. There are two HZ inner boundaries that may be defined. Firstly, the “water loss limit” (~ 0.95 AU, Kasting et al. 1993) occurs where a planet would lose its mass of ocean within its current lifetime due to atmospheric escape. Secondly, the “runaway greenhouse limit” (~ 0.84 AU, Kasting et al. 1993) occurs where the planetary surface temperature exceeds the critical point of water. Atmospheric clouds if present could strongly influence the HZ boundaries. Kitzmann et al. (2010) investigated the radiative effects of clouds upon atmospheric temperature for Earth-like planets orbiting F, G, and K stars. Results suggest that cloud type and altitude could significantly impact surface temperature. The HZ limits, as estimated from numerical model studies, also depend on, e.g., planetary mass, density, and atmospheric mass and composition.

Regarding the *inner* HZ, Abe et al. (2011) varied ocean mass and calculated the effect on the inner HZ boundary. Applying an atmospheric column model, Kopparapu et al. (2013) suggest that using updated water absorption coefficients and applying the same approach as in Kasting et al. (1993) lead to the inner HZ moving out to 0.99 AU.

Regarding the *outer* HZ, here, CO₂ clouds could form in the atmosphere although their radiative properties are challenging to estimate since, e.g., their shapes and sizes are not well defined. The “maximum greenhouse effect” is defined to occur at the furthest distance of planet to star for which a planetary surface temperature of 273 K

can be held for a planet having a cloud-free, CO₂ atmosphere.

Atmospheric Evolution

The solar neighborhood includes some rather young stars (e.g., Woolley et al. 1970), which could have planets resembling the early Earth in age. The Earth’s atmosphere has changed significantly over geological time. The above has motivated studying the early Earth in an exoplanetary context. For example, Grenfell et al. (2011) investigated different epochs of hypothetical Earth-like exoplanets. The Sun’s net luminosity was (20–30%) weaker on the early Earth (~ 2.5 – 4.0 Gyrs ago) compared with the modern Earth. Although observations from ancient soils (paleosols) suggest the presence of liquid water on early Earth, numerous climate model studies (see, e.g., Kasting et al. 1988) imply a completely frozen planet – the so-called Snowball Earth. The contradiction between paleosol data and model predictions is named “the faint young Sun problem.” Several possible solutions have been put forward, e.g., supplying additional greenhouse gases such as methane (CH₄) or nitrous oxide (N₂O) (Grenfell et al. 2011) to the early Earth atmosphere. Goldblatt et al. (2009) suggested a stronger greenhouse effect on early Earth due to enhanced atmospheric N₂ (considering up to three times the modern value). Greenhouse warming on early Earth is also expected to be sensitive to surface pressure (P₀). Som et al. (2012) suggested that early Earth featured (P₀ < 2) bars, based on fossilized mud droplet data.

Early Venus and Mars

How early Venus’ atmosphere evolved, whether/for how long the surface was habitable, and how it finally diverged into its modern extreme state are critical questions to address. On Mars, observed surface flow features suggest that liquid water likely existed early in its history. Analogous to the early Earth, there are difficulties for numerical studies to

reproduce sufficiently warm surface temperatures. The study by von Paris et al. (2013) suggested that including pressure broadening (which enhanced the atmospheric greenhouse effect) of N_2 can help address this issue. How the Martian atmosphere developed from possible habitable conditions to its modern-day state is challenging for interior, atmospheric, and impact models. Clearly, understanding the developments of Venus and Mars will provide useful insights for understanding the HZ boundaries around different stars.

Beyond the Solar System

Recent works have expanded the parameter range with the aim of determining which are the key factors affecting the atmospheric habitability of Earth-like planets beyond the Solar System. Factors investigated include, e.g., climate feedbacks, interactive atmospheric climate chemistry (e.g., Segura et al. 2003; Grenfell et al. 2007), radiative effects of clouds (Kitzmann et al. 2013), planetary orbit (e.g., Williams and Pollard 2003), studies of climate evolution (e.g., Selsis et al. 2007), and (of particular interest) planetary mass (see ► “Super-Earths” below) and ocean mass (Abe et al. 2011).

Super-Earths

These objects (with mass M such that $M_{\text{Earth}} < M < 10 M_{\text{Earth}}$) are already starting to be found in the HZ (see below). There exists a lively discussion as to their ability to maintain plate tectonics (e.g., Noack and Breuer 2013), which would favor habitability and affects atmospheric mass and composition via outgassing. The enhanced planetary mass of super-Earths favors slower thermal escape of the original (proto) H_2 -rich atmosphere. For example, Pierrehumbert and Gaidos (2011) suggested that collision-induced greenhouse warming of high pressure (~ 40 bar) H_2 protoatmospheres (which may be relevant for super-Earths) could also lead to a significant increase of the outward HZ boundary – maybe to as far as 10 AU for solar-like stars.

Waterworlds and Desertworlds

“Waterworld” here refers to a terrestrial exoplanet with complete ocean coverage, i.e., without exposed surface continents. “Desertworld” here refers to a terrestrial exoplanet whose surface lacks large-scale oceans and vegetation. On waterworlds, it is currently unclear whether stabilizing climate cycles, i.e., analogous to the carbonate-silicate cycle on Earth, could operate. More work on, e.g., seafloor carbonization and its dependence on, e.g., pressure, pH, etc., are required (see, e.g., Wordsworth and Pierrehumbert 2013). Regarding desertworlds, additional work estimating, e.g., the dependence of ocean mass (e.g., including the lower limit) on, e.g., plate tectonics and habitability would be useful.

Earth-Like Planets Orbiting M Dwarf Stars

These are favored targets for exoplanet search missions. Such objects are already starting to be found in the HZ. Scalo et al. (2007) provide a detailed review of habitability issues. The HZ is rather close to the star (typically ~ 0.2 AU) so that Earth-like exoplanets could be tidally locked, slow rotators. The 3D modeling study of Joshi (2003) suggested that atmospheres of such worlds could effectively transport heat from the dayside to the nightside, hence maintaining habitable conditions. Joshi and Haberle (2012) suggested that including the spectral dependence of the snow-ice albedo for modeled planets orbiting red dwarf stars led to an increase in the outer HZ by up to 30% due to a weaker snow-ice albedo feedback. Shields et al. (2013) investigated similar effects, finding that Earth-like planets in the HZ of M stars could withstand a reduction of up to $\sim 19\%$ in incoming insolation without “going snowball” – partly because of the weaker ice-albedo feedback. Kite et al. (2011) modeled potentially destabilizing (negative) climate feedbacks involving weathering and pressure on tidally locked planets. Decreasing dayside pressure led to a

warming (air is less efficiently transported to the nightside) which in turn led to a faster weathering rate, which further decreases the atmospheric pressure. Leconte et al. (2013) studied (near) tidally locked planets close to the inner HZ boundary and discussed two opposing 3D effects – firstly, water evaporated on the dayside (suggesting a runaway climate effect) but secondly, water froze out on the nightside (opposing the runaway effect). Yang et al. (2013) analyzed a cloud feedback mechanism in their 3D model study, which increased the planetary albedo and hence expanded the inner HZ boundary toward the host star for Earth-like planets orbiting M dwarf stars. A recent highlight is, e.g., planetary studies of the GJ-667 system (e.g., Anglada-Escudé et al. 2013). Finally, the recent Kepler results are starting to suggest that planets in the HZ could be quite common.

Although Earth-like planets in the HZ of M dwarfs are in some ways favored objects, there are nevertheless some aspects that could oppose the habitability of rocky planets orbiting in the HZ of M dwarf stars. Lammer et al. (2007), for example, suggested efficient escape of even hundreds of bars of CO₂ or/and N₂ atmospheres due to nonthermal escape processes for planets in the close-in HZ of M dwarf stars especially during extended early, active stellar phases – this aspect needs further investigation. Also, possibly weak (or even absent) magnetospheres for Earth-like planets in the HZ of M dwarf stars could result in strong bombardment of the planetary atmosphere by stellar and galactic cosmic rays. Associated climate and photochemical effects have been discussed by, e.g., Grenfell et al. (2012, 2013) and Segura et al. (2010).

Atmospheric Habitability of K and F Stars

K stars are also favored targets for exoplanet search missions, being rather cool, but unlike the case of the M dwarfs, planets in their HZs are unlikely to be tidally locked. Segura et al. (2003) and Grenfell et al. (2007) modeled the climate and

photochemistry of Earth-like planets in the HZ of K and F stars and showed the importance of coupling climate and photochemistry when calculating biosignature abundances. For example, they showed that key bioindicators such as O₃ and important greenhouse gases such as CH₄ respond sensitively to the stellar input spectrum and the planet's position in the HZ. The 3D study of Godolt (2012) discussed a climate feedback, which could warm (cool) the atmospheres of Earth-like planets orbiting in the HZ of K stars (F stars) – they found that enhanced (suppressed) incoming longwave infrared radiation for the M dwarf star scenario favors stronger (weaker) planetary atmospheric heating, and the effect is strengthened by enhanced (decreased) water vapor evaporation and a stimulated (suppressed) hydrological cycle. Additional exoplanets orbiting K stars, which could be habitable, are recently emerging, e.g., HD85512b (Pepe et al. 2011).

Habitability Beyond the Classical HZ

The main motivation here is to estimate how common is habitability (in all its possible forms) in the Universe. Most studies to date have focused on the Earth (“what we know”). On the other hand, one should clearly keep an open mind on the new and exciting results to come. Beyond the classical definitions, one might include alternatives to the classical requisites of life, including energy coming, e.g., not only from main sequence stars or from white dwarf HZs which move continuously inward with time. Also, Neubauer et al. (2011) calculated the (much-expanded) HZ based on non-water solvents.

Applications

Key applications of the above theoretical studies (e.g., in an exoplanet context) are, e.g., to generate scientific debate by helping to understand the main physical responses (e.g., between atmospheric dynamics, climate and composition, and

their effect on habitability), to produce scientific databases (e.g., theoretical atmospheric spectral catalogs), which help interpret current and future-planned data, and to drive future instrumentation design by predicting the range of observed signals expected and the associated signal-to-noise ratio.

Future Directions

Theoretical studies to assess our understanding of habitability are needed now, to prepare the way for next-generation missions such as the James Webb Space Telescope (JWST) and the European Extremely Large Telescope (E-ELT), which could detect the first exoplanetary atmospheric biosignatures (although this task is very challenging).

Cross-References

- [Biomarkers \(Atmosphere\)](#)
- [Habitability of the Solar System](#)
- [Habitability, Effect of Eccentricity](#)
- [Habitability, Effects of Stellar Irradiation](#)
- [Habitable Zone](#)
- [Paleosols](#)
- [Plate Tectonics](#)

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Habitable Planet, Characterization

Lisa Kaltenegger¹ and Franck Selsis^{2,3}

¹Cornell University, Ithaca, NY, USA

²Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Floirac, France

³CNRS, LAB, Floirac, France

Keywords

Biomarkers · Extrasolar planets · Habitability · Habitable zone · Planetary atmospheres · Spectroscopy

Definition

The spectrum of a planet can contain signatures of atmospheric species, which create its spectral fingerprint. The presence and abundance of atmospheric species, in the context of the properties of the star and the planet, can elucidate the underlying physics and characterize a planetary environment. Here, we concentrate on characterizing a habitable planet and see what features might have a biological origin.

History

Sagan et al. (1993) analyzed a spectrum of the Earth taken by the Galileo probe, searching for signatures of life, and concluded that the large amount of O₂ and the simultaneous presence of traces of CH₄ are strongly suggestive of biology. To characterize a planet's atmosphere and its potential habitability, we look for absorption features in the reflection and transmission spectrum of the planet. On Earth, some atmospheric species exhibiting noticeable features in the planet's spectrum result directly or indirectly from biological activity: The main ones are O₂, O₃, CH₄, and N₂O. CO₂ and H₂O are, in addition, important as ► [greenhouse](#) gases in a planet's atmosphere and potential sources for a high O₂ concentration from photosynthesis.

Overview

We discuss how we can read a planet's spectrum to assess its habitability and search for the signatures of a biosphere. After a decade rich in giant exoplanet detections, observation techniques have now reached the ability to find planets of less than $10 M_{\text{Earth}}$ (so-called ► [super-Earths](#)) that may potentially be habitable. Extrasolar planet searches have shown an extraordinary ability to combine research with astrophysics, chemistry, biology, and geophysics into a new and exciting interdisciplinary approach to understanding our place in the universe.

Introduction

The current status of exoplanet characterization shows a surprisingly diverse set of giant planets. For a subset of these, some properties have been measured or inferred using observations of the host star, a background star, or the combination of stellar and planetary photons (► [Radial-Velocity Planets](#), [Microlensing Planets](#), ► [Transiting Planets](#), and ► [Astrometry](#)). These observations have yielded measurements of planetary mass, orbital elements and (for transits) the planetary radius, and, during the last few years, physical and chemical characteristics of the upper atmosphere of some of the transiting planets.

The detection of an Earthlike planet is approaching rapidly thanks to radial velocity surveys (► [HARPS](#)), transit searches (Corot, Kepler), and space observatories dedicated to their characterization that are already in the

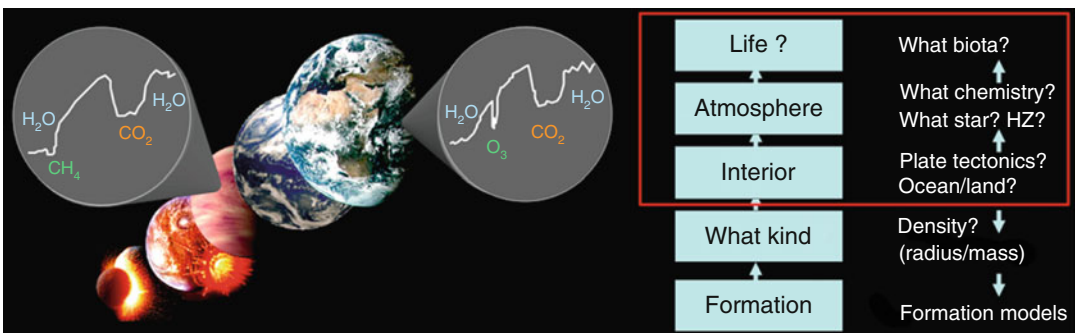
development phase (► [James Webb Space Telescope](#)), as well as future large ground-based telescopes and dedicated space-based missions. Space missions like CoRoT (CNES; Rouan et al. 1998) and Kepler (NASA; Borucki et al. 1997) provide statistics on the number, size, period, and orbital distance of planets, extending to terrestrial planets on the lower mass range end, while future space missions are designed to characterize their atmospheres.

Future space missions have the explicit purpose of detecting other Earthlike worlds, analyzing their characteristics, determining the composition of their atmospheres, investigating their capability to sustain life as we know it, and searching for signs of life. This can set our own planet, the only known habitat, in context with other rocky worlds and expand our statistics of 3 for extrasolar rocky planets that could potentially support life (► [Habitability of the Solar System](#)). They have the capacity to investigate the physical properties and composition of a broader diversity of planets, to understand the formation of planets, and to interpret potential biosignatures (see Fig. 1).

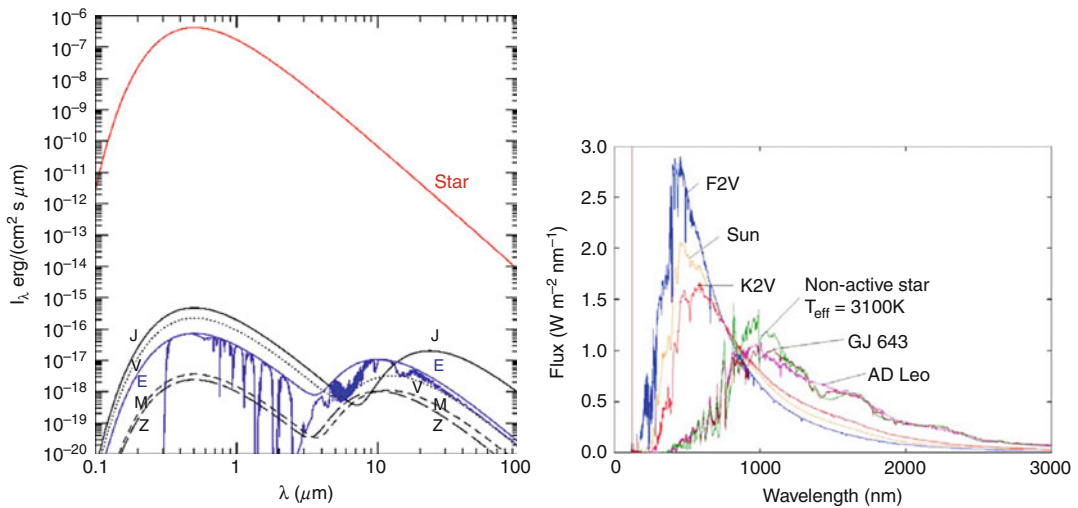
Basic Methodology

Characterize a Habitable Planet

A planet is a very faint, small object close to a very bright and large object, its parent star. In the visible part of the spectrum, we observe the starlight reflected off the planet, while in the infrared



Habitable Planet, Characterization, Fig. 1 Connection between spectra and characterization of rocky exoplanets

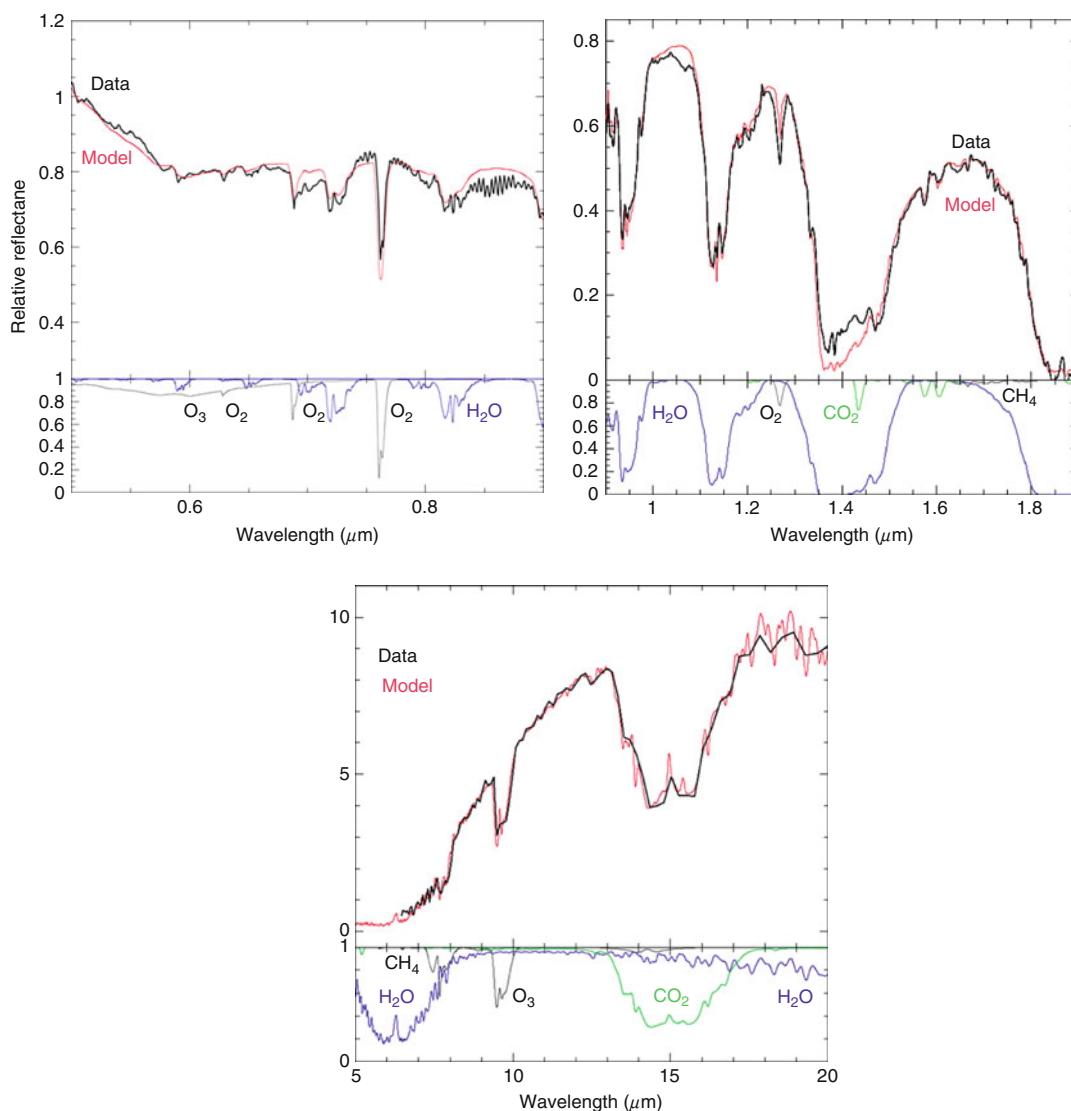


Habitable Planet, Characterization, Fig. 2 SAO model of our solar system (*left*) (assumed here to be black bodies with Earth spectrum shown). Spectra of different host stars (Segura et al. 2005) (*right*)

(IR), we detect the planet's own emitted flux. The Earth-Sun intensity ratio is about 10^{-7} in the thermal infrared ($\sim 10 \mu\text{m}$) and about 10^{-10} in the visible ($\sim 0.5 \mu\text{m}$) (see Fig. 2). The trade-off between contrast ratio and design is not discussed here, but leads to several different configurations for space-based mission concepts. The suggested interferometric systems operate in the mid IR ($6\text{--}20 \mu\text{m}$) and observe the thermal emission emanating from the planet. The coronagraph and occulter concepts detect the reflected light of a planet and operate in the visible and near infrared ($0.5\text{--}1 \mu\text{m}$). The viewing geometry results in different flux contributions of the overall detected signal from the planet's bright and dark side for the reflected light and the planet's hot and cold regions for the emitted flux. The contrast ratio of hot extrasolar giant planets (EGP) to their parent stars' flux is much smaller and can partially be observed with current telescopes. The contrast ratio of a rocky planet to a smaller parent star is much more favorable, making Earthlike planets around small stars very interesting targets for the immediate future.

Our search for signs of life is based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth, in that it requires liquid water as a solvent, has an energy source, and features a carbon-based chemistry (see,

e.g., Brack 1993; Des Marais et al. 2002). Life on the basis of a different chemistry is not considered here because the vast range of possible life-forms might produce signatures in their planet's atmosphere that are so far unknown. Therefore, we assume that extraterrestrial life is similar to life on Earth in its use of the same input and output gases and that it exists out of thermodynamic equilibrium (Lovelock 1975). ► **"Biomarkers"** are used here to mean detectable species, or a set of species, whose presence at significant abundance strongly suggests a biological origin (e.g., the simultaneous presence of $\text{CH}_4 + \text{O}_2$ or $\text{CH}_4 + \text{O}_3$ (Lovelock 1975)). Bioindicators are indicative of biological processes but can also be produced abiotically. It is their abundance and detection along with other atmospheric species and in a certain context (for instance, the properties of the star and the planet) that point toward a biological origin. The spectrum of the planet can contain signatures of atmospheric species, which creates its spectral fingerprint (► **Biomarkers Atmospheric**, ► **Evolution Over Geological Time** and ► **Biomarkers**, ► **Spectral**). Figure 3 shows observations and model fits to spectra of the Earth in three wavelength ranges (Kaltenegger et al. 2007). The data shown in Fig. 3 (left) is the visible Earthshine spectrum (Woolf et al. 2002), (right) is the near-infrared Earthshine spectrum (Turnbull et al. 2006), and



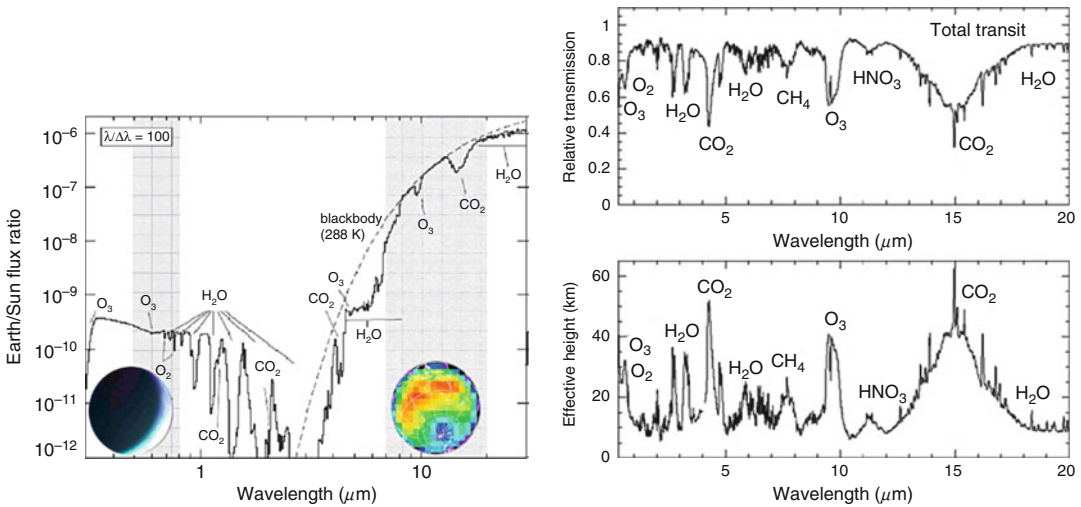
Habitable Planet, Characterization, Fig. 3 Observed reflectivity spectrum in the visible (Woolf et al. 2002) (top), near-infrared (Turnbull et al. 2006) (middle), and emission spectrum in the infrared (Christensen and Pearl

1997) (bottom panel) of the integrated Earth, as determined from Earthshine and space, respectively. The data is shown in black and the Smithsonian Astrophysical Observatory (SAO) model in red. The reflectivity scale is arbitrary

(bottom) is the thermal infrared spectrum of Earth as measured by a spectrometer en route to Mars (Christensen and Pearl 1997). The data are shown in black and the SAO model in red. In each case, the constituent gas spectra in a clear atmosphere are shown in the bottom panel, for reference.

Both spectral regions contain the signature of atmospheric gases that may indicate habitable conditions and, possibly, the presence of a

biosphere: CO₂, H₂O, O₃, CH₄, and N₂O in the thermal infrared and H₂O, O₃, O₂, CH₄, and CO₂ in the visible to near-infrared in reflected (Fig. 4 left). The Earth's spectra are shown in Fig. 4. The presence or absence of these spectral features (detected individually or collectively) will indicate similarities or differences with the atmospheres of terrestrial planets and their astrobiological potential (see Kaltenegger and



Habitable Planet, Characterization, Fig. 4 Synthetic reflection and emission spectra (*left*) and transmission spectra (*right*) of the Earth from UV to IR shown. The

intensity is given as a fraction of solar intensity (*left*) as well as the relative height in the atmosphere. The atmospheric features are indicated

Traub (2009) and Palle et al. (2009) for details on Earth's transmission spectrum).

Key Research Findings

Characterizing Planetary Environments

It is relatively straightforward to remotely ascertain that Earth is a habitable planet, replete with oceans, a greenhouse atmosphere, global geochemical cycles, and life – if one has data with arbitrarily high signal-to-noise ratio and spatial and spectral resolution. The interpretation of observations of other planets with limited signal-to-noise ratio and spectral resolution, as well as absolutely no spatial resolution as envisioned for the first-generation search instruments, will be far more challenging and implies that we need to gather information on the planetary environment to understand what we will see.

The following step-by-step approach can be taken to set the planetary atmosphere in context. After detection, we will focus on the main properties of the planetary system: its orbital elements as well as the presence of an atmosphere, using the light curve of the planet, or/and a crude estimate of the planetary nature from very low-resolution information (three or four wavelength channels).

Then a higher-resolution spectrum will be used to identify the compounds of the planetary atmosphere and to constrain the temperature and radius of the observed exoplanet. In that context, we can then test if we have an abiotic explanation of all compounds seen in the atmosphere of such a planet. If we do not, we can work with the exciting biotic hypothesis. O_2 , O_3 , and CH_4 are good biomarker candidates that can be detected by a low-resolution (resolution <50) spectrograph. Note that if the presence of sets of biogenic gases such as ($O_2/O_3 + CH_4$) may imply the presence of a massive and active biosphere, their absence does not imply the absence of life. Life existed on Earth before the interplay between oxygenic photosynthesis and carbon cycling produced an oxygen-rich atmosphere.

Temperature and Radius of a Planet

Knowing the temperature and planetary radius is crucial for the general understanding of the physical and chemical processes occurring on the planet (tectonics, hydrogen loss to space). In theory, spectroscopy can provide some detailed information on the thermal profile of a planetary atmosphere (► [Atmosphere](#), Structure). This, however, requires a spectral resolution and a sensitivity that are well beyond the

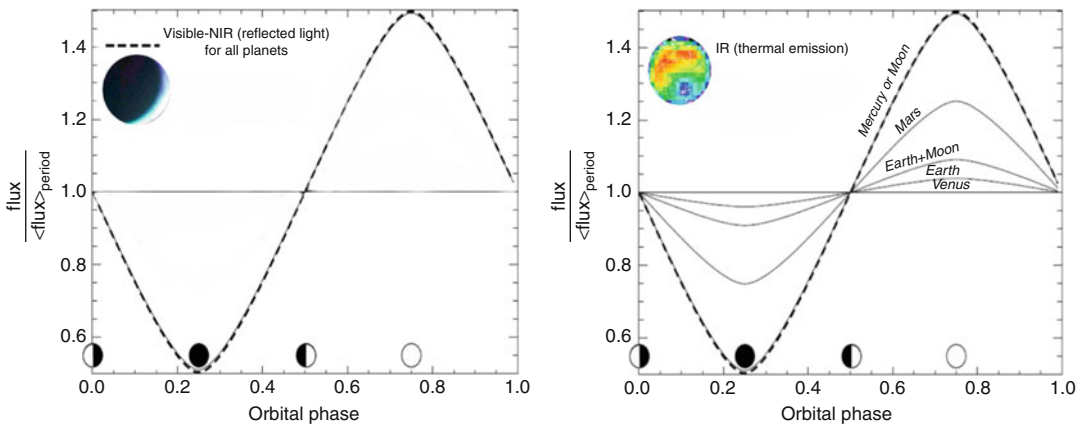
performance of a first-generation spacecraft. Here we concentrate on the initially available observations.

One can calculate the stellar energy of the star F_{star} that is received at the planet's measured orbital distance. The surface temperature of the planet at this distance depends on its [albedo](#) and on the greenhouse warming by atmospheric compounds. However, with a low-resolution spectrum of the thermal emission, the mean effective temperature and the radius of the planet can be obtained. The ability to associate a surface temperature to the spectrum relies on the existence and identification of spectral windows (regions of transparency) which allow probing the surface or certain atmospheric levels. Such identification is not trivial. For an Earthlike planet, there are some atmospheric windows that can be used in most of cases, especially between 8 and 11 μm as seen in Fig. 4. This window would, however, become opaque at high H_2O partial pressure (e.g., in the inner part of the [habitable zone](#) (HZ) where a lot of water is vaporized) and at high CO_2 pressure (e.g., a very young Earth or the outer part of the HZ). The accuracy of the radius and temperature determination will depend on the sensitivity and resolution of the spectrum, the precision of the Sun-star distance, the cloud coverage, and also the distribution of brightness temperatures over the planetary surface. For transiting planets, the

accuracy of the radius of the planet depends on how well the host star is characterized.

The measured IR flux can directly be converted into a brightness temperature that will provide information on the temperature of the atmospheric layers responsible for the emission. If the mass of a planet can be measured (by radial velocity and/or astrometric observations), an estimate of the radius of the rocky core can be made by assuming a bulk composition of the planet which can then be used to convert IR fluxes into temperatures. Important phase-related variations in the planet's flux are due to a high day/night temperature contrast and imply a low [greenhouse effect](#) and the absence of a stable liquid ocean. Therefore, habitable planets can be distinguished from airless or Mars-like planets by the amplitude of the observed variations of T_b (see Fig. 5).

The orbital flux variation in the IR can distinguish (in the detection phase) planets with and without an atmosphere (see also Selsis 2002; Gaidos and Williams 2004). Strong variation of the thermal flux with the phase reveals a strong difference in temperature between the day and night hemisphere of the planet, a consequence of the absence of a dense atmosphere which would transport heat between the hemispheres. In such a case, estimating the radius from the thermal emission is made difficult because most of the received flux comes from the small and hot substellar area.



Habitable Planet, Characterization, Fig. 5 Orbital [light curve](#) for [blackbody](#) planets in a circular orbit with null obliquities, with and without an atmosphere in

the visible (*left*) and thermal infrared (*right*) (After Selsis 2002). Flux normalized to the average over a complete period

The ability to retrieve the radius would depend on the assumptions that can be made on the orbit geometry and the rotation rate of the planet (► [Habitable Zone](#), ► [Effect of Tidal Locking](#)). In most cases, degenerate solutions will exist. When the mean brightness temperature is stable along the orbit, the estimated radius is more reliable. The radius can be measured at different points of the orbit and thus for different values of brightness temperature T_b , which should allow estimating the error made.

Note also that a Venus-like exoplanet would exhibit nearly no measurable phase-related variation of its thermal emission, due to the fast rotation of its atmosphere and its strong greenhouse effect, and thus can only be distinguished through spectroscopy from habitable planets. The mean value of T_b estimated over an orbit can be used to estimate the ► [albedo](#) of the planet, A , through the balance between the incoming stellar radiation and the outgoing IR emission.

The thermal light curve (i.e., the integrated infrared emission measured at different positions on the orbit) exhibits smaller variations due to the phase (whether the observer sees mainly the day-side or the nightside) and to the season for a planet with an atmosphere, than does the corresponding visible light curve (see Fig. 5). In the visible ranges, the reflected flux allows us to measure

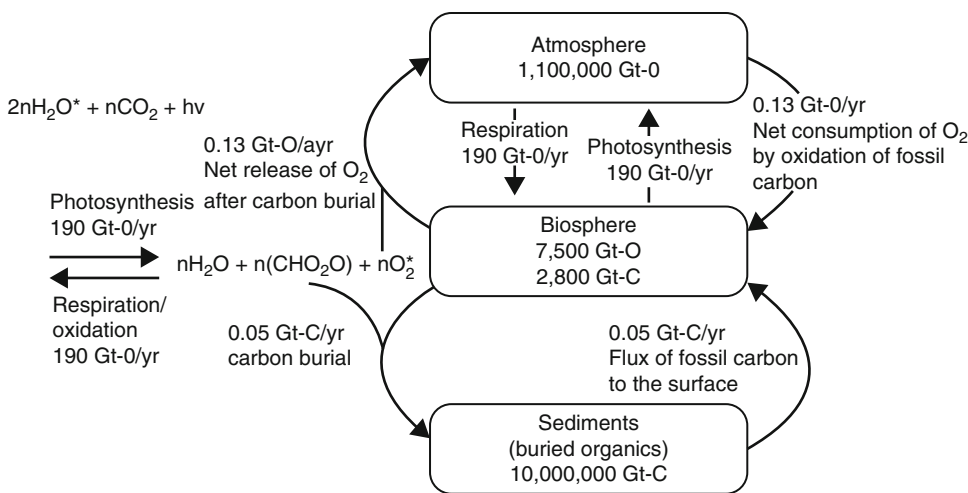
the product $A \times R^2$, where R is the planetary radius (a small but reflecting planet appears as bright as a big but dark planet). The first generation of optical instruments will be very far from the angular resolution required to directly measure an exoplanet radius.

Potential Biomarkers

Spectral ► [biomarkers](#) are discussed in a separate entry in this encyclopedia. We simply add here Fig. 6 on the terrestrial oxygen cycle. Note that possible abiotic sources of biomarkers must be carefully evaluated.

Cryptic Worlds, Surface Features and Cloud Features

► [Clouds](#) reduce the relative depths, full widths, and equivalent widths of spectral features, weakening the spectral lines in the whole described as wavelength range (Kaltenegger et al. 2007). Earth has an average of 60% cloud coverage, which prevents easy identification of any surface features without knowing the cloud distribution. If one records the planet’s signal with a very high time resolution (a fraction of the rotation period of the planet) and individually high signal-to-noise ratio (SNR), one could determine the overall contribution of clouds to the signal (Cowan et al. 2009; Palle et al. 2008). During each of these



Habitable Planet, Characterization, Fig. 6 Oxygen cycle on Earth (Kaltenegger and Selsis 2010); Gt is gigatons

individual measurements, one has to collect enough photons for a high individual SNR per measurement to be able to correlate the measurements to the surface features, which precludes this method for first-generation missions that will observe a minimum of several hours to achieve an SNR of 5–10. For Earth (Cowan et al. 2009; Palle et al. 2008), these measurements show a correlation to Earth's surface features, because the individual measurements are time resolved as well as have an individual high SNR, making it a very interesting concept for future generations of missions.

Assuming one had a planet with a cloud-free atmosphere or could distinguish the signal from the overall cloud distribution from that due to the surface reflectivity, one could discover continents and seas on an exoplanet by observing the daily variation of the surface albedo in the visible (Ford et al. 2001; Palle et al. 2008). On a cloud-free Earth, the diurnal flux variation at visible wavelengths caused by different surface features rotating in and out of view could be high, assuming hemispheric inhomogeneity. When the planet is only partially illuminated, a more concentrated signal from surface features could be detected as they rotate in and out of view on a cloudless planet (William and Gaidos 2008).

Our knowledge of the reflectivity of different surface components on Earth – like desert, ocean, and ice – helps in assigning the vegetation red edge (VRE) of the Earthshine spectrum to terrestrial vegetation. On Earth around 440 million years ago (Pavlov et al. 2003; Schopf 1993), an extensive land plant cover developed, generating the red chlorophyll edge in the reflection spectrum between 700 and 750 nm. While they efficiently absorb visible light, photosynthetic plants have developed strong infrared reflection (possibly as a defense against overheating and chlorophyll degradation) resulting in a steep change in reflectivity around 700 nm, called the red edge. The primary molecules that absorb the energy and convert it to drive photosynthesis (H_2O and CO_2 into sugars and O_2) are chlorophyll A (0.450 μm) and B (0.680 μm). The exact wavelength and strength of the spectroscopic “vegetation red

edge” (VRE) depend on the plant species and environment. Averaged over a spatially unresolved hemisphere of Earth, the additional reflectivity of this spectral feature is typically only a few percent (see also (Montanes-Rodriguez et al. 2005; Tinetti et al. 2006; Kaltenegger and Traub 2009). Several groups (Arnold et al. 2002; Christensen and Pearl 1997; Montanes-Rodriguez et al. 2007; Woolf et al. 2002; Turnbull et al. 2006) have measured the integrated Earth spectrum via the technique of Earthshine, using sunlight reflected from the non-illuminated, or “dark,” side of the Moon. Earthshine measurements have shown that detection of Earth's VRE is feasible if the resolution is high and the cloud coverage is known. On planets around other stars, different biota could develop and produce different reflective features (Kiang et al. 2007).

On Earth, photosynthetic organisms are responsible for the production of nearly all of the oxygen in the atmosphere. However, in many regions of the Earth and particularly where surface conditions are extreme, for example, in hot and cold deserts, photosynthetic organisms can be driven into and under substrates where light is still sufficient for photosynthesis. These communities exhibit no detectable surface spectral signature. The same is true of the assemblages of photosynthetic organisms at more than a few meters depth in water bodies. These communities are widespread and dominate local photosynthetic productivity. There could be such very interesting Earth-analog worlds that could have habitats but not exhibit biological surface feature in the disk-averaged spectrum (Cockell et al. 2009).

Earth's hemispherical integrated vegetation red edge signature is very weak, but planets with different rotation rates, obliquities, land-ocean fraction, and continental arrangement may have lower cloud cover and higher vegetated fraction. Knowing that other pigments exist on Earth and that some minerals can exhibit a similar spectral shape around 750 nm (Seager et al. 2005), the detection of the red edge of chlorophyll on exoplanets, despite its extreme interest, will not be unambiguous.

Summary

Any information we collect on habitability is only important in a context that allows us to interpret what we find. To search for signs of life, we need to understand how the observed atmosphere physically and chemically works. Knowledge of the temperature and the planetary radius is crucial for the general understanding of the physical and chemical processes occurring on the planet. These parameters, as well as an indication of habitability, can be determined with low-resolution spectroscopy and low photon flux, as assumed for first-generation space missions. The combination of spectral information in the visible (starlight reflected off the planet) as well as in the mid IR (planet's thermal emission) allows a confirmation of detection of atmospheric species and a more detailed characterization of individual planets and the opportunity to explore a wide domain of planet diversity. Being able to measure the outgoing shortwave and longwave radiation as well as their variations along the orbit, to determine the albedo and identify greenhouse gases, would in combination allow us to explore the climate system at work on the observed worlds, as well as probe planets similar to our own for habitable conditions.

Future Directions

The results of a first-generation mission will most likely include an amazing scope of diverse planets that will set planet formation and evolution, as well as our own planet, in an overall context.

Cross-References

- [Albedo](#)
- [Astrometry](#)
- [Atmosphere, Structure](#)
- [Biomarkers Atmospheric, Evolution Over Geological Time](#)
- [Biomarkers, Spectral](#)
- [Blackbody](#)
- [Clouds](#)
- [CoRoT Satellite](#)

- [Greenhouse Effect](#)
- [Habitability, Effect of Eccentricity](#)
- [Habitability, Effects of Stellar Irradiation](#)
- [Habitability of the Solar System](#)
- [Habitable Zone](#)
- [Habitable Zone, Effect of Tidal Locking](#)
- [HARPS](#)
- [Kepler](#)
- [Lightcurve](#)
- [Radial-Velocity Planets](#)
- [Super-Earths](#)
- [Transiting Planets](#)

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Habitable Zone

Lisa Kaltenegger¹ and Antígona Segura²

¹Cornell University, Ithaca, NY, USA

²Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

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Exoplanets · Habitability · Life

Definition

The circumstellar habitable zone (HZ) is the circular region around one or multiple stars where standing bodies of liquid water could exist on a rocky planet’s surface similar to Earth in composition and mass with an atmosphere (e.g., Kasting et al. 1993; Haghighipour and Kaltenegger 2012; Kaltenegger and Haghighipour 2013; Kopparapu et al. 2013) that facilitates the detection of possible atmospheric biosignatures in the atmosphere of such planets (see, e.g., Kaltenegger 2017; Catling et al. 2018; Fujii et al. 2018).

The width and distance of this annulus, using this definition, depend mainly on the stellar luminosity and spectral energy distribution, and change through stellar evolution (Underwood et al. 2003; Lopez et al. 2005; Danchi and Lopez 2013; Ramirez and Kaltenegger 2014, 2016).

A planet in the habitable zone is not necessarily habitable. Multiple mechanisms exist by which a planet cannot attain or can lose habitability, for example, low mass and resulting atmospheric losses or changes in initial composition (e.g., no water). The HZ is a tool that guides missions and surveys in prioritizing planets for follow-up observations.

History

The habitable zone (HZ) concept was proposed for the first time by Huang (1959, 1960) and has been calculated by several authors after that (see, e.g., Rasool and DeBergh 1970; Hart 1979; Kasting et al. 1993; Kopparapu et al. 2012; Underwood et al. 2003; Lopez et al. 2005; Ramirez and Kaltenegger 2016, 2018). The most used limits have been those calculated by Kasting et al. (1993) and later recalculated by Kopparapu et al. (2012), and it is usually called the classic habitable zone. These limits were calculated with 1D cloudless atmospheric models.

New limits of the habitable zone have been calculated by including properties of the planet and the star, as well as 3D models. For example, the internal limit of the habitable zone is closer to the star – compared to the one calculated by

Kopparapu et al. (2012) – for rocky planets with low water inventory in the planetary surface (Abe et al. 2011). Clouds widen the habitable zone moving the inner limit (water clouds) and the outer limit farther from the star (CO₂ clouds) (e.g., Selsis et al. 2007). For low mass main sequence stars (M dwarfs), the habitable zone is so close to the host star that planets enter spin-orbit resonances changing the limits of the habitable zone (Wordsworth et al. 2011; Turbet et al. 2016). Other variations for the calculation of the habitable zone include H₂ atmospheres (Pierrehumbert and Gaidos 2011; Ramirez and Kaltenegger 2017), methane (Ramirez and Kaltenegger 2018), hazes (Arney et al. 2017), and the ice albedo feedback (Joshi and Haberle 2012; Shields et al. 2013). Three-dimensional studies (e.g., Leconte et al. 2013) suggest that the inner HZ edge could be closer to the star (than predicted by some 1D models) due to a Hadley cell response such that IR cooling to space is shifted to lower altitudes where it is more efficient.

Given that stellar luminosity evolves during the star's lifetime, the concept of a continuously habitable zone (CHZ) has been introduced to mean the zone that remains habitable around a star during a given period of time (Hart 1979).

Overview

Future remote sensing characterization of planetary environments can be used to test our understanding of the factors that contribute to planetary habitability. The HZ is usually defined for surface conditions only. Chemoautotrophic life, whose metabolism does not depend on the stellar light, can still exist outside the HZ, thriving in the interior of the planet where liquid water is available. Such metabolisms rely on very limited sources of energy (compared to stellar light) and electron donors (compared to H₂O on Earth). They mainly catalyze reactions that would occur at a slower rate in purely abiotic conditions, and they are thus not expected to modify a whole planetary environment in a way detectable remotely.

Basic Methodology

The limits of classic habitable zone were calculated using a 1D atmospheric model for planets with H₂O-CO₂-N₂ atmospheres (Kasting et al. 1993; Kopparapu et al. 2013). The procedure relied on the inverse climate modeling calculating the flux needed to achieve a given atmospheric setup, instead of obtaining a temperature profile for a given solar flux. The solar or stellar flux is expressed as the effective solar/stellar flux (S_{eff}), that is the solar flux divided by the solar constant ($S_{\odot} = 1360 \text{ W m}^{-2}$, Kopparapu et al. 2013). The solar constant is the integrated solar flux at the top of the atmosphere for present Earth.

For the outer boundary, the model calculated the flux and the CO₂ surface pressure needed to keep the surface temperature at 273 K. As the planet receives less stellar flux, the atmospheric CO₂ is increased in the model until it fails to keep this temperature, this is known as the maximum greenhouse limit. The outer edge limit can change significantly if other gases are added to the model like hydrogen and methane (Pierrehumbert and Gaidos 2011; Ramirez and Kaltenegger 2017, 2018).

The inner limit is determined by the moist-greenhouse effect where the atmosphere losses the cold trap that keeps the water in the troposphere; once H₂O reaches the stratosphere, it is photolyzed and hydrogen escapes to space (Kasting et al. 1993; Kopparapu et al. 2013). There is a second boundary for the internal HZ, called the runaway greenhouse limit, when the oceans are totally evaporated. To calculate both limits, the model determined the solar flux needed to achieve temperatures from 220 K to 2200 K. The inner edge is relatively robust to additions of secondary greenhouse gases, because trace gas absorption is outstripped by water vapor absorption in these extremely dense (>200 bar) water steam atmospheres.

A revision of the calculations by Kasting et al. (1993) reported values of $S_{\text{eff}} = 1.04$ for the inner edge of the Sun HZ (runaway greenhouse limit) and 0.35 for the outer edge of the Sun HZ (assuming a maximum greenhouse effect in the planet's atmosphere; see Kopparapu et al. 2012,

2013). The distance around a star with luminosity L where a planet receives an effective flux S_{eff} is:

$$d = \left(\frac{L/L_{\odot}}{S_{\text{eff}}} \right) \text{au}$$

Thus, the inner edge of the solar HZ using 1D models without cloud feedback is at 0.99 au (moist greenhouse) and the outer edge at 1.7 au. Another set of boundaries for the HZ are called “empirical limits” because they use the cases of Venus and Mars. The inner HZ empirical limit is defined by the S_{eff} received by Venus when it may have lost most of its water by runaway greenhouse (about 1 Gyr ago), that is $S_{\text{eff}} = 1.77$ (0.75 au for the present solar luminosity). The outer edge is defined by the effective solar flux that Mars received at the time that it may have had stable water on its surface (about 3.8 Gyr ago), which corresponds to $S_{\text{eff}} = 0.32$ (1.77 au for the present solar luminosity). Note that the inner edge of the empirical habitable zone is highly uncertain because of the unknown evolution of Venus.

Kopparapu et al. (2013) used the same methodology for the Sun and for F, G, K, and M main sequence stars, obtaining a general relationship for calculating the limits of the habitable zone valid for main sequence stars with effective temperatures (T_{eff}) from 2600 K to 7200 K. Ramirez and Kaltenegger (2016) extended those limits to main sequence stars with 10,000 K.

For calculations of the HZ limits, it is assumed that planets have similar mass to Earth, rocky compositions and the surface temperature is controlled by a global carbonate-silicate cycle that stabilizes the CO_2 level, like on Earth (Walke 1977). This implies that the planet is geologically active and continuously outgasses CO_2 and that carbonates form in the presence of surface liquid water, which may require continental weathering. Without this stabilization, the Earth would not be habitable over geological times. This in turn affects the composition of the atmosphere at the outer edge of the habitable zone. As the amount of CO_2 increases, the greenhouse effect increases, warming the surface and releasing more CO_2 from carbonates and from that dissolved in

oceans. The feedback only works up to the temperature where the increase in the albedo due to increasing in CO_2 concentration (producing more Rayleigh scattering and cloud formation; see, e.g., Forget and Pierrehumbert 1997) is stronger than the greenhouse effect of CO_2 . Because of the relation between the albedo of the planet and the effective temperature of the star, the limits of the habitable zone cannot be simply scaled to the stellar luminosity.

Key Research Findings

The limits of the circumstellar habitable zone (HZ) around a main sequence star are given in Table 1. However, the limits of the HZ are known qualitatively, more than quantitatively. This uncertainty is mainly due to the complex role of ► clouds and three-dimensional climatic effects not yet included in the modeling. Thus, planets slightly outside the computed HZ could still be habitable, while planets at habitable orbital distance may not be habitable because of their size, chemical composition, or other characteristics that could prevent habitability.

Applications

The concepts of the HZ help to define an astronomical search zone for habitable planets with remotely detectable species in their atmosphere that indicate habitable conditions, such as surface liquid water (e.g., Segura and Kaltenegger 2010; Kaltenegger 2017).

Future Directions

The habitable zone concept is still evolving as more is learnt about planetary formation and evolution and as we continue to improve the radiative transfer, ► clouds, and three-dimensional atmospheric models that allow more accurate calculations of a planet’s temperature profile. The recollection of more data from detected exoplanets and their host stars allows the inclusion

Habitable Zone, Table 1 Properties and habitable zone limits of the main sequence stars of spectral type F-M considered for the search of Earth analogs, assuming no

other limits than runaway and maximum greenhouse for a rocky planet with CO₂ atmosphere. Note that this model does not take increasing cloud fractions into account

Spectral type	Host star	Luminosity (L _⊙) ^b	Mass (M _⊙) ^b	Habitable zone (AU) ^a	
	Effective temp. (K) ^b			Inner limit ^c 1D models	Outer limit ^d
F	6100–7200	2.0–6.5	1.4–1.6	1.4–2.3	2.3–3.9
G	5300–6030	0.66–1.1	0.9–1.05	0.8–1.0	1.4–1.7
K	4900–5250	0.1–0.42	0.67–0.79	0.3–0.7	0.6–1.2
M	2600–3850	0.0012–0.077	0.06–0.51	0.04–0.3	0.1–0.6

^aData from the online HZ calculator at <http://depts.washington.edu/naivpl/content/hz-calculator>

^bData from: Ostlie and Carroll (1996)

^cRunaway greenhouse limit calculated for planets around stars with T_{eff} = 6100 and 7200 K for F stars; T_{eff} = 5300 and 6030 K for G stars; T_{eff} = 4900 and 5250 K for K stars; and T_{eff} = 3850 and 2600 K for M stars

^dMaximum greenhouse limit for planets around stars with T_{eff} = 6100 and 7200 K for F stars; T_{eff} = 5300 and 6030 K for G stars; T_{eff} = 4900 and 5250 K for K stars; and T_{eff} = 3850 and 2600 K for M stars

of more constrains in models to predict the conditions of habitability for a given planet.

Cross-References

- Albedo
- Atmospheric Processes, Escape
- Atmospheric Modeling: 1D Model
- Atmosphere, Structure
- Biomarkers Atmospheric, Evolution over Geological Time
- Biomarkers, Spectral
- Clouds
- GCM
- Greenhouse Effect
- Habitability, Effect of Eccentricity
- Habitability, Effects of Stellar Irradiation
- Habitable Planet, Characterization
- Habitable Zone, Effect of Tidal Locking
- Planetary Migration
- Rayleigh Scattering
- Spectral Type

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Habitable Zone Around Binary Star Systems

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Exoplanets · Habitability · Life

Definition

In a binary star system, a planet may in principle exist in an orbit around either of the stars or in an orbit that surrounds both stars of the binary. In the latter case, we refer to the planet as a ► **circumbinary planet**. The corresponding habitable zone (HZ) may be assumed to be an annulus around the binary where an Earth-like planet (with

similar atmospheric composition to that of Earth) with a sufficient amount of water can permanently maintain liquid water on its solid surface.

Basic Methodology

To calculate the boundaries of the habitable zone (HZ) around a binary star system (circumbinary orbits), it is assumed that the HZ is an annulus around the binary where an Earth-like planet (with similar atmospheric composition as that of Earth) and sufficient amount of water can permanently maintain liquid water on its solid surface. The locations of the boundaries of the HZ, and therefore the capability of the planet in maintaining conditions for habitability, depend on the total flux received at the top of its atmosphere. Since the atmosphere converts stellar insolation to temperature structure and surface temperature of a planet, its interaction with the stellar radiation plays an important role in considering whether a planet can maintain liquid water on its surface and allow for detectable habitable conditions. This interaction strongly depends on the stellar spectral energy distribution (SED), implying that stars with different energy distributions will contribute differently to the absolute incident flux at the top of the planet's atmosphere. To determine the contribution of a star taking into account its SED, it is necessary to define a *spectral weight factor* $W_i(f, T_i)$, where $i = (\text{Pr}, \text{Sec})$ denoting the primary and secondary stars, respectively, T_i is the star's effective temperature and f represents the atmosphere's cloud fraction. The contribution of each star of the binary to the total flux at the top of the planet's atmosphere can be therefore written as

$$W_i(f, T_i)F_i(f, T_i).$$

Here $F_i = L_i/r_{\text{Pl}-i}^2$ denotes the stellar flux and L_i is the luminosity of each star of the binary. The total flux received by the planet is therefore given by

$$W_{\text{Pr}}(f, T_{\text{Pr}}) \frac{L_{\text{Pr}}(T_{\text{Pr}})}{r_{\text{Pl}-\text{Pr}}^2} + W_{\text{Sec}}(f, T_{\text{Sec}}) \frac{L_{\text{Sec}}(T_{\text{Sec}})}{r_{\text{Pl}-\text{Sec}}^2},$$

where $r_{\text{Pl}-\text{Pr}}$ and $r_{\text{Pl}-\text{Sec}}$ are the distances between the planet and the primary and secondary stars, respectively. Defining HZ as a region where the total flux received by an Earth-like planet at the top of its atmosphere is equal to that of Earth received from the Sun, the boundaries of circumbinary HZ can be calculated from

$$\begin{aligned} W_{\text{Pr}}(f, T_{\text{Pr}}) \frac{L_{\text{Pr}}(T_{\text{Pr}})}{l_{x-\text{Bin}}^2} + W_{\text{Sec}}(f, T_{\text{Sec}}) \frac{L_{\text{Sec}}(T_{\text{Sec}})}{r_{\text{Pl}-\text{Sec}}^2} \\ = \frac{L_{\text{Sun}}}{l_{x-\text{Sun}}^2}. \end{aligned}$$

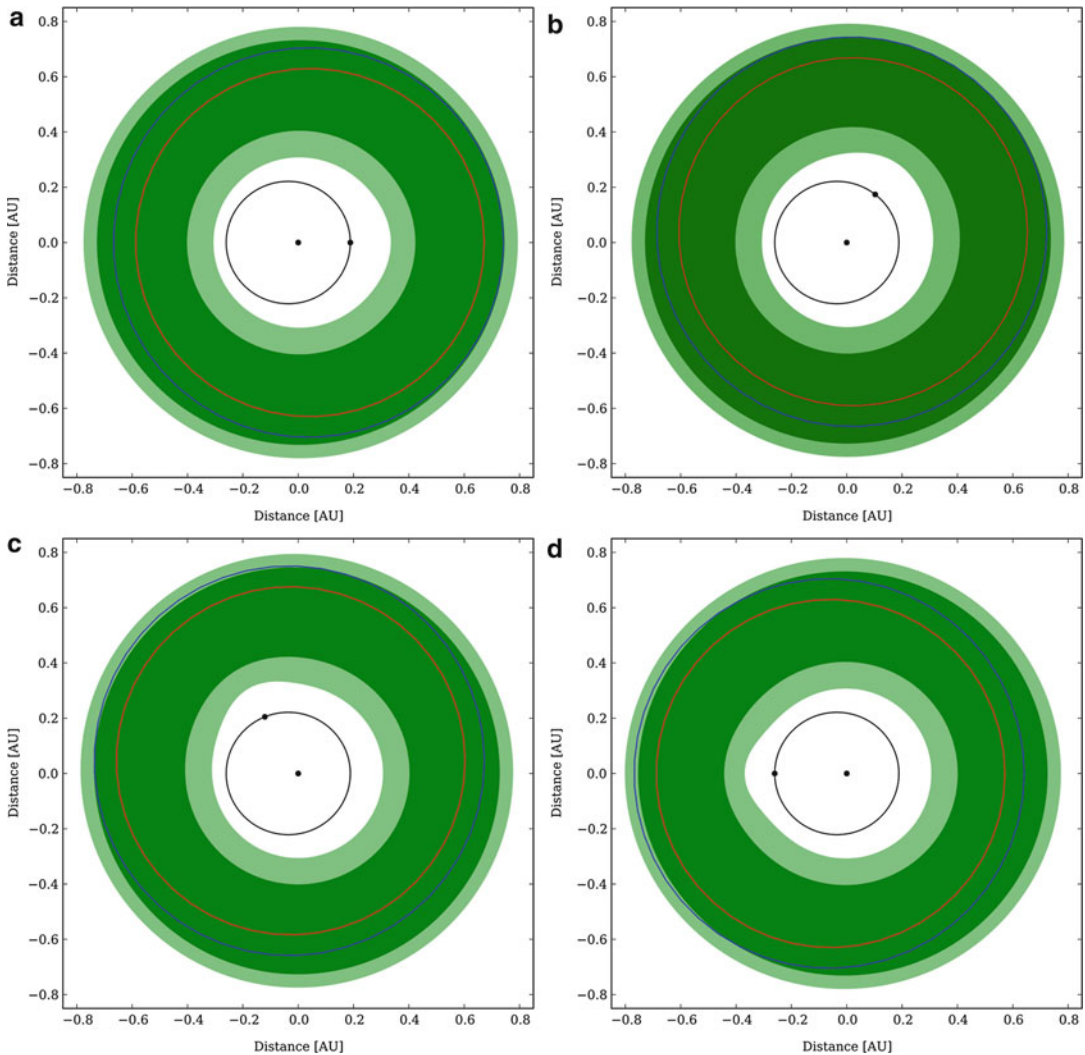
where x -inner, outer boundary of the HZ.

In deriving this equation, it is assumed that the primary star is at the center of the coordinates system (see the entry ► [Circumbinary Planet](#)) and the boundaries of the HZ of the binary ($l_{x-\text{Bin}}$) are measured with respect to this star.

The functional form of the spectral weight factor $W_i(f, T_i)$ varies according to the models of the Sun's HZ. Haghighipour and Kaltenegger (2013) have developed a detailed methodology for calculating this quantity. Mueller and Haghighipour (2014) have utilized that methodology and created a website with a user interface where one can input the physical and orbital parameters of the binary, and the website generates a snapshot of the circumbinary HZ corresponding to those orbital elements. This website can be found at <http://astro.twam.info/hz/>.

As implied by the above equation for calculating the HZ, the inner and outer boundaries of the HZ vary as the stars of the binary rotate around their center of mass. A gallery of the HZs of all currently known circumbinary planets with movies of their time variations can be found at <http://astro.twam.info/hz-ptype/>.

It is important to note that in reality, the habitability of an Earth-like planet in a circumbinary HZ is independent of the fluctuations of the boundaries of the HZ. In this case, the determining factor is the averaged flux received by the planet in one orbit around the binary. During this time, the buffering effect of clouds should compensate for the effects of the temporary displacements of the HZ and allow the planet to maintain a surface



Habitable Zone Around Binary Star Systems, Fig. 1 (a–d) Snapshots of the radial variations of the narrow (*dark green*) and empirical (*light green*) HZs around the Kepler 16 binary system. The *red* and *blue*

circles depict the boundary of orbital stability and the orbits of the currently known planets of the system. (Figure from Haghighipour and Kaltenegger 2013)

temperature conducive to liquid water. Figure 1 shows snapshots of the circumbinary HZ of Kepler 16 system.

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 Mueller T, Haghighipour N (2014) *Astrophys J* 782:26

Habitable Zone in Binary Stars Systems

Nader Haghighipour
 Institute for Astronomy, University of Hawaii-
 Manoa, Honolulu, HI, USA

Keywords

Exoplanets · Habitability · Life

Definition

In a binary star system, a planet may in principle exist either in an orbit around a star or in an orbit that surrounds both stars in the system; in the former case, we refer to it as a ► **circumprimary planet**. To calculate the boundaries of the habitable zone (HZ) around a star of a binary star system (circumprimary orbits), it is assumed that the HZ is an annulus around the star where an Earth-like planet (with similar atmospheric composition to that of Earth) and a sufficient amount of water can permanently maintain liquid water on its solid surface.

Basic Methodology

The locations of the boundaries of the HZ, and therefore the capability of the planet in maintaining conditions for habitability, depend on the total flux received at the top of its atmosphere. Since the atmosphere converts stellar insolation to temperature structure and surface temperature of a planet, its interaction with the stellar radiation plays an important role in considering whether a planet can maintain liquid water on its surface and allow for detectable habitable conditions. This interaction strongly depends on the stellar spectral energy distribution (SED), implying that stars with different energy distributions will contribute differently to the absolute incident flux at the top of the planet's atmosphere. To determine the contribution of a star taking into account its SED, it is necessary to define a *spectral weight factor* $W_i(f, T_i)$, where $i = (\text{Pr}, \text{Sec})$ denoting the primary and secondary stars, respectively, T_i is the star's effective temperature, and f represents the atmosphere's cloud fraction. The contribution of each star of the binary to the total flux at the top of the planet's atmosphere can be therefore written as $W_i(f, T_i)$. Here

$$F_i = L_i / r_{\text{Pl}-i}^2$$

denotes the stellar flux and L_i is the luminosity of each star of the binary. The total flux received by the planet is therefore given by

$$W_{\text{Pr}}(f, T_{\text{Pr}}) \frac{L_{\text{Pr}}(T_{\text{Pr}})}{r_{\text{Pl-Pr}}^2} + W_{\text{Sec}}(f, T_{\text{Sec}}) \frac{L_{\text{Sec}}(T_{\text{Sec}})}{r_{\text{Pl-Sec}}^2},$$

where $r_{\text{Pl-Pr}}$ and $r_{\text{Pl-Sec}}$ are the distances between the planet and the primary and secondary stars, respectively. Defining HZ as a region where the total flux received by an Earth-like planet at the top of its atmosphere is equal to that of Earth received from the Sun, the boundaries of circumprimary HZ can be calculated from

$$\begin{aligned} W_{\text{Pr}}(f, T_{\text{Pr}}) \frac{L_{\text{Pr}}(T_{\text{Pr}})}{l_{\text{x-Bin}}^2} + W_{\text{Sec}}(f, T_{\text{Sec}}) \frac{L_{\text{Sec}}(T_{\text{Sec}})}{r_{\text{Pl-Sec}}^2} \\ = \frac{L_{\text{Sun}}}{l_{\text{x-Sun}}^2}. \end{aligned}$$

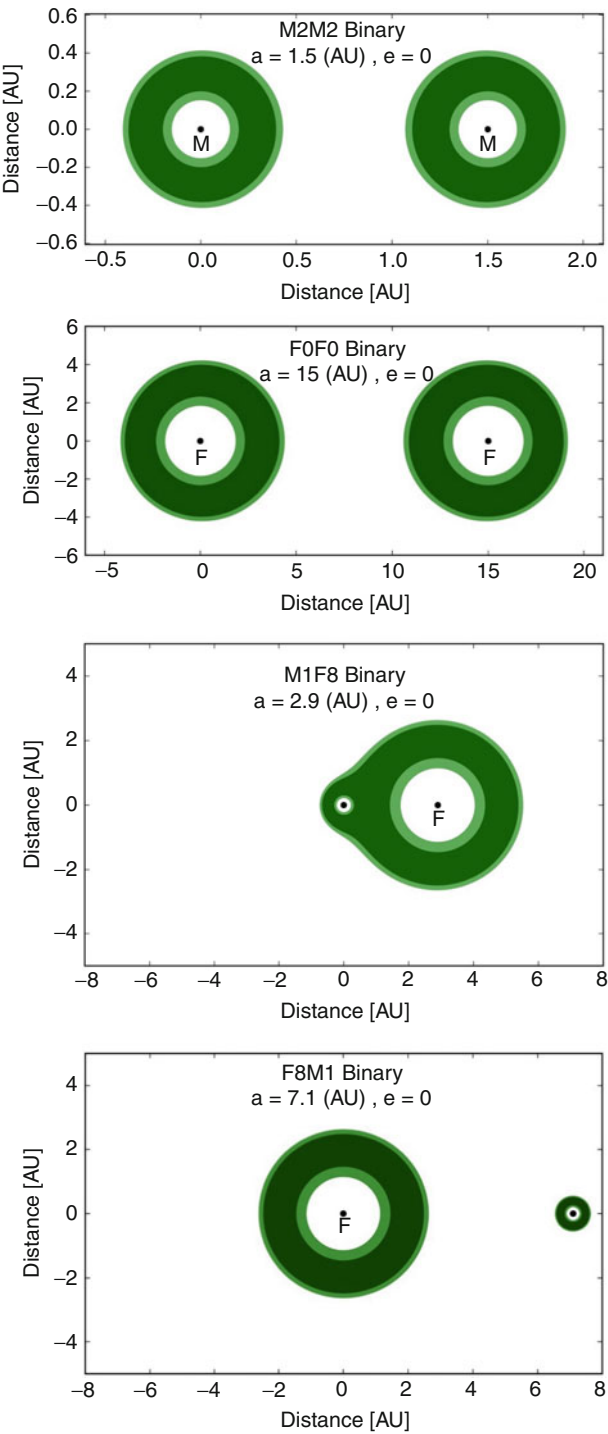
In deriving this equation, it is assumed that the primary star is at the center of the coordinates system (see the entry ► **Circumprimary Planet**) and the boundaries of the HZ of the binary ($l_{\text{x-Bin}}$) are measured with respect to this star.

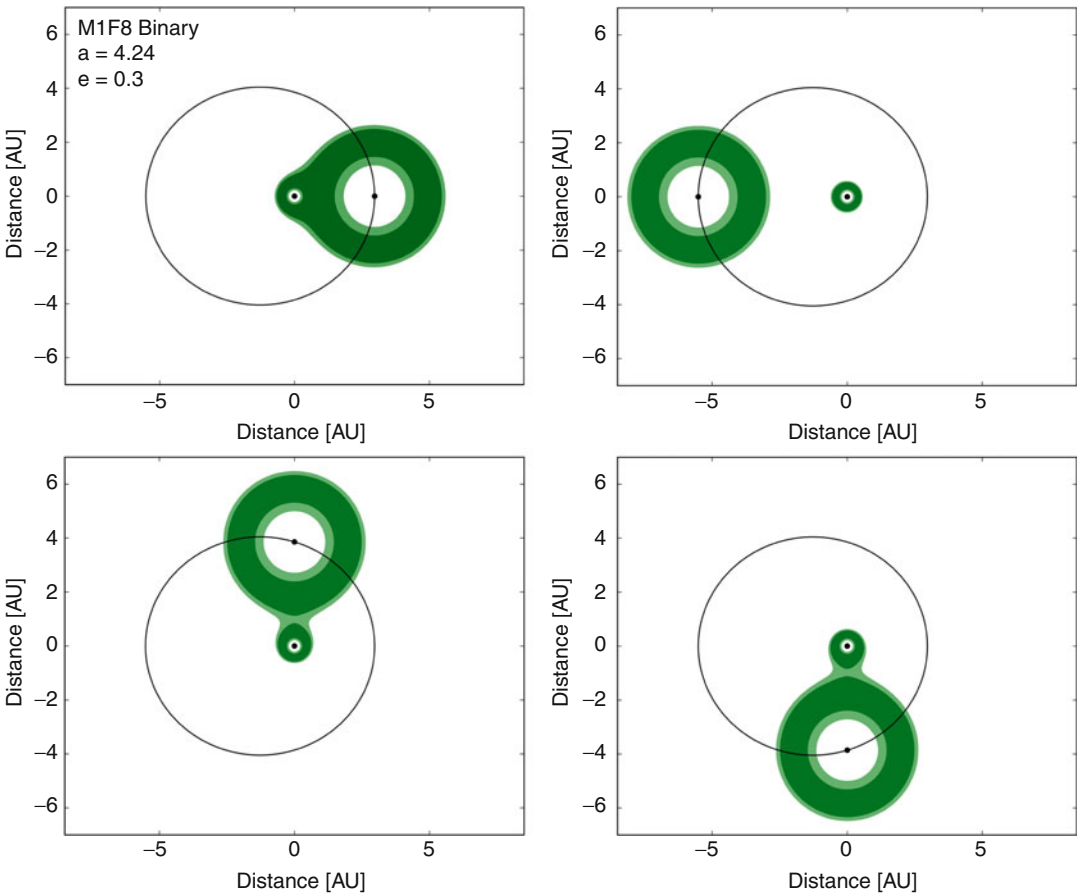
The functional form of the spectral weight factor $W_i(f, T_i)$ varies according to the models of the Sun's HZ. Kaltenegger and Haghighipour (2013) have developed a detailed methodology for calculating this quantity. Mueller and Haghighipour (2014) have utilized that methodology and created a website with a user interface where one can input the physical and orbital parameters of the binary, and the website generates a snapshot of the circumprimary HZ corresponding to those orbital elements. This website can be found at <http://astro.twam.info/hz/>

As implied by the above equation for calculating the HZ, the inner and outer boundaries of the HZ vary as the stars of the binary rotate around their center of mass. It is important to note that in reality the habitability of an Earth-like planet in a circumprimary HZ is independent of the fluctuations of the boundaries of the HZ. In this case, the determining factor is the averaged flux received by the planet in one orbit of the binary. During this time, the buffering effect of clouds should compensate for the effects of the temporary

Habitable Zone in Binary Stars Systems,

Fig. 1 Boundaries of the narrow (*dark green*) and empirical (*light green*) HZs in an M2-M2 (*top*), F0-F0 (*middle top*), F8-M1 (*middle bottom*), and M1-F8 (*bottom*) S-type binary star systems. Note that the primary is the star at (0,0). (Figure from Kaltenegger and Haghighipour (2013))





Habitable Zone in Binary Stars Systems, Fig. 2 Boundaries of the narrow (*dark green*) and empirical (*light green*) HZs in an M1-F8 binary. Note that the primary is the M1 star at (0,0). The panels show the effect

of the F8 star on the extent of the HZ around the M1 primary while orbiting the primary starting from the *top left panel* when the secondary is at the binary periastron. (Figure from Kaltenegger and Haghighipour (2013))

displacements of the HZ and allow the planet to maintain a surface temperature conducive to liquid water. Figures 1 and 2 show snapshots of the HZs around stars of an FF, MM, and FM binary system.

Habitable Zone in Multi-star Systems

Nader Haghighipour
 Institute for Astronomy, University of Hawaii-
 Manoa, Honolulu, HI, USA

References and Further Reading

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 Kaltenegger L, Haghighipour N (2013) *Astrophys J* 777:165
 Mueller T, Haghighipour N (2014) *Astrophys J* 782, article id. 26

Definition

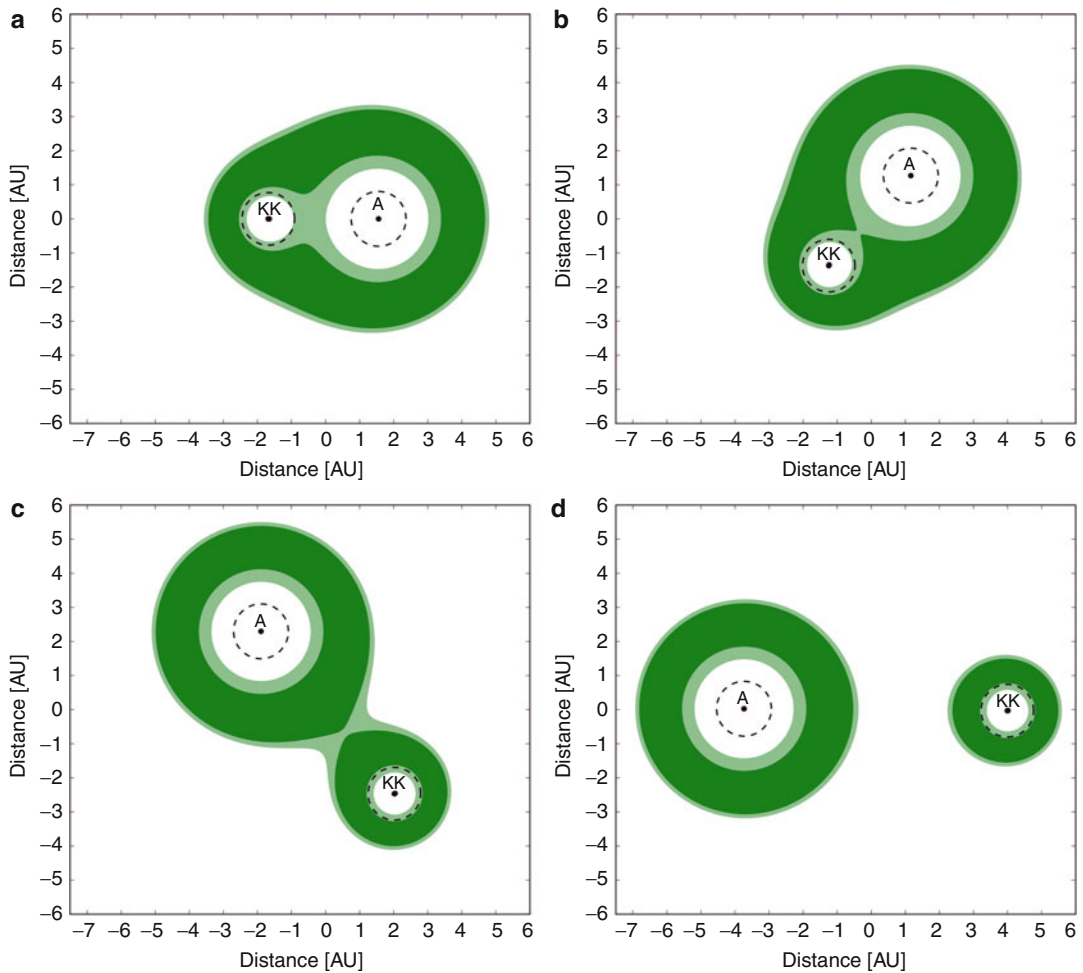
In a multiple star system, a planet may in principle exist in an orbit around one or more stars. Similarly, the habitable zone (HZ) of the system may

be an annulus around one or more than one of its stars, where an Earth-like planet (with similar atmospheric composition to that of Earth) with a sufficient amount of water can permanently maintain liquid water on its solid surface.

Overview

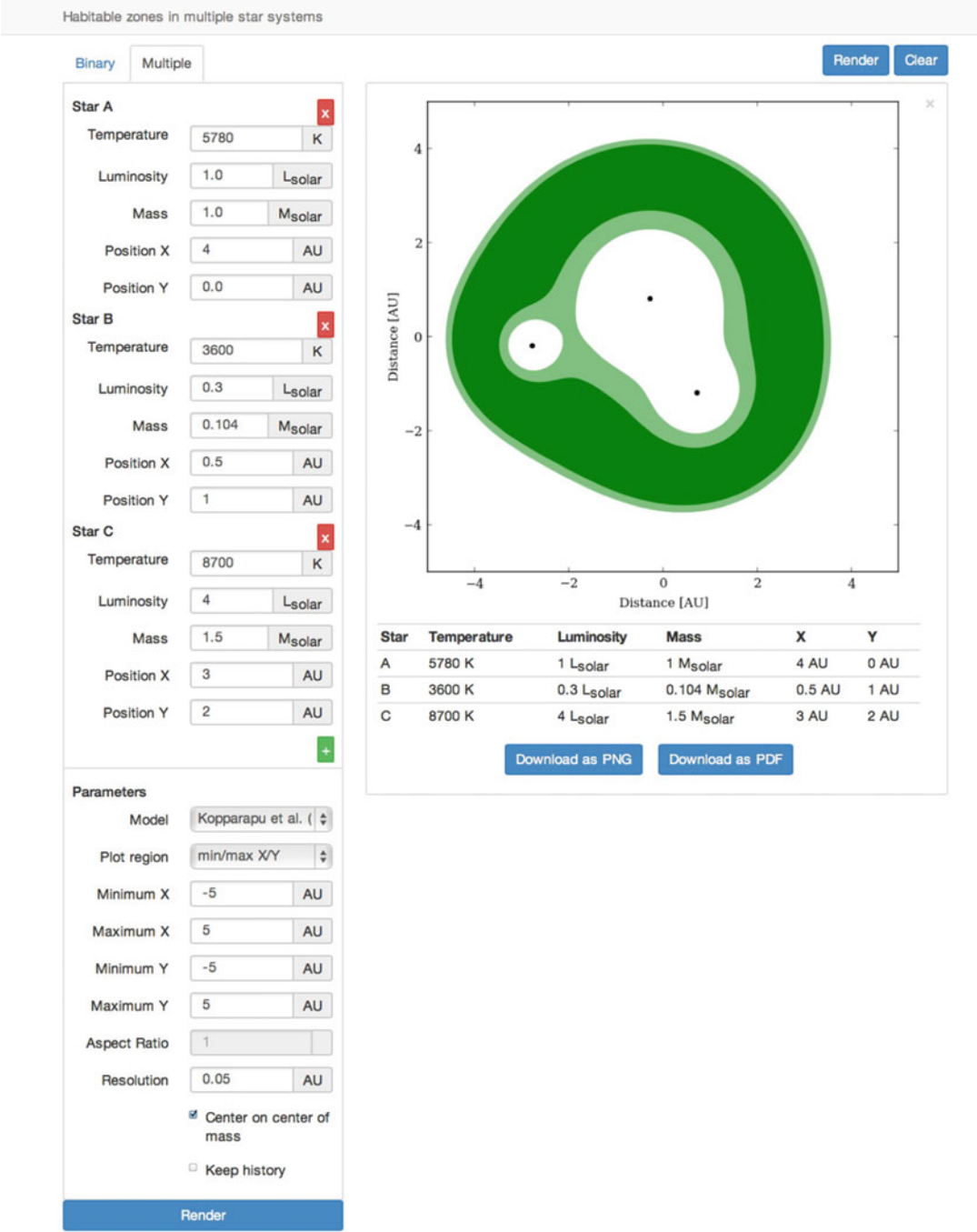
To calculate the boundaries of the habitable zone (HZ) in a multiple star system, it is assumed that the HZ is a region where an Earth-like planet (with

similar atmospheric composition as that of Earth) and a sufficient amount of water can permanently maintain liquid water on its solid surface. The locations of the boundaries of the HZ, and therefore the capability of the planet in maintaining conditions for habitability, depend on the total flux received at the top of its atmosphere. Since the atmosphere converts stellar insolation to surface temperature, the interaction of planet atmosphere with the stellar radiation plays an important role in considering whether a planet can maintain liquid water on its surface and allow for detectable



Habitable Zone in Multi-star Systems, Fig. 1 Time evolution of the HZ of the A-KK triplet in the KIC 4150611 system when the orbit of the A star has a semi-major axis of 5.48 AU and an eccentricity of 0.412. *Dark green* corresponds to conservative HZ and *light green* denotes extended HZ. From *top* to *bottom*, the panels

correspond to the A star being at 0, 19, 86, and 180° with respect to the *horizontal* line passing through zero on the vertical axis. The *dashed circles* correspond to the outer boundary of the stability of planetary orbits. An animation of the HZ of this system can be found at <http://astro.twam.info/hz-multi> (Mueller and Haghighipour 2014)



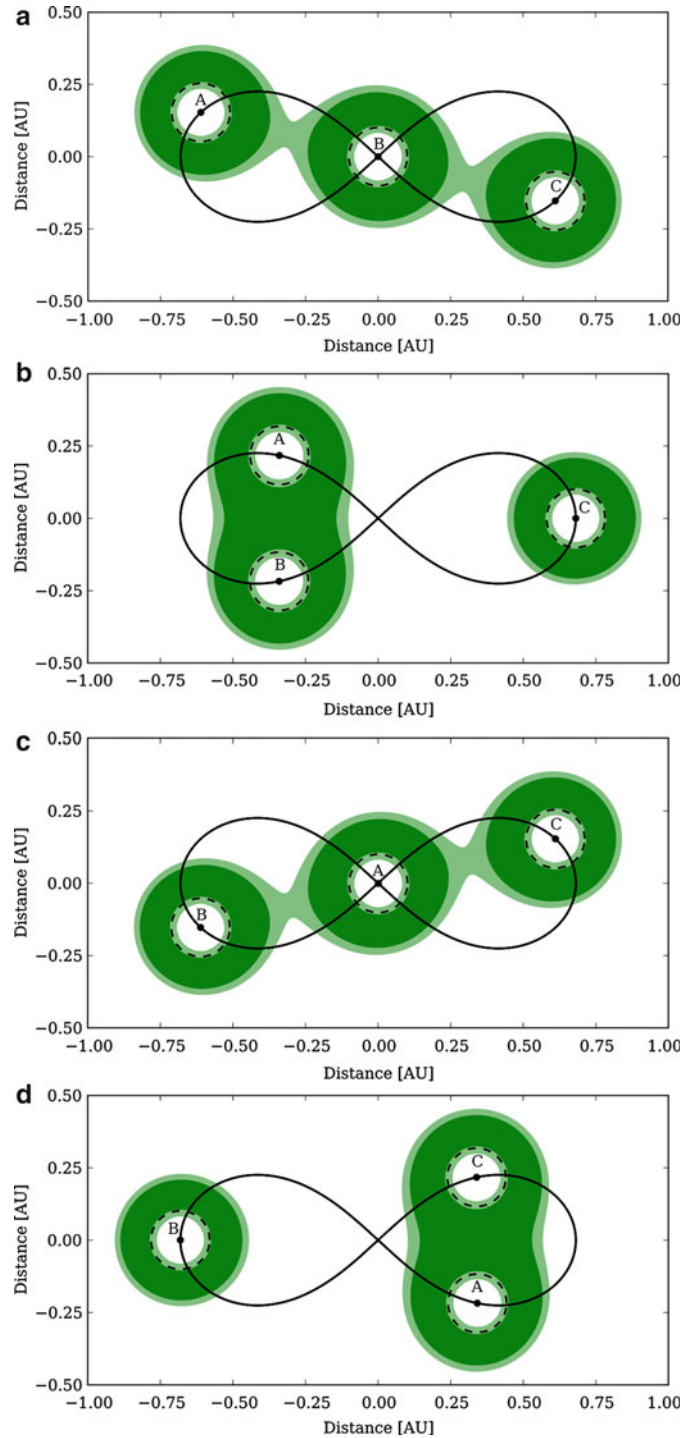
Habitable Zone in Multi-star Systems, Fig. 2 Screenshot of the interactive website <http://astro.twam.info/hz> for calculating the HZ of binary and multiple star systems (Mueller and Haghighipour 2014)

habitable conditions. This interaction strongly depends on the stellar spectral energy distribution (SED), implying that stars with different energy distributions will contribute differently to the

absolute incident flux at the top of the planet's atmosphere. To determine the contribution of a star taking into account its SED, it is necessary to define a *spectral weight factor* $W_i(f, T_i)$,

Habitable Zone in Multi-star Systems, Fig. 3

HZ of a system of three 0.25 solar mass M stars in a figure-eight orbit. From the *top to bottom*, the figures show the evolution of the HZ of the system for one complete revolution around its center of mass. The *dashed circles* show the boundaries of the regions of planetary stability around each star (~ 0.101 AU). As shown here, Earth-like planets can have stable orbits in a small region in the empirical HZ around each star. An animation of the HZ of this system can be found at <http://astro.twam.info/hz-multi> (Mueller and Haghighipour 2014)



where i denotes the i th star, T_i is the star's effective temperature, and f represents the atmosphere's cloud fraction. The contribution of each star of the system to the total flux at the top of the planet's atmosphere can be therefore written as

$$W_i(f, T_i)F_i(f, T_i).$$

Here $F_i = L_i/d_i^2$ denotes the stellar flux where L_i is the luminosity of the i th star of the system and d_i is the distance from star i to the planet. The total flux received by the planet is therefore given by

$$F_{\text{total}} = \sum_{i=1}^N W_i(T_i) \frac{L_i}{d_i^2}.$$

Defining HZ as a region where the total flux received by an Earth-like planet at the top of its atmosphere is equal to that of Earth received from the Sun, the boundaries of a multi-star HZ can be calculated from

$$\sum_{i=1}^N W_i(T_i) \frac{L_i}{d_i^2} = \frac{L_{\text{Sun}}}{l_{x-\text{Sun}}^2}.$$

where $x = (\text{In}, \text{Out})$, and $l_{x-\text{Sun}}$ denotes the boundaries of the Sun's HZ. Any point in the HZ of the system will satisfy the condition

$$\frac{L_{\text{Sun}}}{l_{\text{In-Sun}}^2} \leq \sum_{i=1}^N W_i(T_i) \frac{L_i}{d_i^2} \leq \frac{L_{\text{Sun}}}{l_{\text{Out-Sun}}^2},$$

In deriving this equation, it is assumed that the center of mass of the system is at the center of the coordinate system (Mueller and Haghighipour 2014). Figure 1 shows snapshots of the HZ of the triple star system KIC 4150611 from *Kepler* Input Catalog.

The functional form of the spectral weight factor $W_i(f, T_i)$ varies according to the models of the Sun's HZ. Haghighipour and Kaltenegger (2013) have developed a detailed methodology for calculating this quantity. Mueller and Haghighipour (2014) have utilized that methodology and created a website with a user interface where one can input the physical and orbital parameters of the binary, and the website generates a snapshot of the circumbinary HZ corresponding to those orbital elements. This

website can be found at <http://astro.twam.info/hz/>. Figure 2 shows a screenshot of this website.

As implied by the above equation for calculating the HZ, the inner and outer boundaries of the HZ vary as the stars rotate around their center of mass. However, it is important to note that in reality the habitability of an Earth-like planet is independent of the fluctuations of the boundaries of the HZ. In this case, the determining factor is the averaged flux received by the planet in one orbit. During this time, the buffering effect of clouds should compensate for the effects of the temporary displacements of the HZ and allow the planet to maintain a surface temperature conducive to liquid water. Figure 3 shows the HZ of an interesting triple star system in the famous figure-eight orbit (Mueller and Haghighipour 2014).

Cross-References

- [Habitable Zone](#)
- [Habitable Zone Around Binary Star Systems](#)
- [Habitable Zone in Binary Stars Systems](#)
- [Planets in Binary Star Systems](#)

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- Mueller T, Haghighipour N (2014) Calculating the habitable zones of multiple star systems with a new interactive website. *Astrophys J* 782:26

Habitable Zone, Effect of Tidal Locking

Lisa Kaltenegger

Cornell University, Ithaca, NY, USA

Keywords

Biomarkers · Habitability · Habitable zone · M stars · Resonance · Tidal locking

Definition

Tidal locking is a state of dynamical equilibrium between a planet's spin and orbital angular momentum. Tidally locked planets on circular orbits may become synchronous rotators, presenting the same solid-body hemisphere to the star.

Overview

Tidally locked planets on circular orbits may become synchronous rotators, presenting the same solid-body hemisphere to the star. If the planet's orbit is eccentric, either due to a primordial condition or maintained by interactions with other planets, then the rotation period will be less than the orbital period and the planet will not synchronously rotate. Planets interior to the tidal lock radius may also become trapped in spin-orbit resonances, where they complete an integer ratio of rotations on their axis to orbits around their star. For example, Mercury is within the Sun's tidal lock radius in a 3:2 spin-orbit resonance, completing three rotations on its axis every two revolutions (orbits) around the Sun. For an M dwarf (less massive and cooler than the Sun), the ► [Habitable Zone](#) is so close to the star that the planets are likely to become tidally locked within a relatively short time after they form (Dole 1964; Kasting et al. 1993), but several resonances are possible. Only a planet in a 1:1 resonance receives starlight on only one hemisphere. Detailed models have shown that this does not prevent habitability for planets with even modestly dense atmospheres (Haberle et al. 1996; Joshi et al. 1997; Joshi 2003). Even a tidally locked 'Earth' could remain habitable, provided that atmospheric cycles transport sufficient heat from the dayside to the nightside.

Cross-References

- [Biomarkers, Spectral](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)
- [Habitability of the Solar System](#)
- [Spectral Type](#)

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Habitat

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Synonyms

[Ecosystem](#)

Definition

Habitat is the location in an ► [environment](#) which can be colonized by a biological population. In nature, organisms live in association with other organisms in assemblages called populations. The components and number of individuals in a habitat are governed by the resources and conditions that exist in the habitat. Habitats differ markedly in their characteristics, and a habitat that is favorable for the development of one organism may actually be harmful for another organism. From an astrobiological point of view, habitat is deeply related to the habitability concept which refers to the conditions that can support life in an adverse surrounding.

Cross-References

- [Biotope](#)
- [Environment](#)

HAC

- [Hydrogenated Amorphous Carbon](#)

Hadean

Simon Wilde
School of Earth & Planetary Sciences, Curtin
University, Perth, WA, Australia

Keywords

Precambrian · Jack Hills (Yilgarn Craton ·
Western Australia) · Zircon

Synonyms

[Early Earth](#); [Priscoan](#)

Definition

The earliest eon of geological time, extending from accretion of the Earth (4.567 Ga) to the formation of the earliest known rocks. The oldest rocks currently identified are components of the Acasta gneisses in the Northwest Territories of Canada (4.03 Ga). This date was determined as marking the lower limit of the Hadean by the Precambrian Subcommission on Stratigraphy in 2012. The ages have been rounded to ~4600 Ma and 4000 Ma for the commencement and termination of the Hadean, respectively, as shown on the International Chronostratigraphic Chart.

Overview

The term Hadean was coined in 1972 by Preston Cloud to designate that period of geological time

prior to formation of the earliest known rocks. It was derived from Greek mythology where “ Ἅδης = Hades” first referred to the God of the Underworld and later to the Underworld itself. In geological usage, it is commonly equated with “Hell,” based on the perception that the Earth was extremely hot and turbulent at that time. “Hadean” was an informal term for many years, partly because of the diversity of views as to its precise duration and to more recent work that questioned whether much of this time period on Earth was really “hell like”. Its starting point was variously taken as the formation of the planetary nebula, the onset of accretion, or the time from when the Earth was largely solid. Its termination was placed at 3.8/3.9 Ga by some workers, the age of the most ancient rocks in Greenland. However, more recent usage placed it at 4.0 Ga, based on the age of the world’s oldest gneisses at Acasta, Canada (Bowring and Housh 1995; Bowring and Williams 1999). Identification of zircon crystals up to 4.4 Ga, particularly from the Jack Hills in Western Australia, has led to the view that the Earth had cooled down sufficiently by ~4.3 Ga to support oceans and stable continents (Wilde et al. 2001; Valley et al. 2002), based on the study of oxygen and lithium isotopes in pristine zircon domains. This raised the question as to whether the term “Hadean” should be restricted to the period of time before the formation of oceans and continents, when the surface of the Earth was too hot and unstable to allow liquid water to form and rocks to survive. Furthermore, some workers who did not support the use of “Hadean” preferred to extend the Eoarchean back to incorporate this period of geological time. Further complicating the issue was that another term had been introduced into the literature for essentially the same period of time: “Priscoan”, coined by Brian Harland in 1989 (Harland et al. 1990), although few published articles have used this name. However, in 2012, following extensive discussion by the Precambrian Subcommission, “Hadean” was officially ratified by the International Commission on Stratigraphy. It was accepted that it commenced with the onset of formation of the Earth/Solar System and that it terminated with the oldest known rocks preserved on Earth.

In the past decade, no older rocks have been identified and there has been no requirement to consider modifying the Hadean boundaries. However, the number of localities where Hadean zircon has been identified has increased and they have now been found in Africa, Asia, Australasia, North America, and South America. Although Eoarchean rocks are present in Antarctica and Europe, unequivocal Hadean zircon ages have yet to be determined.

Planetary-scale geological processes took place during the Hadean eon, from the accretion of the Earth to its differentiation into a metallic core, a silicate mantle, and a primordial crust. However, the effect of any Late Heavy Bombardment (Cohen et al. 2000) on Earth has not been established and there is no record of it in either the Hadean zircon or the Eoarchean rocks that overlap with the proposed timing of such an event. Continental crust developed earlier than previously thought, based on geological information retained by the Jack Hills zircons. Several authors speculate that plate tectonics could also have started during the Hadean, yet geological evidence for this is still controversial. A detailed account of these processes is reported in *Earth, Formation and Early Evolution*.

Cross-References

- [Acasta Gneiss](#)
- [Canadian Precambrian Shield](#)
- [Chronological History of Life on Earth](#)
- [Earth, Formation, and Early Evolution](#)
- [Geological Timescale](#)
- [Jack Hills \(Yilgarn Craton, Western Australia\)](#)
- [Late Veneer](#)
- [Zircon](#)

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Hadean Mantle

Maud Boyet
Université Blaise Pascal, Clermont-Ferrand,
France

Keywords

Isotope systematics · Early Earth · Magma ocean · Mantle dynamics · Moon-forming impact

Definition

The structure and the composition of the Hadean mantle are difficult to constrain due to the sparse geological record from this period. Isotope systematics show that the silicate Earth experienced global differentiation events during its infancy.

Strong chemical fractionations and an extensive loss of volatile elements are related to several magma ocean stages, the last one following the giant impact forming the Moon. Although during the Hadean, the mantle must have been hotter and the convection more vigorous, early chemical heterogeneities have not been erased until the Archean, questioning the regime of the Hadean mantle convection.

Overview

The Hadean eon corresponds to the earliest period of Earth's history starting from the beginning of solar system accretion (4.567 Ga, Connelly et al. 2012) to the oldest preserved rocks dated by U-Pb systematics (4.03 Ga, Acasta Gneiss, Bowring and Williams 1999). Geological records from this period that have been preserved over Earth's history are scarce and mostly consist of detrital zircons (Wilde et al. 2001). Rock samples directly derived from the mantle are more difficult to date because they do not contain zircon which is the mineral that is the most robust to metamorphism and alteration. A crustal section of Hadean mafic crust has been discovered in Northern Canada (Nuvvuagittuq Greenstone Belt) with the oldest units dated at 4.1 and 4.3 Ga (O'Neil et al. 2012). The 4.3 Ga age is still debated (Roth et al. 2013), but these findings suggest that the lower limit of the Hadean eon may have to be redefined. Indirect information on the chemical composition of the mantle and the chronology of the silicate differentiation is provided by radioactive systematics that record parent-daughter chemical fractionation. Noble gas systematics traces the mantle degassing, and the xenon isotope signature is consistent with extensive loss of volatile elements within the first 100 Ma of the Earth's history (Allègre et al. 1983; Yokochi and Marty 2005; Mukhopadhyay 2012). ^{142}Nd anomalies measured in Archean samples and the large Hf isotope variations measured in Hadean zircons and Archean rocks are undisputable evidences for early silicate differentiation events during the first 100–150 Ma of the Earth's history (Blichert-Toft et al. 1999; Boyet et al. 2003; Caro et al.

2003; Kemp et al. 2010; Rizo et al. 2011). These isotope signatures are explained by multiple generations of magma oceans during the accretion. The last important event of melting would be a direct consequence of the Moon-forming giant impact dated between 140 and 200 Ma (Maurice et al. 2020; Sio et al. 2020). The impact did not induce complete melting and homogenization of the whole terrestrial mantle, as isotopic signatures of pre-impact heterogeneity are preserved (Lock et al. 2020). Although during the Hadean, the mantle must have been hotter and the convection more vigorous, early chemical heterogeneities have been preserved from mantle mixing until the Archean. These results question the style of the Hadean mantle convection relative to its modern convection regime driven by plate tectonics.

Cross-References

- [Acasta Gneiss](#)
- [Accretion](#)
- [Bulk Silicate Earth](#)
- [Earth, Formation, and Early Evolution](#)
- [Giant Impact](#)
- [Mantle](#)
- [Porpoise Cove Greenstone Belt](#)

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surface) and equatorward flow near the surface. The Hadley circulation cells, one on each hemisphere, cover about half of the Earth’s surface area. The Hadley cells carry heat and moisture from the tropics to the northern and southern mid-latitudes. Hadley cells are also present on other terrestrial bodies like Mars, Titan, or Venus. On a slowly rotating planet like Venus, the Hadley circulation can extend almost to the poles. Circulation cells like the Hadley cells probably exist also on other rocky exoplanets and influence their climate substantially.

Cross-References

- [Atmosphere, Structure](#)
- [Scale Height](#)

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Haeckel’s Conception of Origins of Life

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes, Centre François Viète d’Histoire des Sciences et des Techniques EA 1161, Nantes, France

Hadley Cells

Lisa Kaltenegger

Cornell University, Ithaca, NY, USA

Definition

The Hadley cell on the Earth is a circulation pattern that dominates the tropical atmosphere, with rising motion near the equator, a compensatory sinking motion in the subtropics, poleward flow in the upper troposphere (7–20 km above the

History

Ernst Haeckel (1834–1919) was a German zoologist, great supporter of the evolution theory. He developed his own theory of evolution founded on Darwinism and also on some Lamarckian principles. His theoretical thought was closely connected to his monistic philosophical view.

Regarding the origin of life, he proposed a scenario of ► [abiogenesis](#) based on protoplasmic theory and claimed that evolution of matter could lead to a form of albuminoidal protoplasm. He called *Monera* the primitive entities coming before cells.

Cross-References

- [Abiogenesis](#)
- [Darwin's Conception of the Origins of Life](#)
- [Huxley's Conception on Origins of Life](#)
- [Protoplasmic Theory of Life](#)

Haldane's Conception of Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Keywords

Prebiotic soup

History

John Burdon Sanderson Haldane (1892–1964) was one of the famous British biochemists and geneticists of the first part of the twentieth century. He notably participated to the reflection about evolution questions, and he was one of the main actors on the synthesis of that issues.

During his career, he spoke several times about the problem of the origins of life; however, he never worked as specialist of the topic. He published a very important text on this matter in 1929, in *The Rationalist Annual*. This text is often presented as linked to the text of Aleksandr Ivanovich Oparin (1894–1980) (the Oparin's paper on origins of life was firstly published in Russian in 1924), and it is often said to be Oparin-Haldane's theory. However, these two papers were independently published.

Haldane gave a complete scenario describing primitive conditions on earth and steps of chemical evolution from mineral to organic molecules. The main reactions occurred in the primitive sea, sort of complex chemical solution, named *hot dilute soup* by Haldane.

His text began with a historical narrative about spontaneous generation and by an analysis of the nature of the bacteriophage, which he considered as “a step beyond the enzyme on the road of life, but it is perhaps an exaggeration to call it fully alive” (p. 106).

He suggested a complete scenario beginning with the primitive atmosphere contained little or no oxygen, but carbon dioxide, and claimed that ammonia could be formed by the action of water on nitride contained in the crust. Moreover, in the lack of ozone, ultraviolet rays could be chemically active. One of his most important suggestion is that “when ultraviolet light acts on a mixture of water, carbon dioxide, and ammonia, a vast variety of organic substances are made, including sugars and apparently some of the materials from which proteins are built.” He claimed that in the current nature, such a mixture would be eaten by microorganisms, but in the primitive conditions, in this “hot dilute soup,” big molecules could be synthesized. For him, “the first living or half-living thing” was capable of reproduction; in other words, they were the first genes (p. 107). Then he claimed that “when the whole sea was a vast chemical laboratory,” the condition for the formation of oily films and then primitive cells must have been favorable.

Haldane's proposal, with Oparin's one, revealed the evolution of ideas on the origin of life at the beginning of the twentieth century. Haldane, according to current biology, used his biochemist and geneticist view to describe the steps of a chemical process producing the most simple living beings.

Cross-References

- [Miller, Stanley](#)
- [Oparin's Conception of Origins of Life](#)
- [Urey's Conception of Origins of Life](#)

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Half-Life

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Synonyms

[Period \(half-life period\)](#)

Definition

The half-life $T_{1/2}$ is the time required to halve the number of atoms of a particular radioactive nuclide. It relates to the decay constant λ through $T_{1/2} = \ln 2/\lambda \approx 0.69/\lambda$.

Cross-References

- [Decay Constant](#)
- [Earth, Age of](#)
- [Geochronology](#)
- [Radioactivity](#)

Half-Major Axis

- [Semimajor Axis](#)

Halley, Edmond

Fernando B. Figueiredo

CITEUC, University of Coimbra, Coimbra, Portugal

History

Edmund Halley (1656–1742) was a multifaceted English scientist, fellow of the Royal Society (1678) and Royal Astronomer (1720), which made significant contributions on mathematics, astronomy, navigation and geophysics. Halley's name will remain in history largely due to his work of 1705 on the motion of comets. The

similarity that he founded between the orbital elements for the comets seen in 1531, 1607, and 1682 led him to suggest that this comet, that same comet that would one day bear his name, would return in December 1758. In fact the comet was observed on 25 December 1758 (very slightly later than Halley expected).

Halley's work in astronomy is not restricted to the movement of comets. He made important works in stellar astronomy, having been the first to accurately cataloging the south sky hemisphere. And he was also the first to propose using transits of Mercury and Venus to determine the Earth-Sun distance and therefore the scale of the solar system. He was very interested also on the solution of the determination of longitude at sea. In geophysics Halley published charts of the variation of the compass of the north Atlantic ocean, giving the first charts with lines of equal magnetic declination plotted.

Among all his scientific contribution there one that worth mentioning, his commitment and enthusiasm in the publication of one of the fundamental works of modern science, the *Philosophiæ Naturalis Principia Mathematica* (1687), of his friend Isaac Newton (1643–1727).

Cross-References

- [Comet](#)

Halogen

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

A halogen is a chemical element from Group 17 (in the IUPAC convention) (formerly VII,

VIIA) of the periodic table, composed of fluorine, chlorine, bromine, iodine, and astatine. The man-made element 117 is predicted to be a halogen. The Swedish chemist Berzelius coined the term “halogen” from the Greek *hals*, “salt,” and *gen*, meaning “come to be” – for an element that produces a salt with a metal. The halogens are the only periodic table group that contains elements in all three familiar states of matter at standard temperature and pressure. At room temperature and pressure, fluorine and chlorine are gases, bromine is a liquid, and iodine and astatine are solids. The halogens show several trends as the atomic number increases, including decreasing electronegativity and reactivity and increasing melting and boiling points.

In their elemental form, the halogens exist as diatomic molecules, but these are relatively unstable. Due to their high reactivity and electron affinity, halogens are usually found in nature as molecular compounds or as ions. Halogen anions, known as halides (e.g., Cl^- , Br^- , and F^-), and oxoanions such as iodate (IO_3^-) are commonly found in many minerals and are major components of seawater. Halogenated organic compounds are also produced by living organisms. The halogens all form binary compounds with hydrogen, for example, HF, HCl, HBr, and HI, which are strong Brønsted-Lowry acids.

Halophile

Josefa Anton

Department of Physiology, Genetics and Microbiology, University of Alicante, Alicante, Spain

Keywords

Compatible solute · Hypersaline environment

Synonyms

Salt-loving organisms

Definition

Halophile is an organism that needs high salt concentrations for growth. A widely used definition is that of Kushner and Kamekura (1988) who classify organisms depending on the salt concentration needed for optimum growth. Thus, non-halophiles grow best in media containing less than 0.2 M salts, while halophiles grow best in media containing from 0.2 to 5.2 M dissolved salts. Halophiles can be further divided into slightly halophilic (optimum growth between 0.2 and 0.5 M salt), moderately halophilic (0.5–2.5 M salt), and extremely halophilic (above 2.5 M salt).

Overview

All three domains of life include halophilic microorganisms. Archaeal halophiles, all belonging to the *Euryarchaeota*, can be found among the methanogens and the members of the order *Halobacteriales* that only includes extreme halophiles. Within this order, there is a single family (the *Halobacteriaceae*) that includes 28 genera, some of them of alkaliphilic organisms. The most halophilic organism as well as the ones most frequently found in hypersaline environments is included within this family. Bacterial phyla such as *Cyanobacteria*, *Proteobacteria*, *Firmicutes*, *Actinobacteria*, *Spirochaetes*, and *Bacteroidetes* are also halophiles (Oren 2008). Finally, some eukaryotic organisms – plants, fungi, ciliates, and flagellates – are halophilic. The unicellular green alga *Dunaliella salina* is the most halophilic known eukaryote. Normally, every halophile has a relatively narrow range of salt concentration that allows growth. The proteobacterium *Halomonas* spp. is an exception, being able to grow over a very wide range of salt concentration.

Halophiles are usually found in phylogenetic trees that also include non-halophilic relatives, but three large phylogenetically coherent groups comprise only halophiles. Such is the case of the aerobic ► *Archaea* from the order *Halobacteriales* (also known as haloarchaea), the anaerobic fermentative ► *bacteria* from the order *Halanaerobiales*, and the *Gammaproteobacteria* from the family *Halomonadaceae*.

A group of phylogenetically related halophiles within the *Bacteroidetes* is recovered from hypersaline environments all over the world.

Halophilic microorganisms use two different strategies to cope with the osmotic stress stemming from the high ionic concentration of their environments. *Archaea* of the order *Halobacteriales*, anaerobic *Bacteria* of the order *Haloanaerobiales*, and some members of the *Bacteroidetes* (i.e., *Salinibacter ruber*) accumulate high concentrations of inorganic ions (mostly potassium) in the cytoplasm. These three groups include the most extreme halophiles. The so-called “salt-in” strategy requires an adaptation of the whole intracellular machinery to work in highly saline environments. All other halophilic organisms keep their osmotic balance by producing and/or accumulating “compatible” low-molecular-weight organic solutes (see “compatible solutes”) whose concentration is regulated according to the salinity of the environment.

Habitats for halophilic microorganisms include salt marshes, salt lakes that may be alkaline (Mono Lake, Wadi Natrun), or near neutral (e.g., the Dead Sea, Great Salt Lake, Tuz Lake, Chaka Lake, and some cold hypersaline lakes in the Antarctica), man-made salterns either coastal or inland, hypersaline deep sea masses, salted food, animal hides, saline soils, dessert salt crusts, and subterranean brines.

These environments have been classified depending on whether they originated through the evaporation of seawater or not, thus talassohaline (e.g., solar salterns) and athalassoaline (e.g., the Dead Sea).

Hypersaline environments are extreme habitats and very high salt is not the only condition restricting biodiversity in these systems. They can also have high pH or, depending on their geographical location, high or low temperatures. In addition, some hypersaline environments have very low nutrient availability or high concentrations of toxic compounds such as heavy metals. Accordingly, halophilic organisms may display additional extremophilisms. Alkaliphilic, psychrotrophic, and thermophilic halophiles have been described (for instance,

the thermophilic bacterium *Halothermothrix orenii*, the archaeon *Halorubrum lacusprofundi*, and members of the archaeal genus *Natronobacterium*).

Moderately halophilic bacteria inhabit hypersaline habitats with salinities around 10%. Aquatic environments with higher, near-saturation salt concentrations may be densely populated with extremely halophilic microorganisms, and this leads to bright red, orange, or purple colorations due to the pigments of these organisms. In some multipond solar salterns, microbial diversity is found to decrease at higher salinities. However, the number of microorganisms increases with salinity, reaching very high densities of up to 10^8 cells/ml at near-saturation concentrations. Most of these cells correspond to organisms of the *Archaea* domain although in some environments *Bacteria* can account for up to 30% of the total counts.

Hypersaline environments all over the world contain *Archaea* such as the square haloarchaeon *Haloquadratum walsbyi* and related populations, as well as *Halorubrum* representatives. In the *Bacteria* domain, the *Bacteroidetes* *Salinibacter* spp. and related phylotypes are frequently found in hypersaline settings close to saturation, although in some cases *Proteobacteria* constitute the bulk of extremely halophilic *Bacteria* detected in these systems. At near-saturation concentrations, both cell number and diversity of ▶ Eukarya decrease dramatically, leaving only *Dunaliella* and some extremely halophilic fungi in low numbers. At salinities above 10–15%, large organisms disappear, with the exception of the brine shrimp *Artemia salina* and the larvae of the fly *Ephydra*. Hypersaline environments harbor the highest numbers of viruses reported so far for aquatic systems.

Most dissimilatory prokaryotic metabolisms can function in hypersaline environments although a few of them have never been detected at salt concentrations above 10% (e.g., proton-reducing acetogens, methanogenesis from acetate, or autotrophic nitrite oxidations). For a detailed discussion of the energetics of halophilism, see Oren (1999).

In addition to their evolutive and ecological interest, halophilic microorganisms have some biotechnological applications. Haloarchaea produce bacteriorhodopsin that can be used as photo-active material in optical devices as well as polyhydroxyalcanoates, exopolysaccharides, and halocins. Moderately halophilic bacteria are used for the commercial production of their compatible solutes ectoines and hydroxyectoines, which find application in the cosmetic industry or the biological treatment of saline industrial waste effluents. Halophilic eukaryotes such as *Dunaliella* are used as a natural source of beta-carotene in cosmetics and some food while the shrimp *Artemia salina* can be used in aquaculture.

Cross-References

- ▶ [Alkaliphile](#)
- ▶ [Archaea](#)
- ▶ [Bacteria](#)
- ▶ [Compatible Solute](#)
- ▶ [Eukarya](#)
- ▶ [Euryarchaeota](#)
- ▶ [Extreme Environment](#)
- ▶ [Extremophiles](#)
- ▶ [Halotolerance](#)
- ▶ [Osmolite](#)

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Halotolerance

Josefa Anton

Department of Physiology, Genetics and Microbiology, University of Alicante, Alicante, Spain

Keywords

Compatible solutes · Ionic stress · Salt

Synonyms

[Salt tolerance](#)

H

Definition

Halotolerance is tolerance to ionic stress or the ability of an organism to grow at salt concentrations higher than those required for growth. Halotolerant organisms are able to survive at high salt concentrations but do not require these conditions for growth.

Overview

Halotolerance is a relative term that refers to the ability to survive or thrive at salt concentrations higher than those necessary for growth. A microorganism is considered extremely halotolerant if its growth range extends above 2.5 M salt. A 0.9% NaCl would be considered an isotonic solution by most nonmarine and non-halophilic organisms. In nature, halotolerant organisms can be found in settings such as saline waters and soils that are inhabited by autochthonous halophilic microbiota or even in association with animals. Such is the case of microbiota such as *Staphylococcus* species that live on human skin. Because of their exposure to the salts in sweat, they are very halotolerant and they can also grow well at NaCl concentrations as high as 15%. However, they can also grow in the absence

of salt and are thus said to be halotolerant and not halophile. This property is exploited in the design of selective growth media. Halotolerant organisms have developed metabolic processes, such as the accumulation of compatible solutes that allow them to compensate the osmotic pressure and continue to live in hyperosmotic environments.

Salt tolerance can vary depending on nutritional or environmental factors such as pH, temperature, and redox potential. Since high salt has been traditionally used as a way of preserving food, halotolerant microorganisms can be a cause of spoilage of salt-preserved food.

The three domains of life include many examples of halotolerant microorganisms such as the ► [bacteria](#) of the genera *Alteromonas*, *Lactobacillus*, *Bacillus*, *Myxococcus*, and *Pediococcus*, as well as many cyanobacteria, some methanogenic and thermophilic archaea, and halotolerant fungi such as *Debaromyces*, *Hansenula*, *Cladosporium*, and *Saccharomyces*.

Cross-References

- [Adaptation](#)
- [Bacteria](#)
- [Compatible Solute](#)
- [Halophile](#)
- [Osmolite](#)

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Handedness

- [Chirality](#)

Haphazardness

- [Chance and Randomness](#)

Hapten

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Partial antigen](#)

Definition

A hapten is a small molecule that can elicit an immune response when attached to a larger carrier molecule such as a ► [protein](#). Neither the larger molecule nor the hapten may elicit the response by themselves.

Cross-References

- [Antibody](#)

Hard Landing

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

The term “hard landing” describes the disposition of a spacecraft on another planetary body that is

not controlled and could result in fragmentation of the hardware. A loss of control resulting in a hard landing is called a “crash”! For ► [planetary protection](#) purposes, a hard landing is assumed to result in the release of ► [encapsulated bioburden](#) as well as the spreading of the ► [exposed surface bioburden](#).

Cross-References

- [Encapsulated Bioburden](#)
- [Exposed Surface Bioburden](#)
- [Planetary Protection](#)

Hard Snowball

- [Snowball Earth](#)

HARPS

David W. Latham¹ and Nader Haghighipour²

¹Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[High accuracy radial-velocity planet searcher](#)

Definition

HARPS is a high-resolution spectrograph designed to achieve long-term stability enabling Doppler velocity measurements at the level of 1 m/s, in order to derive radial-velocity orbits for stars orbited by planets as small as the Earth. It is presently the only instrument installed on the 3.6-m telescope at the European Southern Observatory on La Silla in Chile, where it will soon be

joined by the infrared spectrograph NIRPS. The spectrograph is fed by fibers and the optics are enclosed in a vacuum tank, to eliminate the effects of changes in the index of refraction at the echelle grating due to changes in the atmospheric pressure. The temperature of the instrument is stabilized at the level of 0.001 K, which is also critical for the velocity stability. The wavelength calibration was first provided by thorium-argon hollow cathode lamps; Fabry-Perot etalons and Laser Combs were later added as calibration sources. The calibration of the spectrograph is continuously undergoing improvements. HARPS has demonstrated the potential to reach a velocity precision of perhaps 20 cm/s. HARPS and ► [HIRES](#) on Keck 1 in Hawaii are premier instruments for determining the masses of small planets. The data from these two telescopes have been used to detect several potentially habitable planets around stars GJ 667C and Gliese 581. A copy of HARPS, called HARPS-North or HARPS-N, for use in the northern hemisphere is also in function since 2012. Since 2017, ESPRESSO, a new spectrograph installed on the VLT in Paranal has been able to reach even better precisions.

Cross-References

- [Doppler Shift](#)
- [ESPRESSO](#)
- [Exoplanets, Discovery](#)
- [HIRES](#)
- [Radial-Velocity Planets](#)

Harriot (55 Cancri f)

- [55 Cancri](#)

HAT

- [HATNet](#)

HATNet

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[HAT](#); [Hungarian-made Automatic Telescope Network](#)

Definition

The Hungarian-made Automated Telescope Network (HATNet) is a wide-angle ground-based photometric survey for transiting exoplanets operated by the Smithsonian Astrophysical Observatory. Large areas of the sky are monitored robotically using seven small telescopes (11 cm in diameter) located at two different sites in Arizona (five telescopes) and Hawaii (two telescopes), looking for planets that transit their host stars. HATNet has discovered 70 transiting exoplanets, many of which are larger than Jupiter. An important exception is HAT-P-11b, which is a [hot Neptune](#) in the field of view of NASA's [Kepler mission](#). An international extension of the project to the southern hemisphere known as HATSouth became operational in 2009, with six 18-cm telescopes located at three collaborating sites (two telescopes at each site) in Chile, Australia, and Namibia. Since 2009, this survey has discovered 60 Jupiter-sized and larger extrasolar planets.

Cross References

- [Exoplanets, Discovery](#)
- [Kepler](#)
- [MEarth](#)
- [SPECULOOS](#)
- [TESS](#)
- [Transiting Planets](#)
- [TrES](#)
- [WASP](#)

Hayabusa Missions

Anny-Chantal Levasseur-Regourd
Sorbonne Univ./LATMOS, Paris, France

Keywords

[Asteroid](#) · [Sample return](#) · [Rover](#) · [Regolith](#) · [Dust particles](#) · [Rubble pile](#) · [Organics](#)

Definition

► [Hayabusa](#) (meaning peregrine falcon) space missions have been developed by JAXA to explore near-Earth asteroids and collect samples thereof.

Launched in May 2003, the first Hayabusa spacecraft begun its rendezvous with stony asteroid (25143) Itokawa in September 2005. After 2 months of observations, it collected dust samples on its surface. The return capsule departed in April 2007, landed safely in Australia in June 2010, and was transferred to the Japanese curation facility.

Launched in December 2014, Hayabusa2 spacecraft begun its rendezvous with carbonaceous asteroid (162173) [Ryugu](#) in June 2018. After observing its surface and releasing rovers, it collected samples. The spacecraft departed in November 2019 and released its return capsule in December 2020 in Australia. Preliminary curatorial work on the samples takes place in Japan.

Overview

The first Hayabusa spacecraft carried four scientific instruments, AMICA camera, NIRS spectrometer, LiDAR laser instrument, and XRS X-ray spectrometer. Besides its return capsule, it embarked navigational instruments and tested new technical developments. The total mass, including propellant for chemical propulsion and xenon for electrical propulsion was ≈ 530 kg.

This complex mission faced major issues. After the launch from Japan, it was hit by a solar flare that damaged the solar cells, reducing the electrical power and the efficiency of the ion engines. At the end of the characterization phase, Hayabusa released the MINERVA micro-lander, which escaped Itokawa gravitational pull. After having deployed its sampling horn to collect asteroidal dust and sealed it, the spacecraft attempted twice to touch down on the surface of the asteroid.

Hayabusa mission, the first one to bring back asteroidal samples on Earth, was nevertheless most successful. Asteroid Itokawa looks like a contact binary and is quite small (major axes 530 m, 290 m, 210 m). It is rather porous (density $\approx 1930 \text{ kg m}^{-3}$) and could be built from loose-packed rocks held together by gravity, after an impact on a larger parent-body. The topography is varied, with boulders on rough terrains and a featureless central area of fine dust particles forming a smooth regolith in gravitational lows. Such results are of importance when considering orbital deflection techniques, to be implemented if a similar asteroid was discovered on a collision course with the Earth.

Samples analyses have identified more than 1000 dust particles from Itokawa, with sizes mostly below 100 micrometers. They present, as ordinary chondrites, mostly minerals (olivine, pyroxene, plagioclase, troilite) and a low organics content.

Hayabusa2 spacecraft is an upgraded version of the first Hayabusa, with a mass of 610 kg. It typically carried cameras, an IR spectrometer, a LIDAR, together with instruments for navigation, and four rovers to scientifically explore the surface, rovers 1A, 1B, 2 from JAXA, as well as rover MASCOT from DLR and CNES.

This outstanding mission required elaborate studies to select appropriate landing and sampling sites on Ryugu. Mini-rovers 1A and 1B were successfully deployed in 2018 and hopped as expected on the surface. MASCOT rover (with instruments including a camera and an IR spectral microscope) was also deployed in 2018. Rover-2 could unfortunately only perform orbital gravitational measurements before crashing down into the asteroid in 2019.

Asteroid Ryugu has a round shape with an equatorial bulge, typical of a pile of loose rocks, formed by re-accumulation of rubble ejected by impact from a larger asteroid. Its size is about 865 m and it is highly porous (density $\approx 1200 \text{ kg m}^{-3}$). On its rather dark surface (geometric albedo from 0.4 to 0.8), irregularly distributed craters and fluffy boulders have been discovered, as well as color variations, possibly related to previous orbital changes. Most interestingly, Hayabusa2 has revealed significant amounts of organic molecules and hydrated minerals.

Last but not the least, samples have been successfully collected. Surface samples were collected in February 2019. Samples from the subsurface were collected in July 2019, after an impact experiment created an artificial crater of ≈ 10 m. Both sets, corresponding to a total mass about 5.4 g, were stored in separate containers inside the return capsule.

Preliminary analyses of the samples in Japan confirm similarities with CI chondrites. They will be developed in selected worldwide laboratories in 2022, to elucidate water-organics interactions and the evolution of organic matter in the Solar System. Meanwhile, the successful Hayabusa2 mission has been extended, with an expected flyby of an unusual L-type asteroid in July 2026 and rendezvous with a very small (size ≈ 30 m) asteroid in July 2031.

Cross-References

- [Chondrite](#)
- [Itokawa Asteroid](#)
- [Near-Earth Objects](#)
- [Ryugu Asteroid](#)

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Haze Particles

► Aerosols

HC₃O⁺

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Synonyms

Protonated tricarbon monoxide

Chemical Formula



Definition

The ion HC₃O⁺ is the protonated form of tricarbon monoxide (C₃O). It has been identified in the cold dark cloud TMC-1, where other protonated molecules have been also observed (Cernicharo et al. 2020). The ion HC₃O⁺ can be formed in cold dark clouds by proton transfer of other abundant cations like HCO⁺ and H₃⁺, a process which is exothermic due to the high proton affinity of C₃O, 885 ± 5 kJ mol^{−1} (Botschwina 1989). The dipole moment of HC₃O⁺ is calculated to be 3.41 Debye (Cernicharo et al. 2020).

Cross-References

► Proton Transfer

References and Further Reading

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HC₄H

► Diacetylene (C₄H₂)

HC₄NC

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Chemical Formula



Definition

The molecule HC₄NC is a metastable isomer of cyanodiacetylene (HC₅N), which lies 113.8 kJ mol^{−1} above HC₅N (Botschwina et al. 1998). It was detected for the first time in space in the cold dark cloud TMC-1 (Xue et al. 2020; Cernicharo et al. 2020). This species belongs to the family of isocyanopolyyne HC_{2n}NC (with $n = 1, 2, 3, \dots$), which are metastable isomers of cyanopolyyne HC_{2n}CN. Isocyanopolyyne are less abundant than cyanopolyyne in TMC-1 by factors of 45–77 for HC₂NC and 200–600 for HC₄NC (Xue et al. 2020; Cernicharo et al. 2020). The larger member of the family HC₆NC has not yet been detected.

Cross-References

► [Isomer](#)

References

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HC₅NH⁺

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Synonyms

[Protonated cyanodiacetylene](#)

Chemical Formula

HC₅NH⁺

Definition

The ion HC₅NH⁺ is the protonated form of cyanodiacetylene (HC₅N). It has been tentatively identified in the cold dark cloud TMC-1, where other protonated molecules have been also observed (Marcelino et al. 2020). The assignment is based on high-level ab initio calculations together with some astrophysical arguments. The ion HC₅NH⁺ can be formed in cold dark clouds by proton transfer of other abundant cations like HCO⁺ and H₃⁺, a process which is exothermic due to the high proton affinity of HC₅N, 770 ± 20 kJ mol^{−1} (Edwards et al. 2009). The dipole moment of HC₅NH⁺ is calculated to be 3.26 Debye (Marcelino et al. 2020).

Cross-References

► [Proton Transfer](#)

References and Further Reading

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HCl

- [Chlorine Hydrides in the Interstellar Medium](#)
- [Hydrogen Chloride \(HCl\)](#)

HCl⁺

- [Chlorine Hydrides in the Interstellar Medium](#)

HCN Dimer

► Cyanomethanimine

HCN Polymer

Irena Mamajanov¹ and Judith Herzfeld²

¹School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, USA

²Brandeis University, Waltham, MA, USA

Keywords

Addition polymer · Aminomalononitrile · Diaminomaleonitrile · Hydrogen cyanide · Ladder polymer · Polyheterocycle · Polyimine · Protopeptide

Synonyms

Azulmin; Hydrogen cyanide polymer

Definition

► **Hydrogen cyanide** polymers – i.e., heterogeneous solids formed upon spontaneous polymerization of HCN – are likely to have been among the first macromolecules on prebiotic Earth.

Overview

Hydrogen cyanide (HCN) polymerizes spontaneously in the neat liquid and in solution. Due to the abundance of hydrogen cyanide in the Universe (Debes et al. 2008), the potential role of hydrogen cyanide polymers in astrochemistry and the origin of life has provoked much speculation. Gas phase HCN is found both in interstellar molecular clouds and in comets in the solar system.

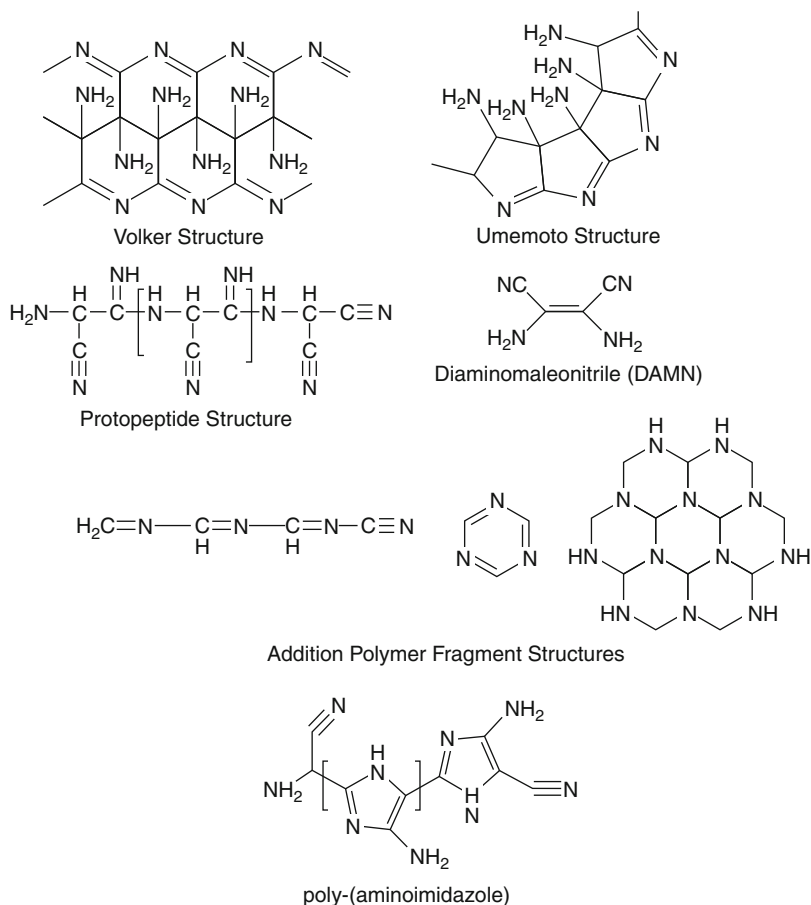
The ► **oligomerization** of HCN was first observed by Proust (1806), and analyses of the

soluble fraction date back to the late 1800s and early 1900s (Lange 1863; Wippermann 1874; Bedel 1923). Volker was the first to propose a structure for the insoluble ► **polymer** in 1960, a so-called “ladder” structure formed by repeats of the HCN dimer in the *trans* configuration (Volker 1960). The *cis* variation was subsequently offered by Umemoto et al. (1987). A more provocative model, from the standpoint of the origins of life, was suggested by Matthews, based on the observation of α -amino acids in polymer hydrolyzates; polymerization was proposed to occur via the HCN trimer aminomalononitrile and result in a structure with a -NCC- backbone that would form ► **polypeptide** upon contact with water (Matthews et al. 1977). However, Ferris has argued that the HCN tetramer, diaminomaleonitrile (DAMN), must be the “direct precursor” to HCN polymers, since dimers and trimers are not expected to accumulate (Ferris et al. 1981).

The above structures have been found to be inconsistent with recently acquired ¹³C and ¹⁵N solid state NMR spectra of polymers formed in neat HCN. These data suggest that the polymers are formed by simple monomer addition, first in head-to-tail fashion to form linear, conjugated chains, and then laterally to form saturated two-dimensional networks (Mamajanov and Herzfeld 2009a). This interpretation of the NMR spectra finds support in other information about the polymerization of neat HCN, including the presence of free radicals (Budil et al. 2003) and the fragmentation pattern in a ► **GC/MS** chemolysis study (Minard et al. 1998) (Fig. 1).

A different kind of HCN polymer has been shown to form upon mild heating of DAMN. ¹³C and ¹⁵N solid state NMR spectra, as well as the optical properties and electrical conductivity of the product, are consistent with an HCN trimer repeat unit. However, rather than forming a protopeptide, the subunits cyclize to form poly-[aminoimidazole] (Mamajanov and Herzfeld 2009b).

Despite extensive effort, there is no scientific consensus concerning the potential role of the HCN polymer in prebiotic evolution.

HCN Polymer,**Fig. 1** Proposed structures for the HCN polymers and related compounds

H

Cross-References

- [Biopolymer](#)
- [Exopolymers](#)
- [Formamide \(NH₂CHO\)](#)
- [GC/MS](#)
- [Heterocycle](#)
- [Hydrogen Cyanide](#)
- [Insoluble Organic Matter](#)
- [Nitrile](#)
- [Oligomer](#)
- [Oligomerization](#)
- [Polymer](#)
- [Polypeptide](#)
- [Prebiotic Chemistry](#)
- [Radical](#)
- [Tholins](#)

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HCNO Isomers

Holger S. P. Müller

I. Physikalisches Institut, Universität zu Köln,
Köln, Germany

Keywords

Isomer

Synonyms

Cyanic acid; Fulminic acid; Isocyanic acid;
Isofulminic acid

Definition

HCNO isomers are molecules having the same empirical formula (HCNO) but a different connectivity. These isomers cannot be transformed from one to another without breaking a bond.

History

About 1825, Liebig and Gay-Lussac found out that silver fulminate had the same empirical

formula as a compound called silver cyanate (more correctly referred to as silver isocyanate), which Wöhler had analyzed about a year earlier. The two compounds were clearly different and thus led to the concept of isomerism.

Overview

To date, four molecules are known with the empirical formula HCNO. The lowest-energy form is isocyanic acid, $\text{H}-\text{N}=\text{C}=\text{O}$; cyanic acid, $\text{H}-\text{O}-\text{C}\equiv\text{N}$, is somewhat higher in energy (103.2 kJ/mol); fulminic acid, $\text{H}-\text{C}\equiv\text{N}-\text{O}$, is considerably higher (295.9 kJ/mol); and iso-fulminic acid, $\text{H}-\text{O}-\text{N}\equiv\text{C}$, is higher still (352.2 kJ/mol). Fulminic acid is a linear molecule; the others are all planar with the heavy atoms being nearly linear and the H atom bent trans to the heavy atom chain. A review of their structural and spectroscopic properties and their energetics was given by Teles et al. (1989). More recently, high-level quantum chemical calculations of the energies have been performed by Schuurman et al. (2004).

Single-crystal X-ray crystallography has shown that solid salts considered to be cyanates are generally much better described as isocyanates. Consequently, adding strong acids to these salts releases isocyanic acid (HNCO), without clear evidence of formation of cyanic acid (HOCN). HNCO was prepared in its pure form in the nineteenth century. In contrast, it appears as if HOCN can only be generated in situ. Interestingly, even though fulminic acid is much higher in energy than cyanic acid, it is possible to prepare HCNO in its pure form. Again, iso-fulminic acid has to be generated in situ.

Rotational spectra of all four isomers have been measured. Not surprisingly, iso-fulminic acid was the last detected (Mladenović et al. 2009). While HNCO was detected in space in 1972, HCNO and HOCN were only detected very recently (see Brünken et al. 2010).

HNCO can trimerize to cyanuric acid, a six-membered ring with alternating C and N atoms.

The anion NCO^- is neither well described as isocyanate with the negative charge at the N atom

nor as cyanate with the negative charge at the O atom. Instead, the charge is delocalized to essentially equal amounts over both atoms. Thus, the CO bond has a formal bond order of 1.5 while that of the CN bond is 2.5. An infrared feature at 4.62 μm , observed in interstellar ices, coincides with the strong asymmetric stretching mode of the NCO^- anion and has been attributed to this species. Unfortunately, features in solid-state spectra are not particularly specific. As a consequence, the assignment may well be correct but is by no means certain.

Of the four isomers, the three lower-energy ones have been detected in the [▶ interstellar medium](#): HNCO, HCNO, and HOCN.

Cross-References

[▶ Molecules in Space](#)

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HCO⁺

[▶ Formyl Cation \(HCO⁺\)](#)

HCOOCH₃

[▶ Methyl Formate \(HCOOCH₃\)](#)

HCP

[▶ Phosphaethyne \(HCP\)](#)

HD 189733b

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii, Honolulu, HI, USA

Keywords

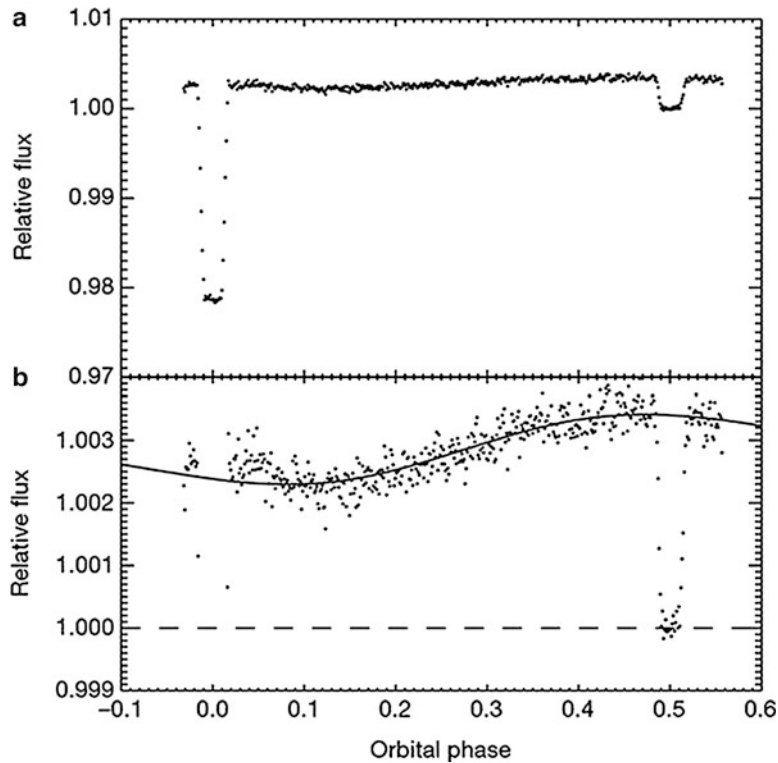
Planetary atmosphere · Transiting planet

Definition

HD 189733b is a transiting [▶ Hot Jupiter](#) that is especially well suited for studies of its atmosphere. Spectroscopic observations with the Hubble Space Telescope and [▶ Spitzer Space Telescope](#) have revealed the presence of molecules such as water vapor and methane (Fig. 1).

History

Early results from radial-velocity surveys suggested that gas giant exoplanets were being found more frequently around stars with higher concentrations of heavy elements in their atmospheres than the Sun (e.g., see Santos et al. 2001; Fischer and Valenti 2005). This motivated some teams to search for planets around samples of metal-rich stars using radial velocities and then to look for transits with follow-up photometry. One of these efforts, the ELODIE metallicity-biased search for transiting Hot Jupiters (da Silva et al. 2006), announced the discovery of HD 189733b (Bouchy et al. 2005). This planet proved to be especially well suited for follow-up studies of its atmosphere because it is in a tight orbit around a nearby star that is somewhat cooler



HD 189733b, Fig. 1 The light curve of HD 189733 observed with the Infrared Array Camera on the Spitzer space telescope at $8\ \mu\text{m}$. More than half the orbit is covered. The deep event at phase 0.0 is the transit of the planet in front of the star. The shallower event at phase 0.5 is the secondary eclipse when the planet passes behind the star and its thermal emission is blocked. The depth of the

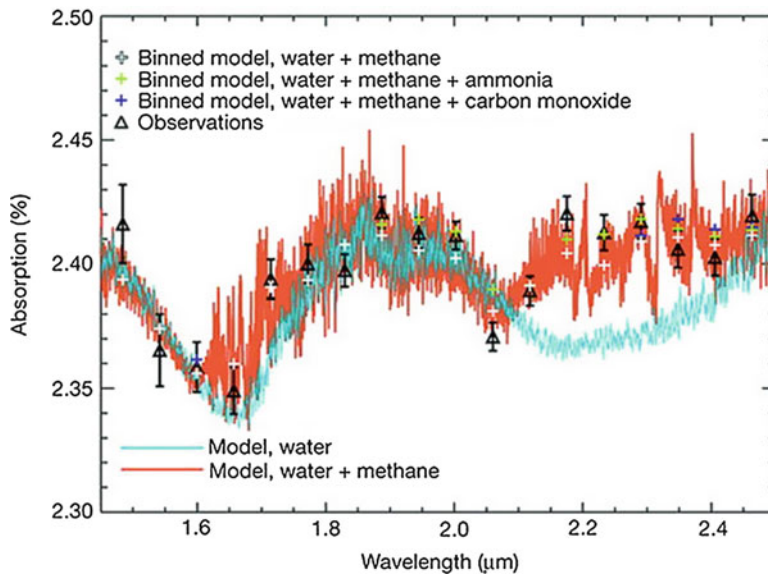
secondary eclipse indicates that 0.34% of the total radiation of the system at $8\ \mu\text{m}$ arises from the planet. This sets the planet's dayside temperature at 1212 K. The emission increases slowly with phase as the planet moves around in its orbit and more of the dayside comes into view. **(b)** Provides an expanded view of the upper portion of **(a)**

than the Sun, thus producing a favorable contrast between the emission from the planet compared to the star (Fig. 2).

Overview

The parent star HD 189733 is significantly cooler than the Sun, with an effective temperature of 4980 K, corresponding to an early K [spectral type](#). The distance to the star is only 19.3 pc, which makes it quite bright, with an apparent visual magnitude of 7.67. The period of the circular orbit is only 2.2186 days long, and thus the planet is strongly heated by the incident radiation

from the star. These factors all combine to make HD 189733b especially well suited for follow-up observations of the thermal emission from the planet's atmosphere. Deming et al. (2006) first reported the detection of secondary eclipses, using the *Spitzer Space Telescope* at $16\ \mu\text{m}$ to measure a drop of 0.55% in the total thermal emission when the planet disappears behind the star. Subsequently, Knutson et al. (2008) monitored the emission at $8\ \mu\text{m}$ over more than half the orbit and showed that the dayside temperature is 1212 K, and the nightside is only 239 K cooler. This implies efficient heat transfer from the day-side to the nightside and thus dramatic weather in the atmosphere of HD 189733b.



HD 189733b, Fig. 2 The observed spectrum (*black triangles*) and two theoretical spectra of the predominantly molecular hydrogen atmosphere, showing the effects of small amounts of water (*blue*) and methane in combination with water (*orange*). The measured spectrum exhibits significant differences at 1.7–1.8 μm and at 2.15–2.4 μm from what is expected due to water vapor alone. These

departures are interpreted as additional absorption features due to the presence of one or more other species in addition to water. When considering only water and methane, the theoretical spectrum best fitting the data was determined by binning the model (shown as *white crosses*) to the spectral resolution of the observations (Swain et al. 2008)

Spectroscopy of the wavelength dependence of the transit depth in the near infrared with the NICMOS instrument on the *Hubble Space Telescope* by Swain et al. (2008) gave dramatic confirmation for the earlier preliminary reports of the detection of water vapor in the H_2 -dominated atmosphere of HD 189733b and suggested in addition the detection of methane. This was later confirmed by McCullough et al. (2014). Subsequent NICMOS spectroscopy of secondary eclipses added carbon monoxide and carbon dioxide to the list of proposed molecular detections (e.g., Swain et al. 2009).

- [Hubble Space Telescope](#)
- [Radial-Velocity Planets](#)
- [Spitzer Space Telescope](#)
- [Transiting Planets](#)

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Cross-References

- [Exoplanets, Discovery](#)
- [Gas Giant Planet](#)
- [Hot Jupiters](#)

HD 209458b

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Keywords

Transiting planet

Definition

HD 209458b was the first exoplanet observed to transit its host star.

History

Arguments based on simple geometry predict that about one out of ten planets orbiting stars similar to the Sun should be seen to ► [transit](#) their parent star if the orbital period is only a few days. HD 209458 was roughly the tenth star to show a radial-velocity orbit implying a possible Hot Jupiter companion, so the discovery that the unseen companion transited the star came right on schedule. Follow-up photometry at times predicted for transits by the spectroscopic orbit with period 3.5247 days revealed dips in the light curve consistent with a ► [gas giant planet](#) 1.32 times the radius and 0.64 times the mass of Jupiter. For the first time it was possible to show that the bulk density of a Hot Jupiter was approximately as expected for a gas giant planet. This left little doubt that the growing population of radial-velocity planet candidates, in the early days of detecting extrasolar planets, must in fact be planets.

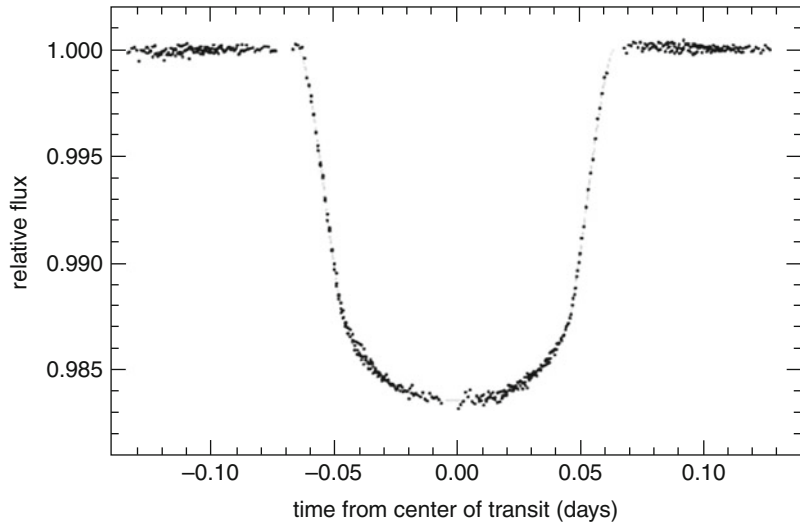
The discovery of HD 209458b transits is another example of simultaneity in science. Discovery papers from two independent teams were published simultaneously and back-to-back in the same issue of the *Astrophysical Journal Letters* (Charbonneau et al. 2000; Henry et al. 2000). The two teams based their transit time predictions on

radial velocities measured independently with ► [HIRES](#) on the Keck I telescope and Elodie on the 1.9-m telescope at the Observatoire de Haute Provence. The follow-up photometry was accomplished with small telescopes, in the case of Charbonneau et al. (2000) using a 4-in lens and ► [CCD](#) camera located in the parking lot of the High Altitude Observatory in Boulder, Colorado. Subsequent observations of transits with the STIS instrument on the *Hubble Space Telescope* illustrated (Fig. 1) the spectacular quality of light curve that could be achieved with a large telescope in space (Brown et al. 2001).

Overview

HD 209458 is a star very similar to the Sun in almost all respects. Because it is relatively nearby, only 47 pc from the Sun, it has the relatively bright apparent visual magnitude of 7.65. This makes it especially attractive for follow-up observations, such as spectroscopy of the atmosphere of the planet HD 209458b, although the planetary candidate ► [HD 189733b](#) is somewhat better in this regard because its host star is cooler. The same STIS spectra that yielded the spectacular light curve when integrated over all the available wavelengths (Brown et al. 2001) were subsequently reanalyzed at much finer spectral resolution, showing the presence of sodium in the planet's atmosphere (Charbonneau et al. 2002). This was the first detection of the atmosphere of an exoplanet. Subsequently, hydrogen was detected by Vidal-Madjar et al. (2003), sodium by Snellen et al. (2008), potassium by Keles et al. (2019), and helium by Alonso-Floriano et al. (2019). Some of these discoveries (e.g., sodium) were challenged in Casasayas-Barris et al. (2021) using ESPRESSO data. Additionally, Giacobbe et al. (2021) confirmed the discovery of different species like water vapor and carbon monoxide, and even confirmed the tentative detection of hydrogen cyanide (HCN) of Hawker et al. (2018). This is the first clear detection of a nitrogen bearing molecule in the atmosphere of an exoplanet. They also detected other molecules such as ammonia (NH₃), methane (CH₄), and acetylene (C₂H₂).

HD 209458b, Fig. 1 The light curve for the transit of HD 209458b obtained with the STIS instrument on the *Hubble Space Telescope*. Observations from several orbits were combined to produce full phase coverage of the transit light curve (Brown et al. 2001)



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Although the bulk density of HD 209458b matches more or less the predictions of models for gas giant planets, the density is somewhat lower than expected. Apparently, the radius of the planet is expanded compared to those predicted by the models. For a while, HD 209458b was anomalous in this regard, but as more transiting Hot Jupiters were discovered, additional examples of inflated gas giants were identified. Although a number of possible physical mechanisms for inflating the radii of these planets have been suggested, the phenomenon remains puzzling.

Cross-References

- [Exoplanets, Discovery](#)
- [Gas Giant Planet](#)
- [HD 189733b](#)
- [HIRES](#)
- [Hot Jupiters](#)
- [Transit](#)
- [Transiting Planets](#)
- [ESPRESSO](#)

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HD 44179

► [Red Rectangle](#)

Heat Flow, Planetary

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Keywords

Radioactive heating · Heat transfer

Synonyms

[Geothermal flux](#); [Heat flux](#)

Definition

The heat flow in the most general sense is the rate of heat transfer per unit area across a given surface. The heat transfer mechanism could be radiation, convection, or conduction. It is measured in W m^{-2} . In geophysics and in planetary geophysics, the surface heat flow is more narrowly defined as the heat conducted through the ► [crust](#) across the planetary surface. In the (older) geophysical literature, the heat flow unit (hfu) is sometimes used, with $1 \text{ hfu} = 10^{-6} \text{ cal cm}^{-2} \text{ s}^{-1} = 41.84 \text{ mW m}^{-2}$.

Overview

Heat is generated in the interior of planets and satellites by the decay of radioactive elements, by exothermic phase transitions and chemical reactions, and by the dissipation of mechanical energy upon, for example, planetary contraction or differentiation and tidal deformation. The rate of heat loss of a ► [planet](#) or satellite provides constraints on the amount of heat being produced in the planet and the temperature distribution in the interior. The heat loss can – in principle – be measured from space with infrared radiometers as the heat radiated by the planet. The latter quantity is also called the planet’s intrinsic ► [luminosity](#) (similar to the luminosity of a ► [star](#)). In the inner solar system, however, the luminosity is dominated by the solar heat that is absorbed in the atmosphere and in the surface ► [rock](#) and radiated back into space. (The contribution by the reflected sunlight can be separated in the electromagnetic spectrum.) Therefore, the heat flow out of the interior of a ► [terrestrial planet](#) must be measured at a depth where perturbations due to the solar radiation and thermal perturbations in the atmosphere are sufficiently small. This depth is a few times the thermal skin depth $\sqrt{\frac{\kappa\tau}{\pi}}$ with κ the thermal diffusivity and τ the period of the thermal perturbation. The period τ ranges from a planetary day (or ► [sol](#)) to centuries if climatic effects are taken into account. Usually, a depth of a few meters will be sufficient but depending on the required accuracy. Measuring the heat flow then requires measuring both the thermal conductivity and the temperature gradient. Many heat flow measurements have been made on the ► [Earth](#), and heat flow maps have been compiled (e.g., Pollack et al. 1993; see also Jaupart and Mareschall 2015 for a review). The variation of the heat flow reflects volcanic and orogenic provinces and chains where heat flow is high and thick continental shields where heat flow is low. The average value is 84 W m^{-2} , and the variation is between a few tens to a few hundreds mW m^{-2} . Heat flow has been measured on the Moon at two sites by the Apollo missions. The values are 12 and 21 mW m^{-2} (Langseth et al. 1976; Warren

and Rassmussen 1987). These values are still subject of debate. A recent review can be found in Siegler and Smrekar (2014). No other planetary heat flow values are available, but heat flow measurements have been repeatedly proposed (e.g., Spohn et al. 2001).

In the outer solar system, the intrinsic luminosities of ► Jupiter, ► Saturn, ► Uranus, and ► Neptune have been measured. These are 5.44 ± 0.43 , 2.01 ± 0.14 , 0.042 ± 0.047 (but not smaller than 0), and $0.433 \pm 0.046 \text{ W m}^{-2}$, respectively (e.g., Guillot and Gautier 2015 for a review). Dissipation of gravitational energy released upon contraction is the major source of heat in the interior of Jupiter. The heat flow value for the other ► giant planets, in particular, the difference in heat flow between Uranus and Neptune, is not well understood. The intrinsic luminosity of the Jovian satellite ► Io has been measured to be about 2 W m^{-2} (Spencer et al. 2000). It is widely agreed that the heat is due to tidal dissipation (compare Tides).

Cross-References

- Apollo Mission
- Crust
- Differentiation, Planetary
- Earth
- Giant Planets
- Heat Transfer, Planetary
- Io
- Jupiter
- Luminosity
- Moon, the
- Neptune
- Planet
- Rock
- Satellite or Moon
- Saturn
- Sol
- Solar System, Inner
- Stars
- Terrestrial Planet
- Tides, Planetary
- Uranus

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Heat Flux

- Heat Flow, Planetary

Heat Shock

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

The term “heat shock” describes a rapidly imposed, short duration heat treatment deployed to control microorganisms. For ► planetary protection and microbiology, this technique is used in enumerating spores, generally in a liquid sample. A combination of high temperature with a short exposure time (i.e., 80 °C for 10 min) kills the vegetative forms of mesophilic ► bacteria, leaving only mesophilic and thermophilic spores remaining viable in the sample. This is because, with such rapid timing, the vegetative

microorganisms do not have enough time to form new spores and are inactivated. When cooled, the liquid solution is spread on nutrient media and incubated to persuade spores remaining in the sample to grow and form colonies. The result of this standardized assay represents an estimate of the number of spores which were present in the original sample.

Cross-References

- [Bacteria](#)
- [Endospore](#)
- [Microorganism](#)
- [Planetary Protection](#)
- [Spore](#)

Heat Transfer, Planetary

Tilman Spohn¹, Lisa Kaltenegger² and Ana-Catalina Plesa³

¹International Space Science Institute, Bern, Switzerland

²Cornell University, Ithaca, NY, USA

³Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

Keywords

Atmospheres · Conduction · Convection · Planetary interiors · Plate tectonics · Radiation · Stagnant lid

Definition

Heat is transferred in planetary and satellite interiors and atmospheres from regions of high temperature to regions of lower temperature. The heat transfer mechanisms are heat conduction, convection, and radiation.

Overview

In planetary interiors, heat is generated by the decay of the ► [radiogenic isotopes](#) ²³⁵U, ²³⁸U,

²³⁷Th, and ⁴⁰K. In addition, latent heat may be released and consumed through phase transitions, including melting and crystallization. The dissipation of kinetic energy of ► [planetesimals](#) colliding with the protoplanets during planetary accretion has heated the planetary interiors, in some cases up to the melting temperatures of their outer layers. The formation of the cores in terrestrial planets through differentiation has further heated the deep interiors. Since planetary surfaces are colder – their temperature being determined by the rate of solar radiation and the atmosphere ► [greenhouse effect](#) – heat is transferred to these surfaces from the deep interior. The resulting flow of heat may be associated with the conversion of heat into mechanical work and the conversion of heat into ► [magnetic field](#) energy. Moreover, the cooling may result in planetary contraction. The dominant heat transfer mechanisms in planetary interiors are heat conduction and convection (for a discussion of heat transfer in planetary interiors, see, e.g., Schubert et al. 2001).

In a typical substantial planetary atmosphere, heat is transferred by convection or radiation in the lower atmosphere (more specifically, the ► [troposphere](#) and ► [stratosphere](#)) and heat conduction and radiation in the upper atmosphere (more specifically, the ► [mesosphere](#) and ► [thermosphere](#)). The pressure level at the radiative-convective boundary (the tropopause) in the lower atmosphere depends on the composition of the atmosphere and the ► [opacity](#) of the major atmospheric constituents. Above this level (i.e., at lower pressures), the outgoing energy is transported by radiation until heat conduction becomes important. The radiative-convective boundary occurs when the atmosphere becomes optically thin to thermal radiation. Usually, this translates into a column optical depth, τ , approximately equal to unity. For τ approximately equal to unity or larger, the atmosphere is opaque, and the radiative energy is reabsorbed by the surrounding media, hence convection is the dominant form of heat transfer. For τ smaller than unity, the atmosphere is transparent and does not absorb efficiently.

Heat conduction. In gases, heat is conducted via the ► [diffusion](#) of molecules. Molecules with

high kinetic energy diffuse from regions of high temperature to regions of lower temperature. Interaction between molecules transfers energy and thereby heat. In solids, energy is transferred via lattice vibrations. In a perfect solid, vibrational energy would travel with sound speed, and heat would be rapidly dissipated. Imperfections in the solid slow the process of energy transfer, such that heat flows analogous to the diffusion of matter. The lattice model of conductive heat transfer thus associates vibrational energy with particles called phonons (it can be shown that vibrational energy must be quantized). The transfer of heat can then be modeled as diffusion in the phonon gas similar to diffusion in a real gas. The thermal conductivity varies with the lattice properties of the solid.

In planetary atmospheres, heat conduction is largely unimportant (except for the uppermost layers) with convection and radiation being more efficient heat transfer mechanisms. In planetary interiors, heat is conducted in regions that are immobile on planetary timescales of $>10^5$ years. One example layer is the stagnant ► **lithosphere** of planets such as ► **Mars**. On ► **Earth** where the lithosphere is broken up in plates that move laterally, vertical heat transfer through the plate is still conductive, while lateral heat transfer is mostly convective, depending on the plate speed. Other prominent layers of conductive heat transfer are

the boundary layers of mantle convection (compare Fig. 1 below and Schubert et al. 2001).

Mathematically, the (conductive) flow of heat $\vec{F}$ can be described by.

$$\vec{F} = -k\nabla T \quad (1)$$

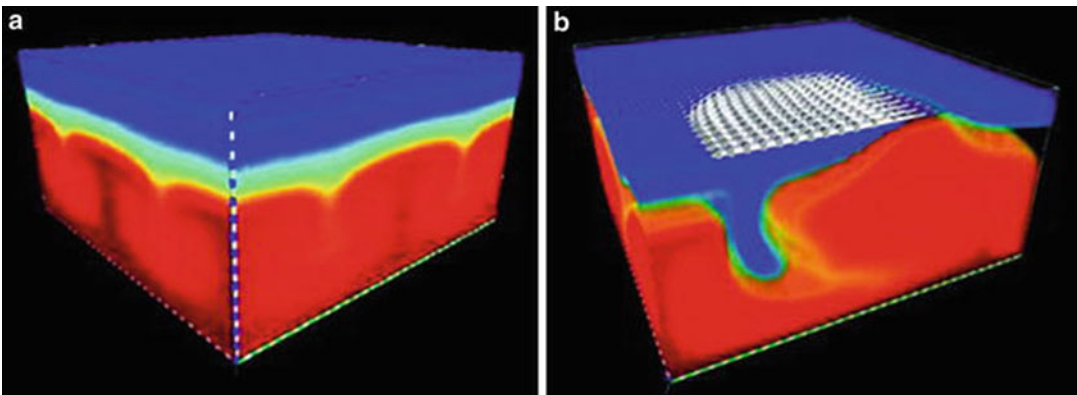
where ∇T is the temperature gradient and k is the thermal conductivity. $\vec{F}$ is a vector quantity having a value and a direction.

The thermal conductivity can be both a function of pressure and temperature. In porous media, the thermal conductivity varies with the porosity and with the properties of any gas or fluid in the pores.

Radiation. Radiation is a heat transfer mechanism in regions that are transparent to electromagnetic waves and is particularly important in planetary atmospheres (see radiation in planetary atmospheres and Thomas and Stamnes 1999) and in stellar interiors (e.g., Hansen et al. 2012). For the highly absorbing planetary interiors, radiation is usually integrated into the mechanism of heat conduction, thereby increasing the thermal conductivity at high temperatures.

Convection. Thermal convection is a consequence of thermal expansion, with the density of gases and fluids decreasing with increasing

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Heat Transfer, Planetary, Fig. 1 Color-coded temperature distributions in stagnant lid (a) and mobile lid convection (b) for strongly temperature-dependent viscosity after numerical calculations by Stein and Hansen (2008). Blue indicates low temperatures and red high temperatures. In stagnant lid convection, the flow is confined to occur

underneath a cold near-surface stagnant layer. In the stagnant layer, heat is transferred by conduction. In mobile lid convection, the cold near-surface layer participates in the convection. Arrows indicate the direction of flow. Mobile lid convection is a mode of convection largely analogous to plate tectonics (Courtesy of C. Stein and U. Hansen)

temperature. On time scales of millions of years, even solids such as rock in planetary mantles can be considered as extremely viscous fluids (► [Rheology \(Planetary Interior\)](#)). Consider a layer of fluid (or gas) sandwiched between a hot plate at the bottom and a cold plate at the top. Fluid near the hot plate will absorb energy, and its temperature will rise. As a consequence of the density decreasing with temperature, the fluid will become increasingly buoyant with respect to the colder fluid above and eventually will rise if the buoyancy is large enough to overcome inertia and internal friction. As it rises, it will transport heat that it may exchange with the fluid through which it rises and – in particular – it transfers heat to the cold top plate. The heat transfer is thus from the hot to the cold plate. In a similar thought experiment, heat can be generated within the fluid, cause buoyancy, and again be transported to the cold plate. The above is – in principle – the mechanism of heat transfer from the hot core through the mantle to the cold planetary surface and the mechanism of the transfer of heat generated in the interior of the planet to the same cold surface. It is the same mechanism of heat transfer from the interior of the hot core to the (colder) core-mantle boundary and from the warm surface of the planet to the colder regions in the atmosphere. In the atmosphere, convection includes large- and small-scale rising and sinking of air masses and smaller air parcels. These vertical motions effectively distribute heat and moisture throughout the atmospheric column. The mechanism also applies in the interiors of ► [giant planets](#) and in oceans. It is termed free convection because the flow is not driven by external forces. Forced convection in planets may be driven by, e.g., tides, ► [planetary](#), and in the atmosphere by variations in solar irradiation. The convective flow of heat $\vec{F}$ across a surface in a fluid is given by.

$$\vec{F} = \nabla \cdot \vec{u} \rho c_p T \quad (2)$$

where $\vec{u}$ is the velocity vector, ρ is the local density, and c_p the heat capacity at constant pressure.

Heat transfer by free convection can be characterized by a set of dimensionless parameters. The first and most important is the Rayleigh number Ra . For fluids heated from below, it is defined as.

$$Ra \equiv \frac{g \alpha \Delta T d^3}{\nu \kappa} \quad (3)$$

In addition to already defined quantities, g is the acceleration due to gravity, α is the thermal expansion coefficient, ΔT is the temperature difference between the top and bottom boundary, d is the layer thickness, ν is the kinematic ► [viscosity](#), and κ is the thermal diffusivity. The thermal diffusivity is related to the thermal conductivity, density, and heat capacity as follows: $\kappa = k/\rho c_p$. For internally heated fluids, ΔT is replaced with Qd^2/k , where Q is the heat production rate per unit volume. The term $g \alpha \Delta T$ in the nominator of Eq. 3 measures the thermal buoyancy. Note that there are two diffusivities in the denominator. The thermal diffusivity κ measures the loss of buoyancy due to thermal conduction, and the kinematic viscosity ν – the momentum diffusivity – measures the deceleration of the fluid due to momentum diffusion.

The steady-state heat transfer rate by convection through a fluid heated from below is measured by the Nusselt number Nu .

$$Nu \equiv \frac{qd}{k\Delta T} \quad (4)$$

with q the heat flow across the top surface. The Nusselt number is the ratio between the surface heat flow q and the heat flow that would be transferred by conduction $k\Delta T/d$. Since convection is an instability that sets in when the heat can be more efficiently transferred by convection, $Nu \geq 1$. In a fluid heated from within, the surface heat flow in the steady state equals Qd , and the Nusselt number as defined above is always unity. The efficiency of convective heat transfer is then measured by the value of the internal temperature: the lower the temperature at which the convection is operating, the more efficient is the internally heated convection.

Experiments with fluids and numerical solutions of the field equations of fluid mechanics show that there is a power law relationship between the Nu and the Ra numbers.

$$Nu = \left(\frac{Ra}{Ra_{crit}} \right)^\beta \quad (5)$$

where Ra_{crit} is the critical Rayleigh number for the onset of convection and β is a constant, the value of which is between 0.2 and 0.33 depending on boundary conditions and the temperature and pressure dependence of material properties. Similarly, for internally heated convection,

$$\theta \equiv \frac{kT}{Qd^2} = \left(\frac{Ra}{Ra_{crit}} \right)^\gamma \quad (6)$$

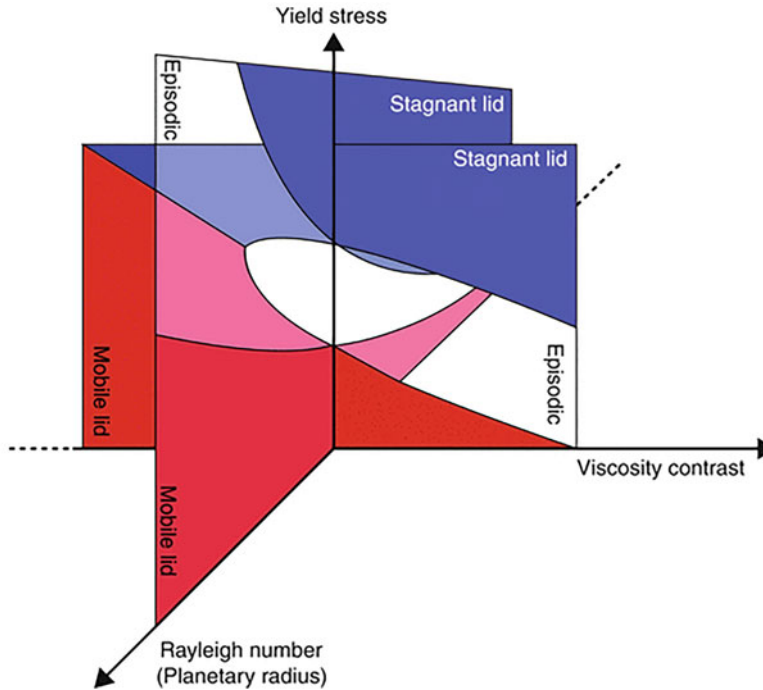
where T is the internal temperature and γ is between 0.2 and 0.25.

The parameters α , ν , and κ are pressure and temperature dependent. Of particular importance for planetary mantles – as numerical calculations and laboratory experiments have shown – is the pressure and temperature dependence of the viscosity (see ► [Rheology, Planetary Interior](#) for a discussion). Note that the solid mantles of terrestrial planets and satellites can be regarded as extremely viscous fluids for processes operating on geological timescales (i.e., on timescales of millions of years or more). The extremely large viscosity in the mantle causes inertia forces (such as the Coriolis force) to be negligible and the flow to be laminar, although at very large Rayleigh numbers, the flow tends to become increasingly chaotic (see, e.g., Ricard 2007). Within a ► [planetary interior](#), and in particular through the lithosphere, the outer boundary layer of the planet, the viscosity may vary over many orders of magnitude. A strongly temperature-dependent viscosity can result in the formation of a stagnant lid (compare Fig. 1). The pressure dependence can be speculated to lead to a second stagnant layer in the deep interior of the planet (e.g., Stamenkovic et al. 2012). The formation of a mobile lid requires the variation of the viscosity to be sufficiently small. The formation of a platelike mobile lid

(the fluid dynamical representation of ► [plate tectonics](#)) may require a viscoelastic rheology in which the yield strength may matter (compare Fig. 2). But it is not completely understood how plate tectonics on the Earth works and what the exact conditions for the stability of plate tectonics are. The latter makes it, of course, difficult to predict plate tectonics on other planets.

While the viscosity and its dependence on pressure and temperature is thought to be a most important parameter for mantle convection, viscosity is of little importance for convection in the planetary atmosphere and the core and in the interiors of the giant planets. In these, inertia forces, in particular the Coriolis force, matter and the flow is mostly turbulent. The Coriolis force provides helicity (corkscrew-like motion) for the flow in the core which is a prerequisite for dynamo action. In the atmosphere, the Coriolis force causes the vortices that dominate the weather system on, e.g., the Earth. In the giant planets, the Coriolis force is again taken to be the reason for the observed vortices (see ► [Jupiter](#)).

An additional heat transport mechanism that may occur on stagnant-lid planets with significant extrusive volcanic activity is heat piping (O'Reilly and Davies 1981). Melt from the interior rises through channels and volcanic pipes and erupts at the surface. The melt ascending through the lithosphere and crust transports heat from the base of the lithosphere to the surface, where the resulting volcanic load may push cold lithospheric material downward, efficiently cooling the upper layers of the planet. The lithosphere becomes thicker the more pronounced this heat pipe process is, but the interior remains warm, as heat is being efficiently removed mainly in the upper layers of the planet, while the deep interior is blanketed by the thick lithosphere. This heat transport mechanism through heat pipes is most significant during the early evolution of terrestrial planets, when large amounts of melt are produced in the interior (Moore et al. 2017; Spohn 1991), but it may still be active today on planets and moons dominated by volcanic activity, such as Jupiter's moon Io (Moore et al. 2017) and perhaps young and strongly tidally heated exoplanets.



Heat Transfer, Planetary, Fig. 2 Qualitative phase diagram for convection of a fluid with viscoelastic rheology including strongly temperature-dependent viscosity. The figure is based on numerical calculations by K. Stemmer and colleagues. It qualitatively shows how the stability fields of the stagnant lid and mobile lid modes of

convection depend on the Rayleigh number, the viscosity contrast across the fluid, and the yield strength for the transition from elastic to plastic deformation. There is a transitional regime termed episodic in which a stagnant lid episodically becomes mobile (Courtesy of K. Stemmer)

Cross-References

- Core, Planetary
- Diffusion
- Dynamo, Planetary
- Earth
- Giant Planets
- Greenhouse Effect
- Interior Structure, Planetary
- Jupiter
- Magnetic Field
- Mars
- Opacity
- Planet Formation
- Planetesimals
- Plate Tectonics
- Radiogenic Isotopes
- Rheology, Planetary Interior
- Satellite or Moon
- Stagnant Lid Convection
- Stratosphere

- Terrestrial Planet
- Tides, Planetary
- Troposphere

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Heat-Stable DNA Polymerase

► *Taq* Polymerase

Heavy Atom Beams

Raffaele Saladino
Department of Ecological and Biological Sciences, University of Tuscia, Viterbo, Italy

Synonyms

Ion beams; High-energy particles

Definition

Heavy ion beams are accelerated high-energy particles heavier than electrons. The generation of heavy atom beams is a relevant challenge for many fundamental and technological applications, including biomedical therapy and astrobiology studies Dalui et al. (2017). The conventional techniques for the generation of heavy atom beams involve an ion source, the accelerating apparatus and a collision cell for the electron detachment or electron capture processes Rajeev et al. (2013). This apparatus can be configured in a very different technological way. Heavy atom

beams fueled astrochemical transformations in the synthesis of complex organic molecules (COMs) are reported under gas and solid-state conditions Caselli and Ceccarelli (2012) covering space, interstellar and planetary like environments Congiu et al. (2020). They are also responsible for the degradation of organic compounds Smith (2011), thus the balance between the rates for the reactions that contribute to formation and destruction of molecules is of pivotal importance for molecular evolution Ehrenfreund et al. (2002). High-energy heavy atom beams simulating cosmic radiation Ferrari and Szuszkiewicz (2009) have been reported as energy source for the prebiotic synthesis of molecules of biological relevance such as nucleobases, amino acids, and sugars Saladino et al. (2016), and the role played by mineral surfaces in the control of regioselectivity and stereoselectivity of the process deeply investigated in the case of nucleotide synthesis Saladino et al. (2017). In addition, the interaction between heavy atom beams and matter can generate a cascade of low-energy electrons and ions fueling non-selective chemistry for the synthesis of multiple reaction products which favor complexity and variety in the construction of chemical structural motifs Arumainayagam et al. (2019).

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Heavy Charged Particle

► [HZE Particle](#)

Heavy Element

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

In the astrophysical context, a heavy element is any element heavier than helium. The term “metal” is also used by astronomers. The definition stems from the fact that only helium and hydrogen (and small quantities of lithium and beryllium) were produced in the few first minutes after the big bang: all other elements were produced afterward, through stellar processing (nuclear reactions or supernovae).

Cross-References

- [Metallicity](#)
- [Nuclear Reaction](#)
- [Primordial Nucleosynthesis](#)

6 Hebe

Hervé Cottin
Univ Paris Est Creteil and Université Paris Cité,
CNRS, LISA, F-94010, Créteil, France

Synonyms

[1847 JB](#)

Definition

6 Hebe is a large S-type asteroid orbiting in the main belt, at about 2.426 AU from the Sun (semimajor axis). Its size is $205 \times 185 \times 170$ km with a mass of about $1.2 \cdot 10^{19}$ kg, making it the 26th largest asteroid of the main belt and 16th in mass. Its orbit has an inclination of 14.751° and an eccentricity of 0.202. This asteroid has drawn specific interest because its proximity to orbital resonances results in a relatively large chance for any 6 Hebe's ejecta to collide with the Earth. Moreover, due to its spectral properties, it has been thought for a long time that 6 Hebe was the source of ordinary H chondrites and IIE iron meteorites. Note that H chondrites are one of the most abundant meteorite family found on Earth: ~34% of falls.

However, the possibility that so many meteorites on Earth could originate from the same asteroid has been weakened by observations of new asteroids with the same spectral properties. Moreover, a detailed surface study of 6 Hebe has concluded that only one-fifth of nearby asteroids with H chondrite type composition could have been produced by 6 Hebe from impacts.

History

Hebe is the sixth asteroid observed. Karl Ludwig Hencke discovered it in 1847.

Cross-References

- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [Meteorites](#)
- [Orbital Resonance](#)

Heavy Hydrogen

► [Deuterium](#)

Heavy Ion

► [HZE Particle](#)

Heavy Nucleus

► [HZE Particle](#)

Heavy Primary

► [HZE Particle](#)

Heliocentric Worldview

Sun Kwok
Department of Earth, Ocean, and Atmospheric
Sciences, University of British Columbia,
Vancouver, BC, Canada

Keywords

Copernicus · Epicycles · Eccentric · Equant

Definition

A cosmological worldview where the Sun is located at the center of the Universe.

History

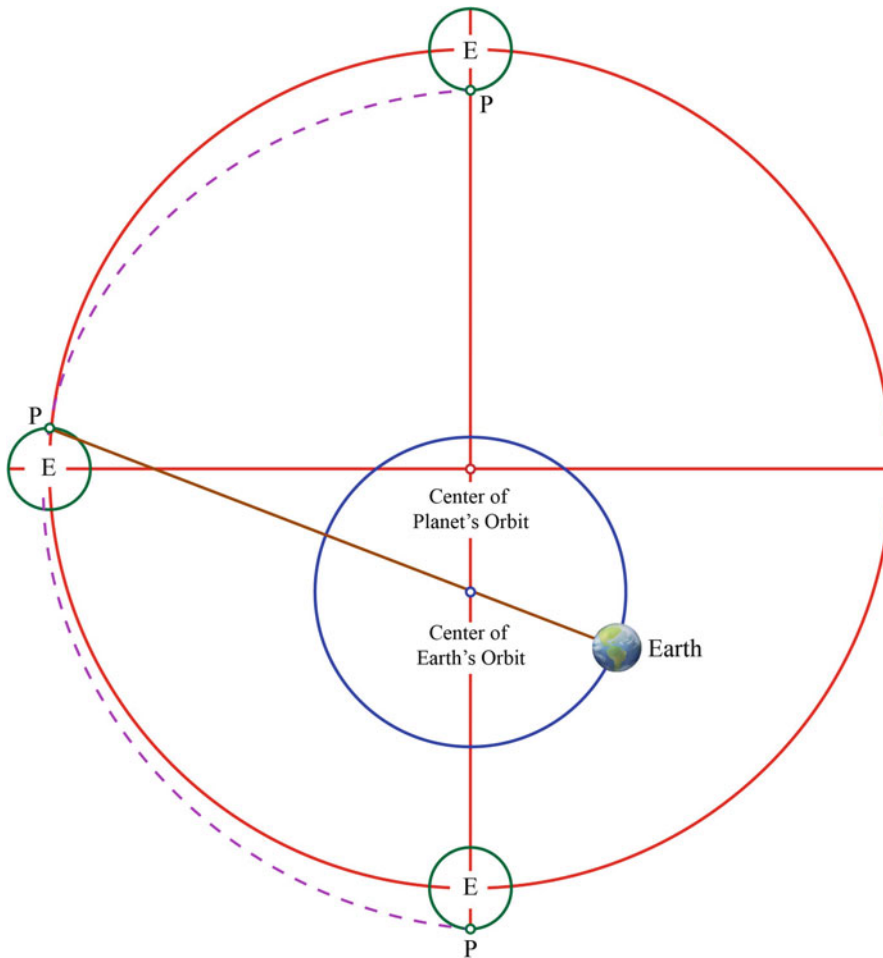
Aristarchus (310–230 B.C.) was the first person to suggest that the Sun, not the Earth, is the center of the Universe. From his measurement that the Sun is 20 times farther away from the Earth than the Moon is, he estimated that the Sun is 7 times larger than the Earth. He argued that it was unreasonable to assume that a larger body (the Sun) should revolve around a smaller body (the Earth).

The heliocentric model was further developed by Nicolaus Copernicus (1473–1543). Copernicus considered the concept of equant in Ptolemy’s model as violating the spirit of uniform circular motion and proceeded to seek an alternative without the use of the equant. Copernicus places the Sun near the center of the Universe, with the Earth and the other five planets revolving around it. The only object that revolves around the Earth is the Moon.

Overview

In 1543, Copernicus published his heliocentric model in the book *Six Books on the Revolutions of the Heavenly Spheres*. In Copernicus’ model, the Earth revolves around a point that is offset (eccentric) from the Sun (Fig. 1). A planet revolves around an epicycle whose center (*E*) revolves around a point which is eccentric from the center of the Earth’s orbit. By employing both eccentric and epicycles, Copernicus was able to simulate the noncircular and nonuniform movement of a planet. Although the Sun is stationary in Copernicus’s model, it is strictly speaking not a Sun-centered (heliocentric) model as the Earth and planets do not revolve around the Sun.

Although Copernicus’s model was not more accurate and had more epicycles than the model of Ptolemy, he did remove some unexpected coincidences in Ptolemy’s model such as the alignment between the lines connecting the planets to the centers of their epicycles being always in parallel with the line connecting the Earth and the Sun, and the planets revolving around the centers of their epicycles at the same rate as the Sun revolves around the Earth. Copernicus’s model also has the aesthetic advantage of providing a natural explanation for the retrograde motions of the planets. From the observed synodic periods (time from conjunction to conjunction or from opposition to opposition) of the planets, he was able to derive the true periods of revolution (sidereal periods) of the planets. The heliocentric model also naturally explains why the planets Mars, Jupiter, and Saturn are brightest during



Heliocentric Worldview, Fig. 1 Copernicus' model of planetary motion. The center of the Earth's orbit (in blue) is offset from the Sun (not shown). A planet (*P*) revolves around in an epicycle (in green) whose center (*E*) revolves

around (in red) a point which is eccentric from the center of Earth's orbit. The final trajectory of the planet is shown by the dashed line (in purple)

opposition, without assuming artificial periods for their epicycles. Most significantly, Copernicus can derive the relative distances between the planets and the Sun, therefore resolving the ambiguity in the order of Mercury and Venus in Ptolemy's model.

The heliocentric distances and sidereal periods of the planets were later used by Johannes Kepler (1571–1630) to formulate his third law of planetary motion. Using the observational data of Tycho Brahe (1546–1601), Kepler showed that planetary orbits have the shape of an ellipse,

with the Sun located at one of the foci of the ellipse. Kepler also suggested that planetary motions are physically driven by the Sun, therefore providing a truly heliocentric model.

Copernicus replaced the hypothesis of rotation of celestial sphere by the hypothesis of a rotating Earth and the apparent annual motion of the Sun by the Earth revolving around the Sun. Copernicus's theory was not immediately accepted because of the lack of observational evidence for a moving Earth and the theoretical objection of our inability to feel such motions.

Empirical evidence for the rotation of the Earth was later found through the detection of the eastward deflection of falling objects in 1831, the rotation of the plane of oscillation of the Foucault pendulum in 1851, and the measurement of the oblateness of the Earth in the twentieth century. Evidence for the Earth's revolution around the Sun was found by the detection of aberration of starlight in 1729, the measurement of stellar parallax in 1838, and the periodic Doppler shift of stellar lines in 1872. Our inability to feel the movement of the Earth was explained by Newton's theory of gravitation, laws of motion, and introduction of the concept of inertial forces.

In the heliocentric model, the sphere of stars no longer rotates around the Earth and there is no need for stars to lie on the surface of celestial sphere. This casted a doubt on the religious doctrine of Heaven being located beyond the celestial sphere. The demotion of the Earth to one of the six planets represented the first step towards the loss of special status of humanity in the Universe.

Cross-References

- Bruno, Giordano
- Geocentric Worldview
- Kepler, Johannes
- Plurality of Worlds

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Helium Nuclei

- Alpha Rays

Hematite

Daniele L. Pinti

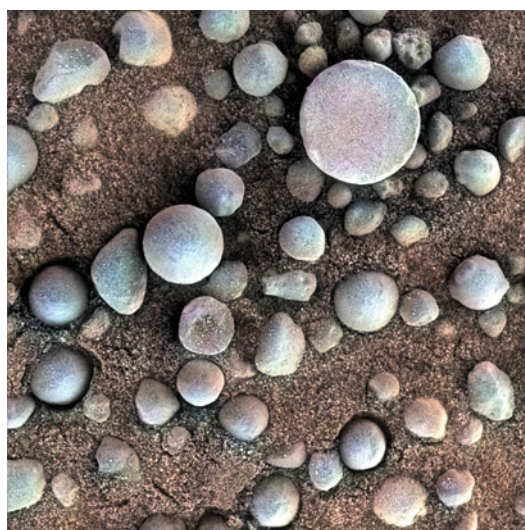
Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Chemical Formula



Definition

Hematite is an iron oxide of the trigonal crystal system. Hematite forms in a large variety of geological environments and is mined as one of the main ores of ► [iron](#) on Earth. Hematite is the major iron oxide in the ► [banded iron formations](#) (BIFs), which were deposited during global oxidation events. Hematite can be associated with aqueous fluids, particularly as hot spring precipitates. On planetary surfaces, hematite is thus a potential indicator of past presence of water. Hematite spherules, called “blueberries” (Fig. 1)



Hematite, Fig. 1 Mars rover Opportunity showing hematite “blueberries” spherules spread over the Martian soil at Fram Crater. (Photo credit: NASA JPL: <https://mars.nasa.gov/resources/6944/martian-blueberries/>)

due to their blue hue in false-color images released by NASA, were found by the Mars exploration rover Opportunity in 2004 at the *Fram crater*. Embedded in a sulfate-salt matrix or loose on the surface (Fig. 1), these hematite spherules might originate from accretion underwater.

Cross-References

- [Banded Iron Formation](#)
- [Goethite](#)
- [Great Oxidation Event](#)
- [Hydrothermal Environments](#)
- [Iron](#)
- [Iron Cycle](#)
- [Iron Oxidation](#)
- [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- [Iron Reduction](#)
- [Jarosite](#)
- [Mars](#)
- [Oxygenation of the Earth's Atmosphere](#)

Heme

Henderson James CleavesII
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A heme is a ► [protein](#) prosthetic group that consists of an ► [iron](#) ion chelated in the center of a ► [porphyrin](#). A substantial fraction of porphyrin-containing metalloproteins have heme as their prosthetic group. Heme-containing proteins have a number of biological functions, including diatomic gas transport (e.g., hemoglobin), chemical catalysis (e.g., peroxidase), and electron transfer (e.g., cytochrome). The heme iron serves

as a source or sink of electrons during redox chemistry; however, in several peroxidases, the porphyrin molecule also serves as an electron source. In the transportation of diatomic gases, the gas binds to the heme iron, often inducing a conformational change in the surrounding protein.

The original function of heme-containing proteins may have been electron transfer in primitive sulfur-based ► [photosynthesis](#) pathways in ancestral cyanobacteria before the evolution of oxygenic photosynthesis. Melvin Calvin suggested that heme may have served as a primitive peroxidase prior to the formation of proteins.

Cross-References

- [Iron](#)
- [Photosynthesis](#)
- [Porphyrin](#)
- [Protein](#)

HEPA Filters

Catharine A. Conley
NASA Headquarters, NASA Ames Research
Center, Washington, DC, USA

Synonyms

[High-efficiency particulate-absorbing filters](#); [High-efficiency particulate air filters](#); [High-efficiency particulate-arresting filters](#)

Definition

These filters are manufactured and tested to ensure that filtered air has undergone a reduction in the level of particulate contamination. An HEPA filter, e.g., H14, is certified and tested to filter 99.975% of the particles with a size of 0.3 µm. Filtration of particles larger or smaller is more effective than the size for which the rating is

provided. Such filters are used in space industry to isolate some volumes from a dusty or contaminated environment. For ► [planetary protection](#), they are used in clean rooms to filter the incoming air and in BSL-4 laboratories to filter both air inlets and outlets.

Cross-References

- [Biological Safety Level](#)
- [Cleanroom](#)
- [Planetary Protection](#)

Herschel Mission

Göran L. Pilbratt¹ and Mark J. McCaughrean²

¹Science Directorate Science Division (SCI-SC), European Space Agency, Noordwijk, The Netherlands

²Senior Advisor for Science & Exploration (SCI-A), European Space Agency, Noordwijk, The Netherlands

Keywords

Astrochemistry · Galaxy formation · Galaxy evolution · Infrared galaxies · Infrared observatories · Interstellar chemistry · Interstellar dust · Interstellar medium · Interstellar molecules · Molecular clouds · Protostars · Space observatories · Star formation · Stellar evolution

Definition

The Herschel Space Observatory was a ► [European Space Agency](#) (ESA) facility for far-infrared and submillimeter astronomy, providing unprecedented observing capabilities in the ~55–670 μm spectral range. NASA collaborated through the provision of detector technologies and science operations support. With its 3.5 m diameter primary mirror and three science instruments,

Herschel was launched on 14 May 2009 and performed its final science observation on 29 April 2013 once its liquid helium coolant had been exhausted, having carried out ~23,500 h of successful science observing. All data and associated data products are publicly available to the worldwide astronomy community through the Herschel Science Archive. The main science objectives addressed by the mission were ► [interstellar medium](#) physics, star formation and evolved ► [stars](#), and galaxy evolution.

History

Herschel has a long history. Conceived of as the Far Infrared and Sub-millimetre Telescope (FIRST) and proposed to ESA in November 1982 in response to a call for mission proposals issued in July 1982, it was incorporated into the ESA “Horizon 2000” long-term plan in 1984. Over the years, it was the subject of multiple studies adopting a variety of mission designs, spacecraft configurations, telescopes, and science payloads. In November 1993, the ESA Science Programme Committee (SPC) decided that FIRST would be implemented as the fourth “Cornerstone” (CS4) mission. The science payload was selected in 1997–1999, the major industrial contractors in 2000–2001, and in April 2001, the corresponding industrial activities commenced. Meanwhile, in December 2000, FIRST was renamed “Herschel” in recognition of the 200th anniversary of the discovery of infrared light by German-born British astronomer and composer, William Herschel (1738–1822).

The three science instruments, HIFI, PACS, and SPIRE, were delivered and integrated in 2007; final integration, testing, and verification activities took place in ESA’s ESTEC Test Centre from January 2008 to January 2009, after which the Herschel spacecraft was flown to Europe’s spaceport, the Guiana Space Centre in Kourou, French Guiana, for the launch campaign. Herschel was launched together with Planck on an Ariane 5 ECA on 14 May 2009, operated from a large halo orbit around the second Lagrange point (L2) in the Sun–Earth system, and performed its

final science observation on 29 April 2013, when it ran out of superfluid liquid helium coolant. The spacecraft was put into a heliocentric “disposal orbit,” where it will remain indefinitely, and finally turned off on 17 June 2013.

Herschel observers and science data users were supported in the exploitation of Herschel data throughout the post-operation phase, which formally ended in December 2017, but continued at a low level into 2019. The total mission cost is estimated at €1200 million.

Overview

Mission

The Herschel Space Observatory was the fourth “Cornerstone” mission in the European Space Agency (ESA) “Horizon 2000” science plan. Herschel was a facility for far-infrared and submillimeter astronomy, providing unprecedented observing capabilities in the $\sim 55\text{--}670\ \mu\text{m}$ spectral range. With a 3.5 m diameter silicon carbide primary mirror, it offered a much larger telescope and extended longer-wavelength spectral coverage compared to earlier infrared missions such as the Infrared Astronomical Satellite (IRAS), the Infrared Space Observatory (ISO), Akari, and Spitzer. Additionally, it bridged the wavelength gap to ground-based submillimeter facilities, and its data still provide a key observational database for follow-up observations, in particular with the Atacama Large Millimeter/sub-millimeter Array (ALMA).

Herschel was launched together with ESA’s Planck cosmic microwave background mission at 13:12:02UTC on 14 May 2009 by Ariane 5 ECA VA-188 from Europe’s spaceport, the Guiana Space Centre, in Kourou, French Guiana. It operated in a large quasi-halo orbit around the second Lagrange point (L2) in the Sun-Earth/Moon system, with a daily ground contact period of normally about 3 h. Herschel successfully carried out its observing programs until it ran out of superfluid helium coolant on 29 April 2013, putting a permanent end to any further taking of science data. The spacecraft was put into a heliocentric “disposal orbit” and finally turned off on 17 June 2013.

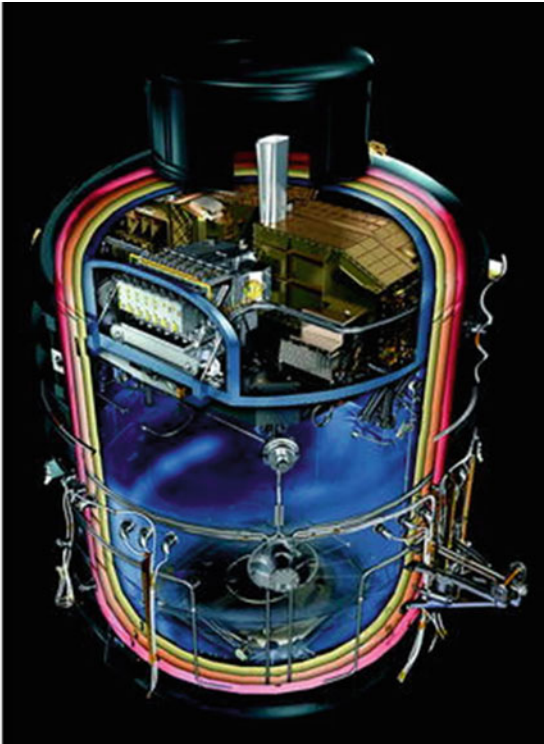
Spacecraft and Telescope

The Herschel spacecraft (Fig. 1) provided the appropriate working environment for the science instruments receiving photons from the telescope, pointed the telescope with required accuracy, autonomously executed the observing timeline, and performed onboard data handling and communication with the ground. The design is modular, consisting of the “payload module” (PLM) supporting the telescope, the “service module” (SVM), and the sunshade/sunshield. The mission lifetime was determined by the exhaustion of the superfluid helium used to cool the scientific instruments in their cryostat: it was designed to meet a requirement of 3.5 years and in fact lasted just under 4 years.

The PLM is dominated by a cryostat vacuum vessel containing a suspended superfluid liquid helium (SLHe) tank, an optical bench with the three scientific instrument focal plane units (FPU) supported on top of the tank, all surrounded by three vapor-cooled shields to minimize parasitic heat loads. The tank contained $\sim 335\ \text{kg}$ or 2320 l of SLHe at launch and a phase separator allowed a continuous evaporation of the liquid into cold gas, keeping the FPUs and their detectors at their required operating temperatures.

The primary mirror of the telescope is 3.5 m in diameter and made of 12 individual petal of silicon carbide brazed into a single unit. It was passively radiatively cooled and had an inflight operating temperature of about 88 K and very low emissivity. The total wavefront error (WFE) of the telescope was less than $5\ \mu\text{m}$ at the focal surface interfacing to the instruments.

The SVM houses “warm” payload electronics on four of its eight panels and provides the necessary infrastructure for the satellite such as power, altitude and orbit control, the onboard data handling and command execution, communications, and safety monitoring. It also provided a thermally controlled environment, which was critical for some of the instrument units. Finally, the SVM also provides mechanical support for the PLM, the sunshield/sunshade, and a thermal shield to thermally decouple the PLM from the SVM. It also supported the main mechanical load path during launch.



Herschel Mission, Fig. 1 *Left:* Herschel being prepared for acoustic testing in the ESTEC Test Centre in June 2008, providing a good view of the telescope. *Right:* A cut-away image of the payload module showing the three scientific

instrument focal plane units on the optical bench on top of the helium tank. Also illustrated is the “Russian doll” structure minimizing “parasitic” heat loads (ESA)

Science Instruments

Herschel has three science instruments provided by European member states and the scientific community, with NASA supplying detector technologies for two of them. The main characteristics of the Photodetector Array Camera and Spectrometer (PACS), the Spectral and Photometric Imaging REceiver (SPIRE), and the Heterodyne Instrument for the Far Infrared (HIFI) are shown in Table 1.

Basic Methodology

Operations and Science Ground Segment

Mission operations were provided by the Mission Operations Centre (MOC) at ESA’s European Space Operations Centre (ESOC) in Darmstadt, while the science operations were conducted at five centers:

Herschel Mission, Table 1 Herschel science instrument main characteristics

Acronym	Instrument	Principal investigator
PACS	Imaging camera and grating spectrometer, spectral coverage ~55–205 μm	A. Poglitsch, MPE, Garching (DE)
SPIRE	Imaging camera and FTS spectrometer, spectral coverage 194–671 μm	M. Griffin, U. Cardiff (UK)
HIFI	Heterodyne spectrometer, spectral coverage 157–212 and 240–625 μm	F. Helmich, SRON, Groningen (NL)

- The Herschel Science Centre (HSC) at the European Space Astronomy Centre (ESAC), near Madrid, provided by ESA

- Three dedicated Instrument Control Centres (ICCs), one for each instrument, provided by the respective PIs
- The NASA Herschel Science Center (NHSC), at JPL in Pasadena, provided by ► [NASA](#)

Mission operations ended after the observatory was passivated in 2013, while science operations led by the HSC, supported by the ICCs and the NHSC (primarily for the US science community), continued until the end of 2017, supporting the community in exploiting the science data throughout the post-operation phase. Data processing software and science archive were improved during this time, refined products ingested into the archive, and documentation enhanced, finally yielding the Herschel Legacy Archive.

Observing

Herschel was operated as an observatory, with roughly a third of the observing time guaranteed to the three instrument teams and the rest available as open time to the worldwide community. Astronomers made competitive applications for the open time on Herschel competitively by responding to calls for proposals (Announcements of Opportunity – AOs), providing the science objectives and the definition of the actual observations being proposed. There were two open AOs issued after the mission had been launched, resulting in roughly 600 proposals each time. All proposals were reviewed by the independent Herschel Observing Time Allocation Committee (HOTAC), and just over half were accepted at each AO. The observations by the successful proposers were then carried out. A small amount of the open time was allocated as discretionary time.

Given that Herschel would not have the benefit of a pre-existing all-sky survey for much of its wavelength coverage, it was decided early on that large so-called key programs (KPs) in the form of “large spatial and spectral surveys” would be selected pre-launch and executed early in the mission. A dedicated AO for KPs was issued prior to flight and roughly 48% of the total observing time was allocated to them – the majority of Herschel’s highly cited papers result from KP data.

Herschel successfully observed until it ran out of superfluid helium coolant in April 2013. Since 29 October 2013, all Herschel science observations have been publicly available from the Herschel Science Archive (HSA) to the worldwide astronomical community. The HSA offers over 37,000 successful observations obtained in ~23,500 h of science observing (exceeding the nominal mission by ~20%), covering almost 10% of the sky. In addition, there are over 6,600 science calibration observations publicly available from the archive.

Key Research Findings

The “Cool Universe”

Herschel’s broad remit was to study the low-temperature or “cool universe.” It was the first and to date only space facility dedicated to the far-infrared and sub-millimeter regions of the electromagnetic spectrum. Roughly half the energy emitted in the universe since the formation of the cosmic microwave background (CMB) has been absorbed by dust in the ► [interstellar medium](#) (ISM) in our ► [Milky Way](#) and other galaxies, and subsequently reemitted lower temperatures and thus at the longer Herschel wavelengths. The integrated spectrum of the reradiated emission peaks in the 100–200 μm range. In addition to the dust continuum, gas in the ISM emits in a profusion of spectral lines that lie in the Herschel wavelength range.

The main scientific focus of Herschel was the formation and evolution of stars and galaxies, and the physics and chemistry within the ISM from which they form and interact with. This spanned our own Milky Way and extragalactic space beyond. In addition, Herschel studied disks of gas and dust around young stars providing information and comparisons with the global properties of extrasolar planetary systems around nearby stars, and also observed a range of objects in our own solar system, including planets, moons, comets, and asteroids.

In October 2013, shortly after the end of the mission, a symposium titled “The Universe Explored by Herschel” symposium was held,

with ~360 participants making in excess of 100 oral and ~200 poster presentations. Several other symposia dedicated to Herschel science topics have since been held.

Since the end of mission, papers based on Herschel data have continued to be published at a steady rate of 200–300 a year, illustrating the continued importance of its far-infrared and sub-millimeter observations: at the time of writing (August 2021), approximately 3,000 papers have been published in total. It is impossible to give a full overview here – rather, a few illustrative highlights are briefly described below. See the references for links to more complete information.

The Galactic Plane

One of the largest legacy data sets generated by Herschel is its complete 360° photometric survey of the entire galactic plane in five bands from 70 to 500 μm . Figure 2 shows a small fraction of the Herschel survey data centered at galactic longitude $l = -10^\circ$, combined with shorter wavelength data from NASA's Spitzer mission – dramatic structure is clearly visible on all scales. Together with ancillary data at other wavelengths including those of Spitzer, these data enable astronomers to address a number of fundamental questions regarding the global workings of our Galaxy, in particular with respect to (high-mass) star formation and the resulting feedback on the ISM environment. The aim of such studies is to derive

global star formation rates, in order to construct a new 3D model of the Milky Way and to map the essential critical parameters including column density thresholds, and the rate and efficiency of star formation in our galaxy.

A Stellar Nursery

Figure 3 shows a combined Herschel and Planck view of a stellar nursery in the Aquila Rift at a distance of approximately 260 parsecs. Far-infrared (250, 350, and 500 μm) data from Herschel SPIRE reveal the low-temperature dust cloud comprising many filaments, in which some 700 clumps of gas and dust are found. Approximately 100 of these are thought to be protostars in the final stages of collapse into stars. Analysis of these and other Herschel SPIRE and PACS data in other regions led astronomers to propose that filaments play a key role in the collapse of clouds to star-forming clumps, individual stars, and clusters such as Westerhout 40 seen at left. Overlaid on the Herschel data are “streamlines” illustrating the magnetic field orientation as derived from Planck data – the interplay between gravity, radiation, and magnetic fields lies at the core of the star formation process.

Astrochemistry Revealed

In addition to its long-wavelength photometric imaging capabilities, Herschel was also able to undertake high-sensitivity, high spectral

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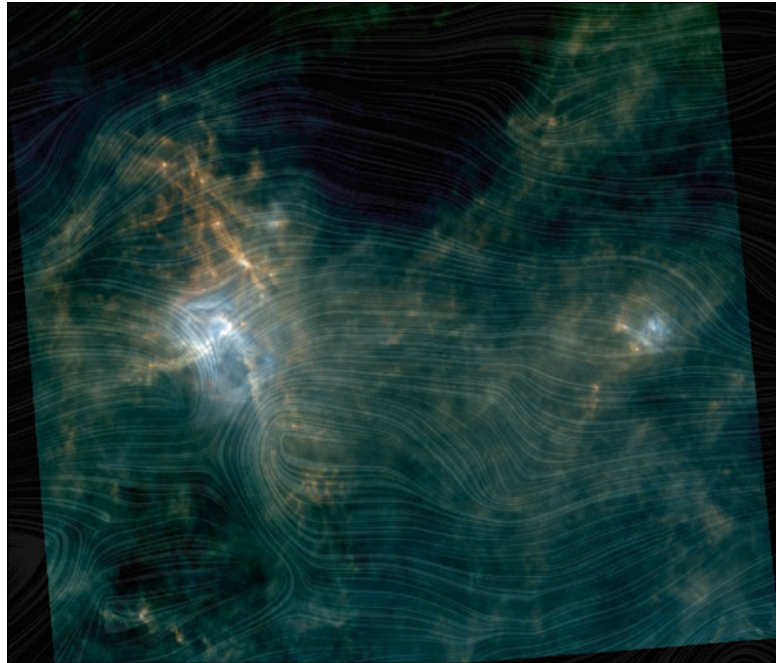


Herschel Mission, Fig. 2 ESA Herschel and NASA Spitzer view of approximately 3% of the Galactic Plane. Combining Spitzer/MIPS 24 μm (blue), Herschel/PACS 160 μm (green), and Herschel/SPIRE 250 μm (red) data, it covers 12° in galactic longitude centered at $l = -10^\circ$ and

stretches $\sim 1.5^\circ$ above and below the plane. Observations from the Herschel Hi-GAL Key Programme (PI: S. Molinari) and the Spitzer MIPS/GAL Program (PI: S. Carey). (Image processing by H. Bouy (CAB CSIC), E. Bertin (IAP), and B. Merin (ESA))

Herschel Mission,

Fig. 3 The Aquila Rift star-forming region as seen by Herschel and Planck. The underlying image is an RGB combination of Herschel SPIRE data at 500, 350, and 250 μm , respectively, and the overlaid “streamlines” illustrate the direction of the magnetic field, as derived from Planck data. (ESA/Herschel/Planck, J. D. Soler, MPIA)



resolution surveys of the many emission lines in its wavelength range coming from cool gas in the ISM, enabling comprehensive studies of astrochemistry.

Figure 4 shows part of a HIFI spectral scan made towards the Orion Nebula, one of the nearest regions of massive star formation: among the molecules identified in this spectrum are water, carbon monoxide, formaldehyde, methanol, dimethyl ether, hydrogen cyanide, sulfur oxide, sulfur dioxide, and their ► [isotope](#) analogues.

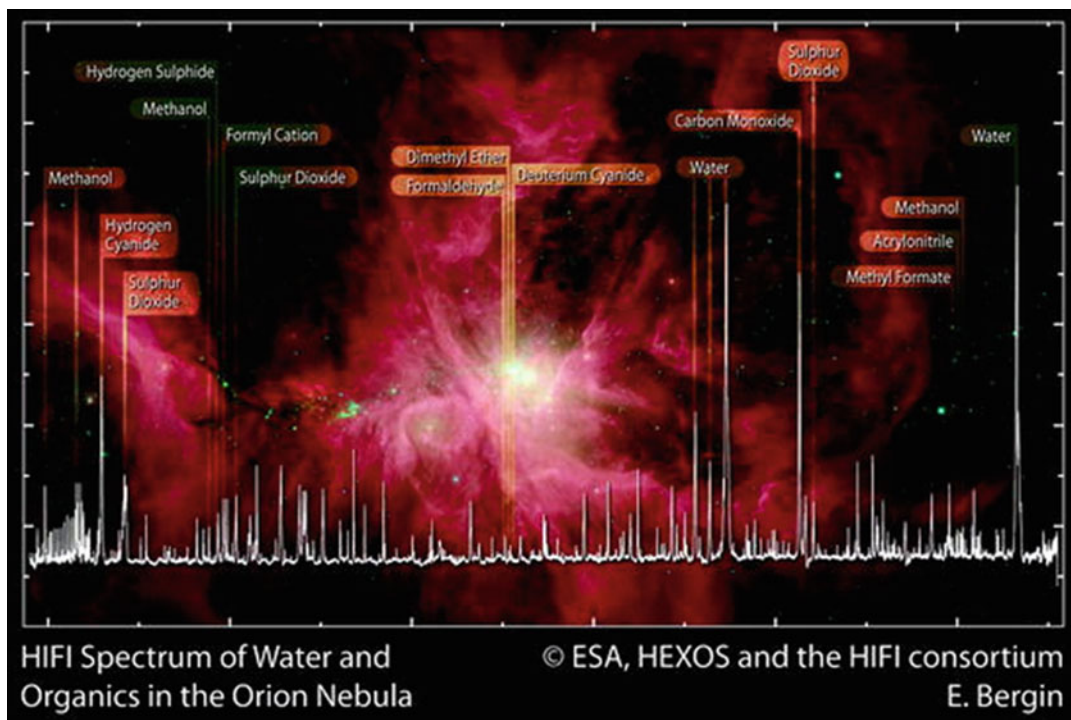
This spectrum demonstrates the spectral richness of regions of star and planet formation; the complete survey has more than 20,000 lines, enabling a much deeper understanding of the astrochemistry of the region. Similar broad spectral surveys were conducted in many regions throughout the Milky Way.

Water

A particular focus of Herschel spectroscopy was the study of water in gas form throughout the universe. For example, one key program (WISH) was dedicated to tracing water through the various

stages of star and planet formation, enabling a detailed analysis of the physical and chemical conditions and processes. A comprehensive review of the WISH results, along with other Herschel observations of water, was published by van Dishoeck et al. (2021)

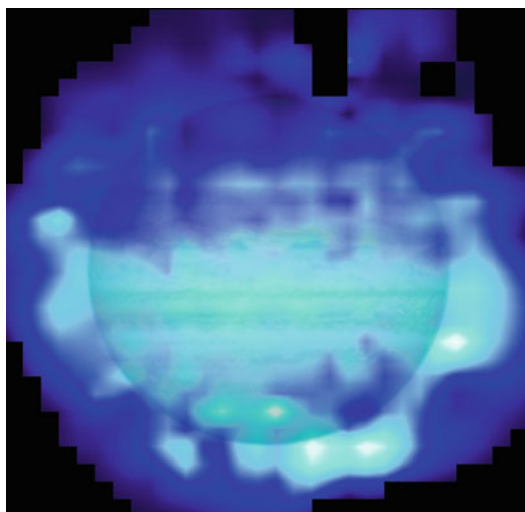
Closer to home, a combined PACS and HIFI spectroscopic study of Jupiter found direct proof that the bulk of the water currently present in the planet’s stratosphere was delivered by Comet Shoemaker-Levy 9, the many fragments of which struck the planet in 1994. The PACS observations in a grid of 25 points across the disk of Jupiter showed that the water is predominantly confined to the southern hemisphere, where the comet struck. The HIFI observations indicate that the bulk of water is confined to pressures lower than 2 millibars, corresponding to high stratospheric altitudes – well above the uppermost part of the troposphere which effectively acts as a “cold trap.” As a consequence, the water in the stratosphere is inferred to have been delivered from an external source, identified as the 1994 comet fragment impacts (Fig. 5).



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Herschel Mission, Fig. 4 A part of a Herschel/HIFI spectral scan (white curve) of the Orion Nebula, covering a frequency range of approximately 1.06–1.15 THz,

overlaid on a Spitzer Space Telescope mid-infrared image of the region. (ESA/HIFI/HEXOS/E. Bergin)

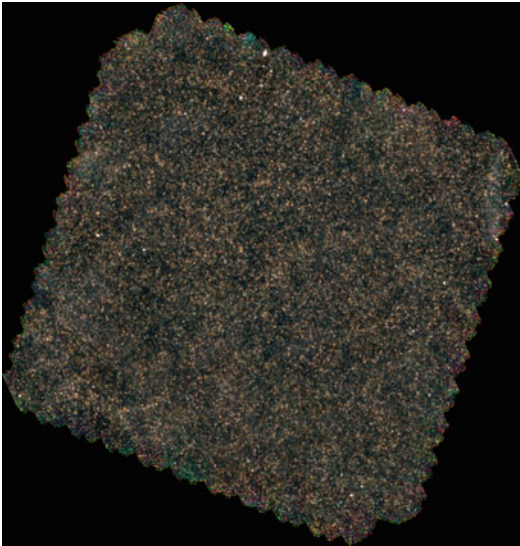


Herschel Mission, Fig. 5 The distribution of water in the stratosphere of Jupiter. White and cyan indicate highest concentration of water, while blue indicates smaller amounts. The map has been superimposed over an image of Jupiter taken at visible wavelengths with the Hubble Space Telescope. (ESA/Herschel/T. Cavalié et al.; Jupiter image: NASA/ESA/R. Beebe (New Mexico State University))

The Evolution of Galaxies

In addition to its wide-ranging studies of the Milky Way, Herschel also dedicated a significant fraction of its observing time to galaxies across the universe, in both pointed observations of individual galaxies and deep and/or wide-field surveys of populations of galaxies spanning a wide range in redshift.

Many of these surveys were conducted in well-known “deep field” locations including the Lockman Hole, the Chandra Deep Field North, the two GOODS field, and the COSMOS field (see Fig. 6), and more, regions that have been well-studied by telescopes covering much of the electromagnetic spectrum. Together, these surveys enabled important studies of the evolution of star formation, cosmic recycling, feedback, and the role of black holes across cosmic time.



Herschel Mission, Fig. 6 This image shows the COSMOS field as seen at far-infrared and submillimeter wavelengths with the Herschel SPIRE instrument. The COSMOS field is a two-square degree patch of the sky that is being extensively observed across the electromagnetic spectrum to study star formation in distant galaxies. The image contains thousands of galaxies; each dot in the image is a galaxy. (ESA/Herschel/SPIRE/HerMES Key Programme)

Cross-References

- [Infrared Space Observatory](#)
- [Interstellar Medium](#)
- [Lagrange Points](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Protostars](#)
- [Spitzer Space Telescope](#)

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Further Reading

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- Herschel Science Archive at: http://herschel.esac.esa.int/Science_Archive.shtml
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Herschel, William

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

William Herschel (1738–1822) was a German-born musician and, most famously, astronomer, who spent most of his life in Britain. He discovered Uranus in 1781, thereby doubling the size of the known solar system. Other important astronomical discoveries concerned the atmosphere of Venus and others planets of the Solar system: between 1787 and 1789 he discovered Mimas and Enceladus, Saturn’s sixth and seventh satellites, and in 1787, he identified the first two satellites of Uranus, Oberon and Titania. With the assistance of his sister Caroline Herschel (1750–1848), an important astronomer by herself, whose most significant contribution to astronomy was the discovery of several comets, he worked on a catalog of nebulae and star clusters (the observational reductions were primarily made by Caroline). As an astrobiologist, it is interesting to note that Herschel believed it likely that the Moon and planets harbored life.

William Herschel had only one child, John Frederick William Herschel (1792–1871), also an astronomer who made important contributions to stellar astronomy (namely star clusters and nebulae).

The European Space Agency's Herschel Space Observatory that was launched on May 14, 2009, was conceived to study the darkest and coldest parts of the Universe by the light of the far-infrared and submillimeter portions of the spectrum.

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Hertzsprung-Russell Diagram

Thierry Montmerle¹ and Sylvia Ekström²

¹Institut d'Astrophysique de Paris, CNRS/Université Paris 6, Paris, France

²Observatoire Astronomique de l'Université de Genève, Faculté des Sciences, Université de Genève, Versoix, Switzerland

Keywords

Effective temperature · Luminosity · Stars · Stellar evolution

Synonyms

Color-magnitude diagram; HR diagram; Luminosity-temperature diagram

Acronyms

HRD

Definition

The Hertzsprung-Russell diagram plots the ► [magnitude](#) and color of stars, which are

converted via theoretical models and distances into stellar luminosities and surface ("effective") temperatures. Comparison with theoretical tracks, the "paths" in the diagram corresponding to changes in observed properties as the star evolves, then allows the determination of the mass or age of a star or cluster. Note in the following the astrophysical use of the term "burning" to signify nuclear fusion (e.g., of hydrogen to helium).

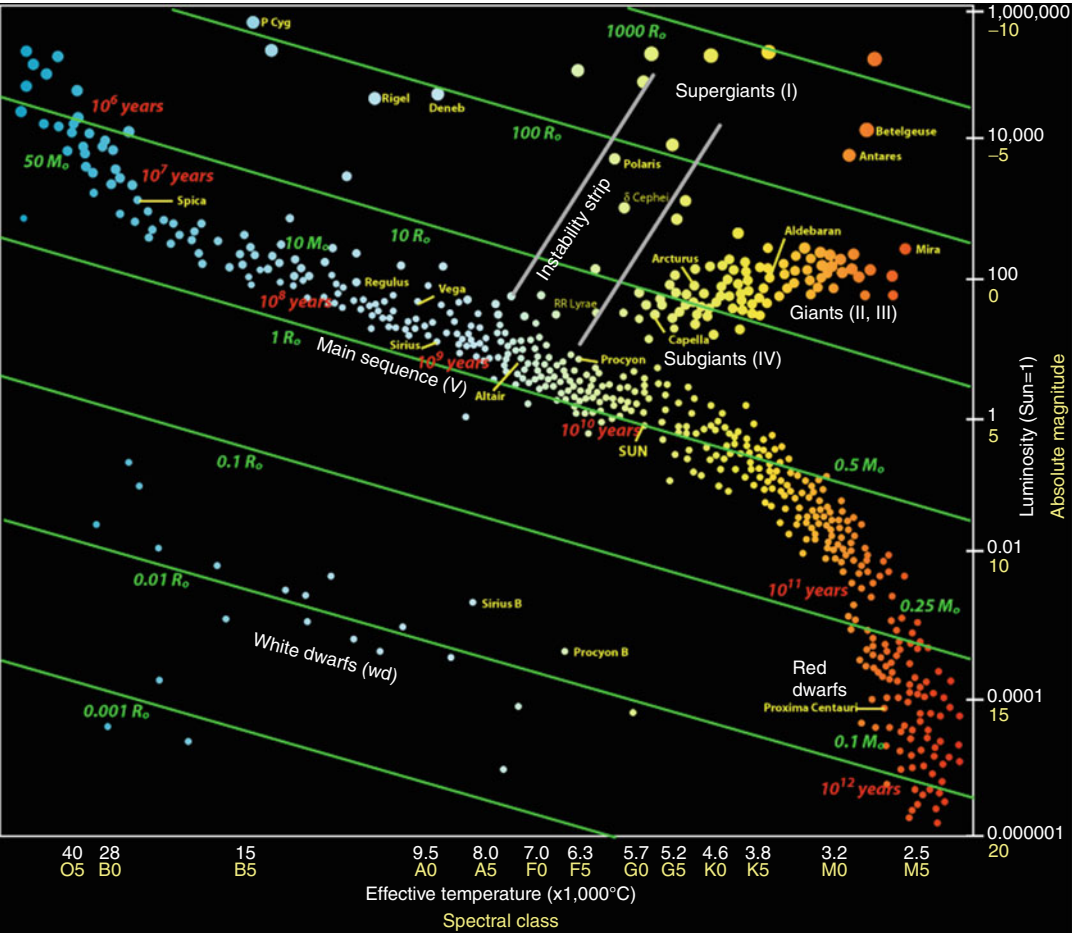
Since the beginning of the twentieth century, astronomers have been using the "Hertzsprung-Russell diagram" (from the name of its discoverers, in the early twentieth century; hereafter HRD) to classify stars and understand their evolution, from their formation to their very late stages.

Overview

When plotted in the HRD, the stars do not appear randomly distributed (see Fig. 1). There are some regions that are more populated and others that are almost empty. There is an evident relation between the density of a region and the duration of the ► [stellar evolution](#) phase that occurs in that region. During their evolution, stars pass from long-lasting hydrostatic burning (nuclear fusion) phases to quick structural readjustments. While it is easy to observe the stars in regions where the hydrostatic burnings occur, very few stars can be observed during their readjustment phases.

Basic Methodology

Observationally, astronomers first determine the magnitude and ► [spectral type](#) of the stars. These numbers are then transformed into luminosity and temperature, which are physical quantities that can be compared with models. This assumes the capability (1) to know the distance (to convert magnitudes into luminosities), which is determined by various methods (to an accuracy of ~20–30% in the case of young stars), and (2) to convert from spectral types to temperatures,



Hertzsprung-Russell Diagram, Fig. 1 Hertzsprung-Russell diagram (Courtesy Javier García Nombela, art-res.net). The observational units are in yellow (absolute magnitude versus spectral class) and the theoretical ones in white (luminosity versus effective temperature). Some

significant regions are indicated in gray. The duration of the main sequence for the different masses is indicated in red. Lines of isoradius are sketched in green. The names of some known stars are indicated

which can be done with models of stellar photospheres. For “simple” stars like the Sun, the temperature determination is very precise (<1%), but for more complex spectra, like the T Tauri stars which have a circumstellar disk, the uncertainty may reach 10–20% or more.

Key Research Findings

Populated Regions

When the HRD is used with a sample of observed stars, it gives statistical information about the surface characteristics of stars, defining specific

regions. Each region can be associated to a particular evolutionary phase by the knowledge of stellar evolution and theoretical tracks (see below). There are many interesting regions standing out in the diagram. Among them, one can mention the following ones.

Main Sequence

The great majority of the stars lie in the diagonal, the main sequence (MS), which represents the zone where stars convert hydrogen into helium, i.e., the first and longest phase of the nuclear life of stars. This phase can last billions of years for a star like the Sun. Since stars follow a

mass-luminosity relation, with $L \propto M^3$ during the MS, the location of a star on the MS allows an estimation of its mass. After this phase, the fusion of hydrogen goes on in a shell, while the core contracts and the envelope expands: the stars cross rapidly the HRD and become red giants or supergiants.

Giants and Supergiants

The giants and supergiants regions mark the location of the HRD where hydrostatic helium burning occurs.

Stars between 0.8 and $2 M_{\odot}$ (solar masses) leave the MS to climb on the red giant branch until they undergo a flash which ignites helium fusion in their core. After the flash, they settle on the horizontal branch (giants region) where they burn helium quietly. Between 2 and $10 M_{\odot}$, the core helium burning starts smoothly, following the same path in the HRD. Above $10 M_{\odot}$, most of the central helium burning occurs in the red supergiants region.

After central helium exhaustion, stars between 2 and $10 M_{\odot}$ populate the asymptotic giant branch, where an unstable double shell burning (a shell of helium burning and another of hydrogen burning) drives thermal pulsations.

Instability Strip

The instability strip marks a region in the HRD where stars become unstable to radial pulsations. This region is occupied by stars of different types, among which two are commonly used as distance calibrators:

1. RR Lyrae, which are old giants of low **metallicity** on the horizontal branch.
2. Classical Cepheids, which are helium burning stars between 4 and $12 M_{\odot}$.

The distance calibration is based on the attenuation from the absolute magnitude (which represents the intrinsic stellar luminosity) to the apparent magnitude (reflecting the observed brightness; Hertzsprung 1913). While in the normal case, it is extremely difficult to determine the absolute magnitude of a star, RR Lyrae and Cepheids present, respectively, a metallicity-

luminosity and a period-luminosity relation that have long been thought to offer an easy knowledge of their absolute magnitude, since the periods and metallicities can be measured. It is now known that those relations are more complex and less direct than previously considered (see Sandage and Tammann 2006, and references therein), and their use as distance calibrators must be considered with caution.

White Dwarf Location

At the end of the evolution, stars below $\sim 10 M_{\odot}$ expel their envelope as a *planetary nebula* and settle on the white dwarf branch, where they progressively cool.

Theoretical Tracks

When theoretical tracks are plotted in the HRD, they offer an evolutionary link between the different populations by giving the time sequence of the surface characteristics by which the stars pass throughout their evolution.

An example of a theoretical HRD is given in Fig. 2 (Schaller et al. 1992). It plots the evolution of the stars from the central hydrogen ignition to the end of helium burning. For low- and intermediate-mass stars, that is the end of the evolution, while for massive stars (above $10 M_{\odot}$), the nucleosynthetic activity continues in the core, up to silicon burning. However, after helium exhaustion, the evolution of massive stars accelerates significantly so the core and the envelope decouple: their external properties remain almost identical throughout the advanced phases up to the time of the supernova explosion.

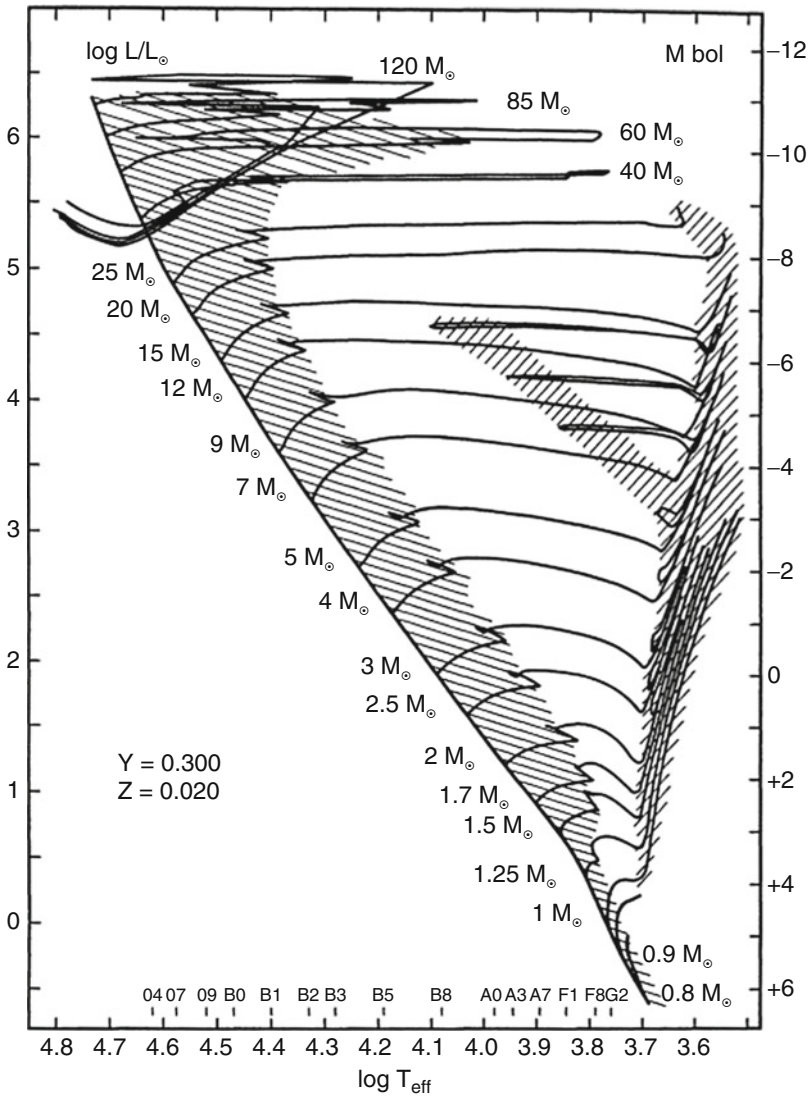
Before the Main Sequence: Hayashi Tracks

From the main sequence onwards, the energy output is always *thermonuclear* in origin, with successive nuclear reaction networks driving important changes in the overall stellar structure.

Before the main sequence, however, the situation is entirely different, since the stars slowly shrink as the radiation generated by gravitational contraction is evacuated in the form of light. In other words, the energy of “pre-main sequence” stars (protostars and T Tauri stars) is *not* nuclear in origin but is drawn only from *gravitation*. This

Hertzsprung-Russell Diagram,

Fig. 2 Theoretical tracks of stellar evolution in the Hertzsprung-Russell diagram (From Schaller et al. 1992), showing luminosity (relative to the Sun) (scale on the left) and bolometric magnitude (M_{bol} , scale of the right) versus effective temperature. The shaded area represents the regions of H and He burning. Stellar mass indicated along the main sequence line



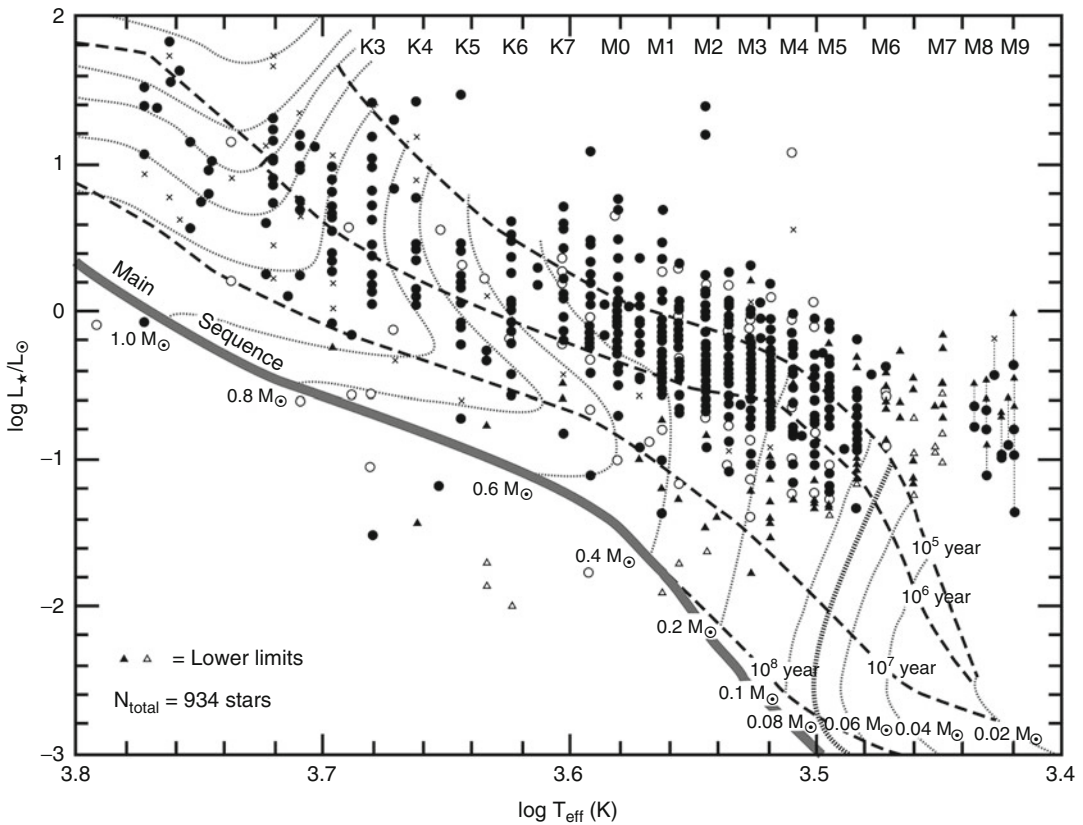
“simplification” explains that, as early as 1966 (when only low-power computers were available!), theoretical models of pre-main sequence evolution could be devised by Hayashi and his collaborators in Japan.

This early work on “Hayashi” evolutionary tracks in the HRD distinguished two main phases which are still used as a reference today:

1. The “convective” phase, in which the stars are fully convective and evolve essentially isothermally (i.e., at the same temperature, so that the theoretical HRD tracks as a function of mass are all vertical).

2. The “radiative” phase, in which a radiative core develops inside the star, which then becomes hotter but evolves at an almost constant luminosity (following the contraction in radius).

Figure 3 illustrates pre-main sequence evolutionary tracks, running through observational points for the young Orion nebula cluster: each point represents a star, ordered by luminosity and temperature. For a star like the Sun, the convective phase lasts about 10 million years, during which the temperature is held almost constant, around 4600 K, and the luminosity drops by a



Hertzsprung-Russell Diagram, Fig. 3 Hertzsprung-Russell diagram of 934 low-mass members of the young Orion Nebula Cluster (Hillenbrand 1997) and theoretical pre-main sequence tracks, labeled in masses and ages (dotted lines). The spectral types corresponding to surface

temperatures (T_{eff}) are also indicated. Most stars appear to be younger than a few million years, with masses from $0.1 M_{\odot}$ or less, up to a few $M_{\odot}$ (higher masses are located outside of this diagram). (From Montmerle et al. 2006)

factor of ~ 20 with respect to the early T Tauri stage (when the young Sun starts to be optically visible). Then the radiative phase lasts from ~ 10 million to ~ 100 million years at a roughly constant luminosity ($\sim 1 L_{\odot}$), until the thermonuclear reactions transforming hydrogen into helium start. This marks the beginning of the main sequence, already described, on which the Sun has been for ~ 4.5 billion years and still is today.

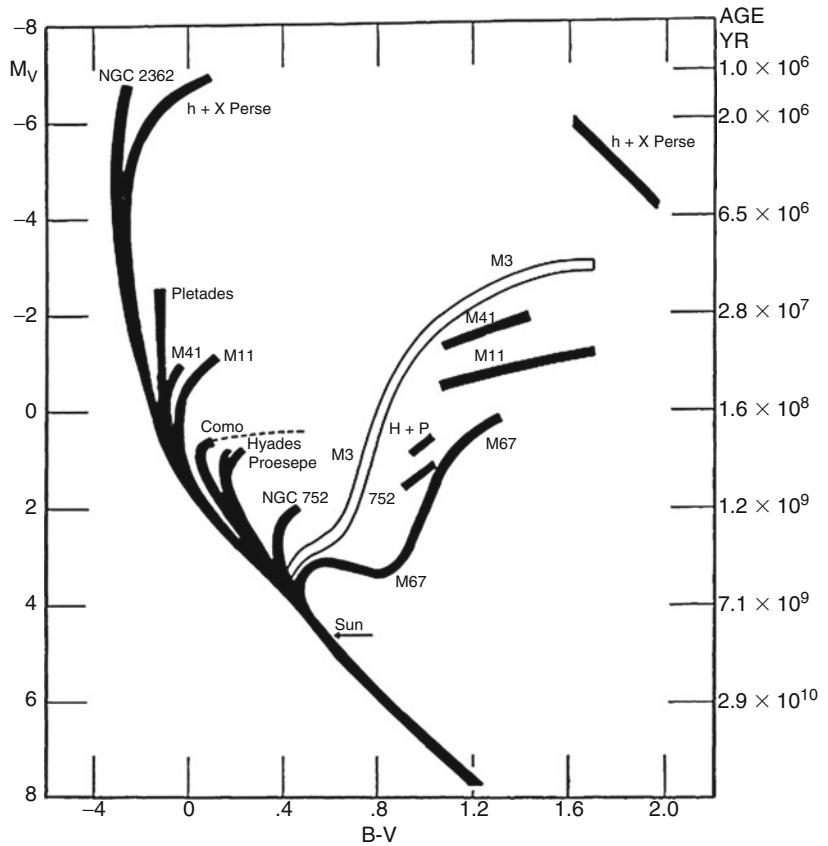
Applications

Once located in the HRD, observed stars can be compared to theoretical tracks. From such a confrontation, one can evaluate the mass and evolutionary status of the star.

The HRD can also be used to plot a whole cluster (see Fig. 3 for a young cluster and Fig. 4 for an evolved cluster). The graph obtained will be then compared to theoretical **isochrones** (location of stars with different masses at a given age), so the age of the cluster can be determined.

The comparison between observed stars and theoretical tracks is neither straightforward nor simple. As mentioned above, the comparison between observation and theory implies a conversion from observational units (color and magnitude) to theoretical ones (effective temperature and luminosity), with some uncertainties in the conversion. Some observed stars may be unresolved binaries, giving access only to the addition of their magnitude and to the mean of their color index. Some stellar parameters (as the

Hertzsprung-Russell Diagram, Fig. 4 Color-magnitude diagram of several galactic clusters (From Sandage 1958). The age of the turn-off from the main sequence is indicated on the *right* axis. Historically, this is the first compilation of this type. The shortest ages (less than a few 10 million years) are wrong, because the “pre-main sequence” evolutionary phases were not known at the time



chemical composition or the rotation rate, e.g.) can modify the location in the HRD of the theoretical tracks. A good knowledge of the observed object and an adequate choice of the stellar models are needed to get valuable information from such a comparison. Note that some physical inputs in the models are still uncertain (treatment of convection, mass loss prescription, magnetic fields) and can alter the tracks.

Future Directions

The stellar evolutionary tracks are established for a fixed mass sufficiently precisely that one can have an estimate of the mass and age of a star. But a major phenomenon still defies modelers. This is mass loss and its interplay with evolution, for which only crude theories exist. In the case of T Tauri stars, especially in the early stages, accretion (from a circumstellar disk) is important but is

taken only phenomenologically into account in the evolutionary models.

Cross-References

- [Isochrone](#)
- [Magnitude](#)
- [Main Sequence, Star](#)
- [Metallicity](#)
- [Pre-main-Sequence Star](#)
- [Spectral Type](#)
- [Star Formation, Theory](#)
- [Stellar Evolution](#)
- [Supernova](#)

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Hesperian

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

The middle of three systems (of time-stratigraphic units) or periods (the chronological equivalents to systems) in the Martian stratigraphic scheme, named after the region of Hesperia Planum (*Hesperia*: “The Occident”; see U.S. Geological Survey Gazetteer of Planetary Nomenclature). Depending on the different models to determine absolute ages on planetary surfaces by crater statistics, the Hesperian began ~ 3.8 billion years ago and ended at some point between 3.55 and 1.8 billion years ago.

Cross-References

- Amazonian
- Chronostratigraphy

- Crater, Impact
- Mars
- Mars Stratigraphy
- Noachian

Heterocycle

Shin Miyakawa¹ and Kensei Kobayashi²

¹Tokyo Institute of Technology, Yokohama, Japan

²Department of Chemistry, Yokohama National University, Yokohama, Japan

Definition

A heterocycle is an organic compound that contains within a ring structure, which can be aliphatic or aromatic, at least one element other than carbon, such as nitrogen, oxygen, or sulfur. Examples are purines, pyrimidines, imidazoles, and quinolines. The nitrogen heterocyclic ring system imidazole occurs in histidine (one of the 20 coded protein amino acids), and some purines and pyrimidines which occur in DNA and RNA as nucleic acid bases.

These structures have been detected in carbonaceous chondrites (e.g., purines, pyrimidines, and hydantoin). Ethylene oxide, an O-containing heterocycle compound, has been identified in the interstellar medium. In prebiotic experiments, these compounds can be formed by electric discharges and proton irradiation of gas mixtures containing carbon, nitrogen, oxygen, and hydrogen, such as CH_4 - N_2 - H_2 - O_2 . Heterocycles including purines and pyrimidines have been detected in carbonaceous chondrites.

Cross-References

- Ethylene Oxide ($\text{C}_2\text{H}_4\text{O}$)
- Histidine
- Hydantoin
- Nucleic Acid Base

Heterotroph

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

A heterotroph is any organism that needs organic compounds as a ► [carbon source](#) for the synthesis of its own cellular components. According to their source of energy, organisms can be classified as photoheterotrophs or chemoorganotrophs. Chemoorganotrophs often use reduced organic compounds as a source of both energy and carbon. Mixotrophs using inorganic compounds as an energy source and reduced organic compounds as a carbon source are an exception.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [Biosynthesis](#)
- [Carbon Source](#)
- [Chemoorganotroph](#)
- [Phototroph](#)

Heterotrophic Denitrification

- [Nitrate Reduction](#)

Heterotrophic Hypothesis

Robert Pascal

Institut des Biomolécules Max Mousseron CC1706, Université de Montpellier II, Montpellier, France

Synonyms

[Prebiotic soup hypothesis](#)

Definition

According to the heterotrophic hypothesis for the origin of life, early organisms depended on abiotically synthesized organic molecules for their structural components and as an energy source. The hypothesis is usually considered in connection with abiotic organic matter of atmospheric origin, but is also consistent with extraterrestrial inputs (► [meteorites](#), micrometeorites, comets) or hydrothermal synthesis. The dilution of organic matter in the ocean is considered sufficient reason to rule out its relevance by many opponents.

History

In 1871, the mention of a “warm little pond” by Darwin may be considered as the first mention of this hypothesis. Subsequently, it was more clearly formulated by Oparin ([1924](#)), Haldane ([1929](#)), and Urey ([1952](#)), ideas which ultimately led to the Miller experiment ([1953](#)).

Cross-References

- [Abiotic Photosynthesis](#)
- [Atmosphere, Organic Synthesis](#)
- [Chemical Evolution](#)
- [Darwin's Conception of the Origins of Life](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Extraterrestrial Delivery of Organic Compounds](#)
- [Metabolism](#)
- [Oparin's Conception of Origins of Life](#)
- [Organic Material Inventory](#)
- [Origin of Life](#)
- [Photochemistry, Atmospheric](#)
- [Prebiotic Chemistry](#)
- [Primordial Soup](#)
- [Urey's Conception of Origins of Life](#)

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Hexamethylenamine

► [Hexamethylenetetramine](#)

Hexamethylenetetramine

Greg Springsteen

Furman University, Greenville, SC, USA

Keywords

Ammonia · Condensation · Formaldehyde

Synonyms

[1,3,5,7-Tetraazatricyclo\[3.3.1.1^{3,7}\]decane](#); [11,3,5,7-Tetrazaadamantane](#); [Formamine](#); [Hexamethyleneamine](#); [Hexamine](#); [HMT](#); [Methenamine](#); [Urotropine](#)

Definition

An adamantane-like heterocycle ($C_6H_{12}N_4$) formed from the condensation of six ► [formaldehyde](#) and four ► [ammonia](#) molecules.

Overview

Hexamethylenetetramine (HMT) is a condensation product formed readily from gaseous, aqueous, or organic solutions of ammonia and formaldehyde. It was first synthesized and characterized by the Russian chemist Aleksandr Butlerov (who also discovered the ► [formose reaction](#)) in 1859 and was the first organic compound with a solved X-ray crystal structure. HMT

has a molecular formula of $C_6H_{12}N_4$ and is generated in a highly exothermic condensation (-55 kcal/mol) from six formaldehyde and four ammonia molecules with the loss of six waters. The exothermicity results from the transformation of six pi bonds into six sigma bonds. It is a white crystalline powder with a sublimation temperature of 285 – 295 °C and an adamantane-like chemical structure with tetrahedral symmetry. It is soluble in chloroform, ethanol, and water (850 g/L at 25 °C) and insoluble in diethyl ether.

It is commercially produced by passing gaseous ammonia into a concentrated solution of aqueous formaldehyde with subsequent removal of water under reduced pressure. Solid HMT can be more easily obtained on a small scale by passing gaseous ammonia into a solution of paraformaldehyde dissolved in refluxing toluene with concomitant water removal (i.e., a Dean-Stark trap).

HMT is stable in neutral and basic aqueous media, with an equilibrium constant approaching 10^{10} . In acidic media, however, it is hydrolyzed to methanimine (H_2CNH), formaldehyde, and ammonia. Synthetically, HMT is useful in the alkylation of primary amines (Delepine reaction) and in the generation of amino alcohols by reaction with oxiranes.

HMT is produced as the primary product (35% yield after 45 days at rt) from the UV irradiation of methanol-ammonia-water mixtures and has been synthesized in laboratory experiments that approximate conditions in the interstellar medium. The spectral properties of HMT and its photolysis products (namely, the 2160 cm^{-1} absorption) indicate that it may comprise a portion of interstellar ice grains and icy satellites.

Cross-References

► [Ammonia](#)
► [Formaldehyde](#)

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Hexamine

- ▶ [Hexamethylenetetramine](#)

HGT

- ▶ [Lateral Gene Transfer](#)

High Accuracy Radial-Velocity Planet Searcher

- ▶ [HARPS](#)

High Resolution Echelle Spectrometer

- ▶ [HIRES](#)

High Speed Jetstream

- ▶ [Superrotation](#)

High-Dispersion Spectroscopy

- ▶ [Planet Characterization: High-Resolution Spectroscopy](#)

High-Efficiency Particulate Air Filters

- ▶ [HEPA Filters](#)

High-Efficiency Particulate-Absorbing Filters

- ▶ [HEPA Filters](#)

High-Efficiency Particulate-Arresting Filters

- ▶ [HEPA Filters](#)

High-Energy Particles

- ▶ [Heavy Atom Beams](#)

High-Energy Photons

- ▶ [Gamma Rays](#)

High-Energy Radiation

- ▶ [Gamma Rays](#)

Highland Region

- ▶ [Terra, Terrae](#)

High-Magnesium Granodiorite

- ▶ [Sanukitoid](#)

High-Mass Star

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

Stars with an initial mass on the ► [zero age main sequence](#) above $\sim 8 M_{\odot}$ are considered to be high-mass stars. They evolve in a short timescale (< 25 Myr) by nuclear fusion of successively all available nuclear fuels, up to ^{56}Fe . The most massive of them suffer heavy mass losses through stellar winds, revealing their nuclear-processed layers (He rich or C rich). At the end of their life, they have developed an “onion skin” structure, with heavier elements lying toward the center. Gravitational collapse of the Fe core turns into a supernova explosion, ejecting most of the mass in the form of heavy elements. They are the major nucleosynthesis sites in the universe, and they leave behind either a ► [neutron star](#) or a ► [black hole](#).

Cross-References

- [Black Holes](#)
- [Neutron Star](#)
- [Nucleosynthesis, Stellar](#)
- [Stars](#)
- [Stellar Evolution](#)
- [Supernova](#)
- [Zero Age Main Sequence](#)

High-Performance Liquid Chromatography

- [HPLC](#)

High-Pressure Liquid Chromatography

- [HPLC](#)

HII Region

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Synonyms

[H⁺ region](#)

Definition

An H II region is an astrophysical object belonging to the ► [interstellar medium](#) and consisting in a cloud of hot ► [plasma](#) of protons and electrons at about 10,000 K. The name stems from the old appellation H II for the ionized state of hydrogen (now H⁺), as opposed to the neutral state H I. The plasma is produced by photoionization of the hydrogen in an interstellar cloud caused by the ultraviolet radiation from nearby hot massive stars of ► [spectral type](#) O and B. The stars are generally born in a giant ► [molecular cloud](#) and ionize the gas around them that was not condensed into stars. The occasional recombination of a proton and an electron produces a cascade in the energy levels with emission of photons that explains why H II regions appear as luminous nebulae. Their spectrum contains mainly strong H I recombination lines, especially the H α line responsible for the reddish color, as well as forbidden lines (transitions from metastable states, denoted in astronomy by square brackets) such as those from ionized oxygen and nitrogen ([O III], [O II], [N II]). The plasma is also a source of free-free (bremsstrahlung) emission mainly detected in the radio domain. *Compact* H II *regions* designate the youngest ones. The Orion nebula, easily seen with binoculars, is one archetype of an H II region (Fig. 1).

Cross-References

- [Interstellar Medium](#)

HII Region, Fig. 1 The Orion nebula is the prototype H II region, that is, a cloud of hydrogen in the Galaxy, ionized by hot stars in the vicinity. The *red* color results from the recombination of protons and electrons producing a cascade of energy with emission of light



Hill Radius/Sphere

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Synonyms

[Roche radius](#)

Definition

The region around a planet within which the planet's gravity dominates that of the star it orbits is called the Hill sphere, whose radius is called the Hill radius. The Hill radius is given by $R_{\text{Hill}} = a(m_p/3M_{\text{star}})^{1/3}$, where a is the orbital distance of the planet from the star, m_p is the planet's mass, and M_{star} is the stellar mass. The Earth's Hill radius is roughly 0.01 AU, and Jupiter's is about 0.35 AU. The Hill sphere is the same as the Roche

sphere or Roche lobe, but is not to be confused with the Roche limit.

Cross-References

► [Planet Formation](#)

Hill/Lagrange Stability

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planetary dynamics, stability refers to an aspect of the orbital motion that remains constant in time, for example, that all planets remain bound to their star. Hill stability only requires that the ordering of the orbiting bodies remain constant, meaning that the outermost planet may leave the system. The

advantage of considering Hill stability is that it can be analytically treated. In contrast, Lagrange stability requires any and all orbital oscillations to remain bounded for all times. Lagrange stability is, therefore, a type of Hill stability, but can only be assessed via N-body simulations. Many planetary systems appear to lie near these boundaries.

Cross-References

- [Exoplanets, Discovery](#)
- [Orbit](#)

Hipparcos

Michel Viso
Innovaxiom, Paris, CX, France

Definition

In 1981, ESA approved a mission covering, for the Agency, a new astronomical field. Hipparcos (originally an acronym for High Precision Parallax Collecting Satellite) was developed to determine the positions, distances, and proper motions of more than 100,000 stars with an accuracy improved by a factor of 10–100 compared to ground-based observations. In the process, it collected also data on their variability and identified and characterized binary systems.

Hipparcos, a 500 kg spacecraft, was launched into geostationary transfer orbit by an Ariane-4 launcher on 8 August 1989. However, the apogee boost motor did not fire, and it could not reach its planned geostationary orbit. Operations were conducted from a highly elliptical orbit with a period of around 10 h.

Overview

By November 1989, Hipparcos started its operational mission. The observations lasted 3.5 years, ending in August 1993. Processing and verifying the data took another 3 years. The Hipparcos Catalogue, with 118,218 entries, was finalized

on 8 August 1996, surpassing all of the original scientific goals. A larger but less accurate “Tycho Catalogue,” derived from the star mappers of the satellite’s attitude control system and incorporating 1,058,332 star positions, was also compiled. In 1997, the data set was published in 17 volumes. The enlarged Tycho 2 Catalogue of 2.5 million stars was published in 2000.

Hipparcos was the first space mission dedicated to measuring the positions of the stars. Beyond its impact on basic stellar physics and on galactic structure and dynamics, Hipparcos helped to predict the impacts of ► [Comet Shoemaker-Levy 9](#) on ► [Jupiter](#), identified stars that will pass close to the Sun, established the distances of stars possessing planets even though these planets were discovered only after the end of the mission, identified a group of stars that were captured by our Galaxy when it was young, fundamentally improved the cosmic distance scale (making the universe bigger and younger), and confirmed Einstein’s prediction of the effect of gravity on starlight.

A new ESA mission for astrometry, Gaia, was launched using a Soyouz Fregat in December 2013 from Kuru in French Guiana.

Cross-References

- [Gaia Mission](#)

HIRES

David W. Latham¹ and Nader Haghighipour²
¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[High Resolution Echelle Spectrometer](#)

Definition

HIRES (High Resolution Echelle Spectrometer) is a high-resolution spectrograph on the Keck

I telescope in Hawaii. It was originally designed as a general-purpose instrument, but one of its main applications has been the determination of radial-velocity orbits for stars hosting exoplanets in order to derive planetary masses. Because the input is a slit, an iodine gas absorption cell is introduced into the stellar beam in order to calibrate the instrumental profile and wavelength scale of each stellar observation. The data analysis requires also a high-quality template observation of each star without the iodine and a fundamental calibration of the spectrum of the absorption cell at very high spectral resolution. HIRES has achieved a performance approaching velocities as low as 1 m/s. HIRES has contributed to the discovery of several hundred extrasolar planets including the first super-Earth, GJ 876 d, several potentially habitable planets around stars such as GJ 667C and Gliese 581, and the confirmation of Kepler 78b, an Earth-sized planet detected by the Kepler space telescope. HIRES and ► [HARPS](#) on the 3.6-m telescope at the European Southern Observatory on La Silla are now the premier instruments for determining the masses of small planets.

Cross-References

- [Exoplanets, Discovery](#)
- [HARPS](#)
- [Radial-Velocity Planets](#)

Histidine

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

Histidine is one of the 20 ribosomally encoded protein ► [amino acids](#). It was first isolated by the German physician and biochemist Albrecht

Kossel in 1896. It is distinguished by having a side chain with an imidazole ring, which has a pK_a of approximately 6. Histidine has an isoelectric point (pI) of 7.6; thus, at typical intracellular pH values, relatively small shifts in pH can greatly change its average charge. When protonated, the imidazole ring is positively charged, with the positive charge distributed between both ring nitrogen atoms, which can be represented by two resonance structures. The imidazole ring of histidine is aromatic at all pH values as it contains six π electrons, is a common coordinating ligand in metalloproteins, and is a part of the catalytic sites of many enzymes.

Histidine has not been identified in carbonaceous chondrites and is difficult to be formed in Miller-type prebiotic synthesis experiments, while imidazole can be easily obtained in them.

Cross-References

- [Amino Acid](#)
- [Enzyme](#)
- [Heterocycle](#)

HMT

- [Hexamethylenetetramine](#)

HNC

- [Hydrogen Isocyanide \(HNC\)](#)

HNCHCN

- [Cyanomethanimine](#)

HNCNH

- [Carbodiimide \(HNCNH\)](#)

HO₂

- ▶ [Water, Related Interstellar Radicals and Ions](#)

HOCH₂CH₂OH

- ▶ [Ethylene Glycol \(HOCH₂CH₂OH\)](#)

HOCH₂CHO

- ▶ [Glycolaldehyde \(HOCH₂CHO\)](#)

HOCH₂COCH₂OH

- ▶ [Dihydroxyacetone](#)

Holism

- ▶ [Vitalism](#)

Holophyletic

- ▶ [Monophyletic](#)

Homeostasis

Alvaro Moreno¹ and Kepa Ruiz-Mirazo²

¹Departamento de Lógica y Filosofía de la Ciencia, Universidad del País Vasco, San Sebastián, Spain

²Department of Logic and Philosophy of Science, FICE, UPV-EHU, Biophysics Research Unit (CSIC – UPV/EHU), Donostia, San Sebastián, Spain

Definition

Homeostasis consists in the maintenance of the conditions in which a system is viable, despite

external perturbations or differences with its environment.

History

The French biologist Claude Bernard coined the term in 1865 (from Greek *homoios*, “similar,” and *histemi*, “standing still”), as the capacity of living systems to maintain a stable, functionally adequate “internal milieu” through some mechanism of regulation.

Cross-References

- ▶ [Cell](#)
- ▶ [Metabolism](#)

Homochirality

John F. Malloy¹ and Sara Imari Walker^{1,2}

¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA

²Beyond Center for Fundamental Concepts in Science, Arizona State University, Tempe, AZ, USA

Keywords

Biochirality · Enantiomeric excess · Biosignatures · Chiral selection · Autocatalysis · Mirror symmetry

Synonyms

[100% enantiomeric excess](#); [Enantiopure](#)

Definition

Homochirality refers to a property of a group of molecules composed of chiral units. It is an important structural property of molecules that arises in the study of their stereochemistry, where molecules can have the same molecular formula and

sequence of bonded atoms but different in their three-dimensional spatial structure. An enantiomer is one of two nonsuperimposable mirror molecules that differ in their orientation of a chiral unit, much like your left and right hand differ in their chiral (mirror-image) orientation by the position of your thumb. Indeed, the word ‘chiral’ derives from the Greek word for ‘hand’, and biomolecules displaying a mirror symmetry are either “left-handed” (L) or “right-handed” (D). A macromolecule is homochiral if the constituent molecules share the same enantiomer: that is, if the component molecules all share the same handedness. Homochirality is an important feature of terrestrial biochemistry. All life on Earth is composed of homochiral macromolecules (with rare exceptions); for example, only left-handed (L) amino acids are encoded in proteins, and right-handed (D) sugars form the backbones of DNA and RNA.

Overview

Macromolecular homochirality is a universal feature of life on Earth, and is regarded as a feature that might be distinctive to life (Wu et al. 2012). This ubiquity across all known life makes homochirality a critical area of astrobiological research in both the study of the origin of life and the search for life beyond Earth according to agencies such as NASA (Hays et al. 2015) and the National Academies of Sciences (National Academies of Sciences and Medicine 2019). Major classes of biomolecules are homochiral. All known life almost exclusively uses L-amino acids and D-sugars in its biochemistry, with few exceptions (Caforio et al. 2018; Arkhipova et al. 2019). This preference extends to the macromolecular level where biopolymers are assembled from chiral subunits such that all monomers possess the same chirality: one finds only L-amino acids in proteins and only D-sugars in ► [DNA](#) and ► [RNA](#), with no trace of the “unnatural” D-amino acids and L-sugars in either type of polymer chain (Bonner 1996; Karunakaran et al. 2019), although they may be found in metabolic pathways (Miyamoto et al. 2020). The preference

for only one molecular handedness is essential to the proper folding of known biopolymers and the functioning of most biochemical processes in extant life.

Despite the prominence of homochirality in biochemistry, the origin of biological homochirality is not known and presents one of the longest standing mysteries in studies of the origin of life (Glavin et al. 2020). Laboratory syntheses of amino acids and sugars generally yield racemic mixtures (equal amounts of both the L- and D- enantiomers) under prebiotically relevant conditions (Parker et al. 2011). Therefore, a chiral selection process was required at some stage in the origin or early evolution of life on Earth.

Various theories have been proposed to explain how homochirality might have first emerged. Small excesses of L-amino acids have been observed in meteoritic samples such as from the Murchison meteorite (Cronin and Pizzarello 1997; Koga and Naraoka 2017) and provide the only natural example of molecular asymmetry measured outside of the biosphere. Current space missions such as JAXA’s Hayabusa2 (Watanabe et al. 2017) and NASA’s OSIRIS-Rex (Lauretta et al. 2017) have returned or will return asteroid samples to Earth, allowing for more detailed, uncontaminated analysis in the early 2020s.

Other postulated sources of an initial asymmetry which might have seeded life’s homochirality include the electroweak interaction (Cline 2005); the influence of an asymmetric environment, such as certain mineral surfaces (Hazen 2004; Im et al. 2020), crystal solutions (Hananel et al. 2019); enantiomeric excesses of specific amino acids (Jiang et al. 2014); effects of circularly polarized light (Garcia et al. 2019); random statistical fluctuation (Frank 1953; Ribó and Hochberg 2019), particularly within large chemical systems containing high numbers of chiral species (Laurent et al. 2021); antineutrinos from supernovae (Famiano et al. 2021); noise (Jafarpour et al. 2015); or punctuated combinations of natural events (Gleiser et al. 2008). Most of these sources of asymmetry produce only a small enantiomeric excess, and some type of amplification mechanism is therefore required to achieve the

complete chiral symmetry breaking as observed in living systems (Blackmond 2020).

Amplification can occur through ► **autocatalysis**, when one enantiomer acts as a catalyst for its own formation while simultaneously suppressing the formation of the other enantiomer (Soai et al. 2014). While there are many theoretical examples, the only experimental verification of autocatalysis resulting in symmetry breaking is the Soai reaction, where a small enantiomeric excess of substrate catalyzes the formation of a chiral product, which autocatalytically leads to further chiral product formation (Soai et al. 1995). Amplification has also been demonstrated to occur through crystallization processes (Dutta and Gellman 2017) and phase behavior (Blackmond and Klussmann 2007), and has been proposed to occur via polymerization in the initial stages of life (Chen and Ma 2020).

However, no mechanism for the origin of life's homochirality has been conclusively determined. Due to the universal nature of life's observed homochirality, the question of chirality in potential extraterrestrial biochemistries is pertinent to astrobiological searches for life. Homochirality is therefore among the leading candidates for biosignatures within the solar system (Glavin et al. 2020) and extrasolar worlds (Avnir 2021).

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Homology

David Moreira

Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris, France

Keywords

Common ancestry · Phylogeny · Similarity

Definition

Homology, one of the key concepts in modern evolutionary biology, refers to the similarity between characteristics of organisms due to a common origin from a **common ancestor** (i.e., shared ancestry). Homology can be applied to organs and anatomical structures but also to molecular characters such as DNA sequences. When characters in different organisms are similar but they do not share a common evolutionary origin, they are called analogous (e.g., the wings of birds and insects) and they are the product of convergent evolution. The accurate distinction between true homologous characters and analogous ones is an essential step for phylogenetic analyses.

History

The biological concept of homology was first used by the French naturalist Étienne Geoffroy Saint-Hilaire (1772–1844) to describe anatomical similarities in animals (Saint-Hilaire 1818). Organs of different animal species occupying the same position and having similar connections with other organs were defined as homologous.

This approach allowed defining body plans that were common to very diverse species despite their apparent dissimilarity. Later on, homology studies were carried out in other organisms and, during the twentieth century, also to molecular characters, including DNA and protein sequences.

Overview

Homology is often confounded with similarity, which is erroneous. Homology is an absolute criterion: two characters (e.g., two genes) are homologous or not, namely, they derive from a common ancestral character (e.g., an ancestral [gene](#)) or not. This means that homology, in contrast with similarity, cannot be quantified, so that statements frequently seen in literature like “high homology” or “percent homology” are incorrect (“high similarity” and “percent similarity” would be the correct terms). Likewise, homology does not imply the maintenance of identical functions in different organisms. In fact, homologous structures can evolve to carry out different functions, such as the wings of bats versus the arms of other mammals. Genes derived from a common ancestral gene but carrying out different functions are very common. For example, enzymes involved in cell metabolism in many species, such as the lactate dehydrogenase, are used in animals also as structural proteins called crystallins to build up the lenses of eyes.

Although similarity is not a strict criterion to determine homology because of potential problems of convergent evolution (e.g., integral membrane proteins tend to accumulate hydrophobic amino acids, artificially increasing the similarity of sequences), it is often used to suggest homology between DNA and protein sequences (Zuckerandl and Pauling 1965). In those cases, probabilistic criteria are commonly used to avoid considering as homologous sequences that resemble each other by chance. The correct identification of homologous sequences is an essential prerequisite for molecular phylogenetic analyses, to avoid the use of convergent characters that lead to the reconstruction of artifactual trees. There are two major types of homologous sequences:

orthologous (those that diverge following the divergence of species) and [paralogous](#) (those originated from gene duplication) ones (Fitch 2000).

Cross-References

- ▶ [Common Ancestor](#)
- ▶ [Gene](#)
- ▶ [Orthologous Gene](#)
- ▶ [Paralogous Gene](#)
- ▶ [Phylogeny](#)

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Homolysis

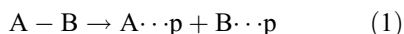
Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Homolytic fission](#)

Definition

In chemistry, homolysis is the scission of a chemical bond in a neutral molecule to give two free radicals.



Homolytic reactions can be induced by UV or visible irradiation (photolysis) or by peroxides.

Homolytic Fission

► Homolysis

Hoogsteen Pair

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A Hoogsteen Pair is a non-canonical/non-Watson–Crick hydrogen-bonded motif observed in nucleic acids.

Two nucleosides from two different nucleic strands, or from distal regions of the same strand, can be held together by Hoogsteen base pairing. Hoogsteen base-pairs often involve the N⁷ position of purine bases as H-bond acceptors and the C⁶ exocyclic amino group of adenine residues as H-donors, which then bond with the Watson–Crick surface of pyrimidine bases.

Karst Hoogsteen discovered the eponymous motif after observing a crystal structure of a nucleic acid complex in which analogues of adenine and thymine formed base pairing motifs with a different geometry from the Watson and Crick motif.

Hoogsteen pairs have considerably different geometries from Watson–Crick base pairs and consequently distinct behavior. Hoogsteen base pairs exist transiently in some DNA molecules in thermal equilibrium with standard Watson–Crick base pairs. They are also observed in protein–DNA complexes and G-quadruplexes.

Cross-References

► [Hydrogen Bond](#)

HOOH

► [Water, Related Interstellar Radicals and Ions](#)

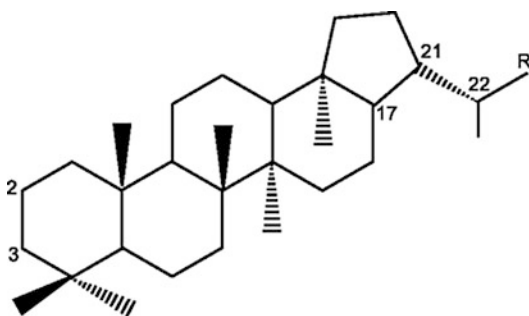
Hopanes, Geological Record of

Ross H. Williams
CRESST/UMCP, Center for Research and
Exploration in Space Sciences and Technology/
University of Maryland, College Park, MD, USA
NASA Goddard Space Flight Center, Solar
System Exploration Division, Greenbelt, MD,
USA

Definition

Hopanes is a class of pentacyclic compounds derived from bacteriohopanepolyols (hopanoids) via diagenetic degradation and thermal maturation. The hopane structure is a saturated hydrocarbon (Fig. 1). Hopanes are molecular fossils of bacterial lipids that serve to adjust membrane permeability and fluidity as well as other adaptations to extreme habitats.

Hopanes are observed in carbonate and shale sediments as old as 1.65 Ga. They are common of, but not limited to, oceanic, lacustrine, hydrothermal environments throughout geological history but are markedly abundant in sediments from some extreme depositional settings, such as the Cretaceous oceanic anoxic events (OAEs). The



Hopanes, Geological Record of, Fig. 1 Core structure of hopanes composed of C–C bonds (lines) and saturated with hydrogen atoms (not shown). The key stereochemical variants occur at C-17, C-21, and C-22 positions. Additional methylation is common at C-2 and C-3. Other structural variants are missing methyl groups. *R* = H, methyl, ethyl, *n*-propyl, *n*-butyl, or *n*-pentyl group

distribution of hopane structures in a kerogen, oil, and bitumen often reflects the degree of thermal maturity and correlates to relative carbonate versus clay content. Further, various hopane distributions can be indicative of source matter or depositional environment.

Cross-References

- [Isoprenoids](#)
- [Molecular Fossils](#)

HOPE Mission

A. Alhammadi¹ and O. Sharaf²

¹Advance Technology Office, Dubai, United Arab Emirates

²Mohammed Bin Rashid Space Centre (MBRSC), Dubai, United Arab Emirates

Keywords

Mars · Atmosphere

Synonyms

[UAE's Emirates Mars Mission](#)

Definition

The UAE's Emirates Mars Mission, dubbed the Hope Probe, is confounding our scientific understanding of Mars' atmosphere, studying the distribution of hydrogen and oxygen in the planet's exosphere and sharing unprecedented findings with the world. Equipped with three instruments, the Hope Probe aims to provide the first complete picture of the Martian atmosphere and build local capabilities in science and technology as the UAE creates a knowledge and innovation-driven economy.

Overview

Emirates Mars Mission (EMM) is the UAE's first interplanetary mission. It was designed to orbit Mars and study the dynamics in the Martian atmosphere on a global scale, and on both diurnal and seasonal timescales. Using three state-of-the-art scientific instruments on board the spacecraft, EMM will provide a set of measurements fundamental to an improved understanding of circulation and weather in the Martian lower and middle atmosphere. Combining this data with the monitoring of the upper layers of the atmosphere, EMM measurements will reveal the mechanisms behind the upward transport of oxygen and hydrogen. The data that is being collected by the mission is considered the most comprehensive measurements of both the weather system in Mars and its correlation with atmospheric loss. The Hope Probe launched in July 2020, and arrived at Mars on the February 9, 2021. The first batch of science data was released to the public in October 2021.

EMM represents the Arab world's first interplanetary exploration and is the result of 15 international collaborations with global partners, including the University of Colorado Boulder's Laboratory for Atmospheric and Space Physics, Arizona State University, and the University of California, Berkeley.

His Highness Sheikh Mohammed bin Rashid Al Maktoum, UAE Vice President, Prime Minister and Ruler of Dubai, called it the Hope Probe to

send a message of optimism for millions of young Arabs. It will usher in a new era of scientific discovery for the good of humankind and has already made history.

Hope Mission

The Arab world's first interplanetary mission was announced in 2014. It took just 7 years to go from concept to launch. The Hope Probe successfully entered the Red Planet's orbit in 2021, coinciding with the 50th anniversary of the UAE, which became an independent nation on December 2, 1971.

While the UAE's space sector is young and developing, it boasts more than a decade of earth observation experience. Among the early satellites developed by the UAE include DubaiSat-1, the country's first probe which was launched in 2009, and KhalifaSat – the first to be 100% designed in the Emirates.

EMM represents a major step forward in the country's technical and scientific capabilities. It was conceived to disrupt and accelerate the UAE's space industry by shaping a scientific community and boosting Emirati advanced engineering and space science research and innovation.

Hope Probe began its journey to Mars from the Tanegashima island in Japan on July 20, 2020, during the height of COVID-19 pandemic. The mission had a 30-day launch window between July 15 and August 12, 2020. On the launch day, the Hope Probe lifted off on a Mitsubishi H-IIA rocket on a trajectory that took it over the Pacific Ocean.

During the first stage, the rocket boosters were expended, as the rocket accelerated away from the Earth. This was followed by jettisoning the fairing as it no longer needed to protect Hope Probe from the Earth's atmosphere. In the second stage, the rocket jettisoned and put the Hope Probe into Earth's orbit. It stayed here until the exact alignment with Mars, after which it was pushed on its trajectory toward the Red Planet. Following this, with the right direction and velocity of 11 km/s, the upper stage gently deployed the Hope Probe.

Traveling 493,500,000 km to Mars, Hope Probe fired all six of its Delta-V thrusters for 27 min to decelerate enough to be swept up by the Red Planet's orbit. It entered Mars' orbit on February 9, 2021 – becoming the first Arab nation to complete this feat of science, technology, engineering, and innovation.

Following its insertion into Mars orbit, Hope Probe entered the next phase of transitioning to science orbit, which saw Hope Probe moved away from its elliptical capture orbit (between 1063 km to 42,461 km from Mars' planetary surface) to a wider scope of 20,000 km by 43,000 km. The transition to the science orbit marked the start of Hope Probe's science mission.

Orbiting Mars every 55 h, the Hope Probe is now monitoring weather changes throughout the day, across the planet, during all seasons. It also monitors the distribution of hydrogen and oxygen in the upper portions of Mars' atmosphere, known as the exosphere. It will also explore the link between weather changes in Mars' lower atmosphere, with the loss of hydrogen and oxygen from the upper layers of the exosphere. For the first time, this will allow scientists to study the link between weather change and atmospheric loss – a process that may have been responsible for Mars' transition, over billions of years, from a thick atmosphere capable of sustaining liquid water on the surface, to the cold, thin, arid atmosphere we see today.

The Hope Probe will study the atmosphere from an orbit of 20,000 km periapsis and 43,000 km apoapsis, with an orbital inclination of 25 degrees. No other Mars spacecraft has had such an orbit; most orbit at a single local time that allows the atmosphere to be measured at only one time of day. It carries three state-of-the-art instruments on board: Emirates eXplorer Imager (EXI), a camera that captures both high-resolution digital color images as well as a few ultraviolet measurements that observe ice and stratospheric ozone in the lower atmosphere; Emirates Infrared Spectrometer (EMIRS), an infrared spectrophotometer to measure temperature and the distribution of dust, water vapor, and ice clouds; and the Emirates Mars Ultraviolet Spectrograph (EMMUS), a UV spectrophotometer to study oxygen and

carbon monoxide levels in the planet's thermal layer, as well as the presence of hydrogen and oxygen in the upper atmosphere.

In 2021, EMM published Hope Probe's first batch of scientific data. The unique data on Mars challenges our existing conception of how the planet's atmospheric gases behave and interact. These observations reveal variations in the concentrations of both atomic oxygen, hydrogen, and carbon monoxide in the atmosphere. Within the data are unique observations of the discrete aurora on Mars and well as data that indicates higher than expected levels of atomic oxygen in the upper atmosphere of Mars. The data is due to release on a 2–3 month cadence to scientists globally.

The unprecedented insights provide a new and unique understanding of the Martian climate.

Hope Probe will continue its scientific journey for a full Martian year (687 Earth days, or about 2 years). If things go well, EMM has an optional 2-year extension to keep the spacecraft in Mars until 2025 to continue its pioneering work.

Cross-References

- ▶ [ExoMars](#)
- ▶ [Mars Express](#)
- ▶ [Mars Global Surveyor](#)
- ▶ [Mars Odyssey](#)
- ▶ [Mars Orbiter Mission](#)
- ▶ [Mars Reconnaissance Orbiter](#)

Horizontal Branch

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The horizontal branch (HB) is the region of the Hertzsprung-Russell diagram occupied by evolved stars – after the ▶ [red-giant](#) stage – of low mass and low metallicity (abundance of

elements heavier than He less than 0.1 that of the Sun), during their central He-burning (He-fusion) phase. The HB is observed in globular clusters, whereas in open clusters (having approximately solar ▶ [metallicity](#)), stars are confined to the bottom of the red-giant branch during core He burning. Metallicity is the key factor explaining that difference (low-metallicity stars have lower opacities and are hotter), but other factors (composition, age, rotation, envelope mass) appear to affect the morphology of the HB.

Cross-References

- ▶ [Globular Cluster](#)
- ▶ [Hertzsprung-Russell Diagram](#)
- ▶ [Metallicity](#)
- ▶ [Open Cluster](#)
- ▶ [Red Giant](#)

Horizontal Gene Transfer

- ▶ [Lateral Gene Transfer](#)

Hot Core

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Keywords

Gas-grain chemistry · Ice evaporation ·
Interstellar molecules · Protostar

Synonyms

[Hot molecular core](#)

Definition

Hot cores are transient regions surrounding massive ► [protostars](#) very early in their evolution. Similar regions are identified around low-mass protostars and are called hot corinos. Hot cores were originally identified as high-temperature regions near massive ► [protostars](#) which showed high abundances of ammonia.

Overview

Hot molecular cores and hot corinos are characterized physically by high gas densities ($>10^6 \text{ cm}^{-3}$) and elevated temperatures of both gas and dust ($\sim 100\text{--}500 \text{ K}$). The gaseous chemical composition is distinct from that of cold molecular clouds, due to evaporation of ice mantles from dust grains, and contains many complex organic molecules. The high temperatures are produced by the luminosity of the protostar and the protostellar accretion disk. Shock waves may also play a chemical role in both heating the gas and in ► [sputtering](#) icy grain mantles back into the gas.

Hot cores are chemically rich and display the products of interstellar grain-surface chemistry in the gas phase. For this reason, they can be used to probe catalytic processes on dust grains. Among the species found in them are methanol, ethanol, dimethyl ether, ethyl methyl ethyl, methyl formate, ethyl formate, ketene, formaldehyde, acetaldehyde, formic and acetic acid, glycolaldehyde, ethylene glycol, several nitriles, and possibly glycine. Some of these organics (e.g., the ethers) could also be formed in the hot gas from those intermediaries formed on and sublimated from the icy mantles on the dust.

Hot cores eventually evolve into ultracompact H II regions as the UV radiation from the massive central star breaks out into the surrounding environment. In the case of low-mass protostars, the hot corino phase is probably terminated by dissipation of the protostellar envelope by accretion onto the circumstellar disk and by powerful outflows.

Cross-References

- [Gas-Grain Chemistry](#)
- [HII Region](#)
- [Hot Corino](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Protostars](#)

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Hot Corino

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

The name hot corino has been given to the immediate environment of a low-mass protostar in which the gas and dust have been heated by the protostellar radiation and shock waves. Hot corinos are characterized by large abundances of complex molecules and high ► [deuterium](#) fractionation ratios, both indicative of sublimation of ► [interstellar ices](#).

History

Hot corinos were so named by Cazaux et al. (2003) because of the similarity with the hot cores found around high-mass protostars.

Cross-References

- [Deuterium](#)
- [Hot Core](#)
- [Interstellar Ices](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Molecules in Space](#)
- [Protostars](#)

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was found in 1995, orbiting the star 51 Peg (Mayor and Queloz [1995](#)).

Cross-References

- [Exoplanets, Discovery](#)
- [Gas Giant Planet](#)
- [Planetary Migration](#)
- [Radial-Velocity Planets](#)

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H

Hot Jupiters

David W. Latham¹ and Nader Haghighipour²
¹Harvard-Smithsonian Center for Astrophysics,
 Cambridge, MA, USA
²Institute for Astronomy, University of Hawaii-
 Manoa, Honolulu, HI, USA

Definition

Hot Jupiter is a designation that is often assigned to gas giant planets in short-period orbits around their parent stars. The characteristics of Hot Jupiters are not well defined, but the orbital period must be short enough (say less than 10 or 20 days) for the planet to be truly “hot,” and the mass must be large enough (say more than about one third of a Jupiter mass) for the planet to be a gas giant. It is commonly accepted that Hot Jupiters originally form much farther from their host stars and migrate inwards either by interaction with the circumstellar disk from which they formed or by gravitational interactions with other planets in the system. For reasons that are not fully understood, there is a pileup in the number of Hot Jupiters with orbital periods near 3 days around solar-type stars. The first Hot Jupiter, which is also the first detected extrasolar planet around Sun-like stars,

Hot Molecular Core

- [Hot Core](#)

Hot Neptunes

David W. Latham¹ and Nader Haghighipour²
¹Harvard-Smithsonian Center for Astrophysics,
 Cambridge, MA, USA
²Institute for Astronomy, University of Hawaii-
 Manoa, Honolulu, HI, USA

Definition

Hot Neptune is a designation that is often assigned to planets with masses or radii similar to those of Neptune in short-period orbits around their parent stars. The characteristics of Hot Neptunes are not well defined, but the orbital period must be short enough (say less than 10 or 20 days) for the planet to be truly “hot,” and the mass must be substantially smaller than that of Saturn (say less than a tenth of a Jupiter mass). It is commonly accepted that Hot Neptunes originally form much farther from their host stars and then migrate inward either by interaction with the circumstellar disk

from which they formed or by gravitational interactions with other planets in the system.

Cross-References

- ▶ [Exoplanets, Discovery](#)
- ▶ [Gas Giant Planet](#)
- ▶ [Planetary Migration](#)
- ▶ [Radial-Velocity Planets](#)

Hot Spring Microbiology

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Hot spring microbiology refers to the study of microorganisms associated with hot springs. Hot springs are characterized by hydrothermal systems that constantly release geothermal gases and fluids from the subsurface due to water sources in contact with shallow magma formations. Many hot springs have temperatures at or near boiling point; thus, microorganisms from these environments are hyperthermophilic or thermophilic and phylogenetically very diverse, including ▶ [archaea](#), bacteria, and viruses. Water chemistry and pH can vary dramatically in these environments. ▶ [Methanogens](#) that belong to the Archaea group and grow at temperature between 80 and 90 °C are present in these systems. Cyanobacteria are often the dominant or sole photosynthetic organisms present in hot springs. Species of *Thermotoga* capable of growing at 90 °C have been isolated in hot springs and marine hydrothermal vents. Thermophilic Crenarchaeota have been isolated from hot, sulfur-rich solfataras, and some methanogenic archaea have also been identified in these environments. Viruses are represented by extreme thermophiles, bacteriophages, living up

to 85–90 °C. These microorganisms play important roles in the carbon, sulfur, and iron cycles in hot spring ecosystems.

Cross-References

- ▶ [Archaea](#)
- ▶ [Crenarchaeota](#)
- ▶ [Extreme Environment](#)
- ▶ [Hot Vent Microbiology](#)
- ▶ [Hyperthermophile](#)
- ▶ [Iron Cycle](#)
- ▶ [Methanogens](#)
- ▶ [Sulfur Cycle](#)
- ▶ [Thermophile](#)

Hot Vent Microbiology

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Synonyms

[Hydrothermal vent microbiology](#)

Definition

Hot vent microbiology refers to the microbial diversity associated with underwater hot springs known as hydrothermal vents. Chemical analysis of hydrothermal fluids shows large amounts of reduced inorganic materials, including H₂S, Mn²⁺, H₂, NH₄, and CO. The system is based on chemolithoautotrophy (nitrifying metal- and sulfur-oxidizing microorganisms and ▶ [methanogens](#)). Hydrothermal vents combine several extreme conditions including temperature (up to 380 °C), pressure (20 MPa at 2,000 m), and pH (plumes of pH 2.5), in the absence of sunlight, all of which determine that primary producers have to use chemical energy for CO₂ fixation. The temperature gradient from the surrounding

water that is heated up to 300–400 °C by magma that pours out through cracks in the lithosphere to seawater, which remains around 2 °C, creates a very unstable environment. Chimney growth from mineral precipitation when hydrothermal fluids come into contact with cold seawater (black smokers) serves as a substrate for associated microorganisms that can metabolize sulfur and metal sulfide compounds. The seafloor vents have important astrobiological connotations because they are considered interesting models for the origin of life on Earth as well as potential habitats on other planetary bodies such as Jupiter's moon, Europa.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Barophile](#)
- [Chemolithoautotroph](#)
- [Deep-Sea Microbiology](#)
- [Hyperthermophile](#)
- [Methanogens](#)
- [Nitrification](#)
- [Sulfur Cycle](#)
- [Thermophile](#)

Hotspot

- [Mantle Plume, Planetary](#)

Hoyle, Fred

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Fred Hoyle (1915–2001) besides a scientist was also an English national figure, born in June 24, 1915, at Gilstead, Bingley West Yorkshire,

England. He graduated at Cambridge University, where he enrolled in 1933. Despite having arrived at Cambridge's Pembroke College with serious gaps in his mathematical background training, a fact he quickly surpasses, Fred Hoyle would prove to be a brilliant student winning the Mathematical Tripos in 1936 and being awarded with the Mayhew Prize as the best student in applied mathematics. During the Second World War he worked for the Admiralty, returning to Cambridge in 1945 as lecturer in mathematics (1945–1956). Between 1957 and 1972 Fred Hoyle will occupy the Plumian chair, one of the major Professorships in Astronomy and Experimental Philosophy at Cambridge's University, and became the founder director of the Institute of Theoretical Astronomy (1967–1972).

Throughout his very active and long scientific live Hoyle will win many awards. He was elected Fellow of the Royal Society of London in 1957 and foreign associate of the US National Academy of Sciences, and he was president of the Royal Astronomical Society between 1971 and 1973, which had awarded him its gold medal in 1968. In 1974 he awarded the Royal Medal of the Royal Society and in 1997 the Crafoord Prize from the Swedish Academy of Sciences. In 1977 he won the Klumpke-Roberts Prize from the Pacific Astronomical Society, and in 1994, along with Martin Schwarzschild, he would win the Balzan Prize. Hoyle was one of the main responsible in the planning and construction of the Anglo-Australian Telescope when he chaired the Science Research Council's advisory committee. Queen Elizabeth II made him knight in 1972.

In astronomy Hoyle's works spans from astrophysics and particle physics to cosmology. Fred Hoyle was the first, in 1946, to establish in solid bases the concept of stars' nucleosynthesis. In 1957, in a joint article with Margaret Burbidge, Geoff Burbidge, and Willy Fowler, Hoyle will publish in the *Reviews of Modern Physics* the famous B2FH paper (the name comes from the last initials of the authors). In this work entitled *Synthesis of the Elements in Stars*, the authors give an explication for the existence in the universe of elements heavier than helium, showing that all of the elements from carbon to uranium

could be produced by nuclear processes in stars, starting with the hydrogen and helium. Hoyle showed that the new young stars are already formed with these heavy elements, which were created in older ones. He also established the theory that other rare elements could be explained by supernovae.

Although ironically the term “big bang” was coined by Hoyle himself in a BBC’s radio show, the truth is that Hoyle did not accept the theory of a primordial explosion as being at the origin of the universe and proposes a model alternative, the Steady State Theory. Hoyle’s name is intimal related to the concept of continuous creation of matter in the universe and to the field equations that achieved this result. In an attempt to adapt his primitive ideas to the measurement results on the background radiation, which over the years were being made, he will publish, coauthored with Burbidge and Narlikar, a book, *A Different Approach to Cosmology* (Cambridge University Press, 2000), presented an alternative to the Big Bang, by employing an oscillating and expanding steady-state universe.

In 1962 he started a famous collaboration with Nalin C. Wickramasinghe on the carbonaceous nature of interstellar dust and interstellar biology. The developments achieved by both will lead them to postulate the organic theory of cosmic dust, which states among other things that the seeds of life (i.e., the basic chemicals of DNA replication), including disease viruses, periodically fall from space transported by meteorites. To Hoyle life on Earth couldn’t have arisen by chance in a primordial soup; he favored and popularized a view called panspermia, the notion that life originated in space and was driven to Earth by electromagnetic radiation pressure.

Most of his controversial ideas were exposed in a lot of his popular non-fiction and science fiction books, including *Frontiers of Astronomy* (1955), *Men and Materialism* (1956), *Star Formation* (1963), *Galaxies, Nuclei and Quasars* (1965), *The Relation of Physics and Cosmology* (1973), *Ten Faces of the Universe* (1977), and *On Stonehenge* (1977). In 1994 he published his autobiography, *Home Is Where the Wind Blows*. Besides books Fred Hoyle also wrote some plays, television stories and A for Andromeda

serial, and an opera, *Alchemy Of Love*, or the *Daemon Servant’s Retribution*, which premiered in New York in 1969.

Cross-References

- [DNA](#)
- [Interstellar Dust](#)
- [Panspermia](#)

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H-phosphonate

- [Phosphite](#)

HPLC

Jason P. Dworkin
NASA Goddard Space Flight Center,
Astrochemistry Laboratory, Code 691, Greenbelt,
MD, USA

Synonyms

[High-performance liquid chromatography](#); [High-pressure liquid chromatography](#); [LC](#); [UHPLC](#)

Definition

HPLC is an efficient method of liquid–solid column chromatography. Using a stationary phase composed of small (3–10 μm) beads increases separation efficiency but requires pumps to force the

mobile phase through the column at pressures >300 bar. Ultra-HPLC (UHPLC) uses $<2\text{ }\mu\text{m}$ particles and pressures $>1,000$ bar. Unlike gas chromatography, the composition of the mobile phase is often varied with time while the column temperature is held constant. Reverse-phase HPLC uses a hydrophilic mobile and hydrophobic stationary phase, the opposite of normal-phase HPLC. HPLC is suited for coupling with different detectors, particularly in so-called hyphenated techniques, such as HPLC coupled to mass spectrometry (LC-MS).

Cross-References

- [Chromatography](#)
- [Ion-Exchange Chromatography](#)
- [Liquid Chromatography-Mass Spectrometry](#)

HR Diagram

- [Hertzsprung-Russell Diagram](#)

HST

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Exoplanet · Planetary disks · Star formation

Synonyms

[Hubble Space Telescope](#)

Definition

The Hubble Space Telescope (HST) is a NASA space observatory (Fig. 1) with a 2.5-m-diameter primary mirror operating in ultraviolet, visible, and infrared light. Launched in 1990, the HST was serviced five times by the

space shuttle and is still in operation. The 11,000-kg spacecraft is placed in low Earth orbit at an altitude of about 575 km. The data archiving and the scientific operations are managed by the Space Telescope Science Institute in the name of the scientific consortium consisting of numerous universities and institutions. The ► [European Space Agency](#) contributes through various participation up to 15% of the total cost.

History

From 1970 to 1978, US astronomers and NASA deployed an intense lobbying effort toward US congressmen to have the Large Space Telescope funded. The decision was taken after the decision of the European Space Agency to support this effort. Originally slated to be launched in 1983, technical delays made it almost ready only by 1986. The Challenger accident then grounded the Space Shuttle fleet for almost 3 years. The telescope had to be kept in a clean room, powered up, and purged with nitrogen. These operations were costing about \$6 million per month, pushing the overall costs of the project up to \$2.5 billion by the time of the launch. During this time period, the engineers performed extensive tests, swapped out a possibly failure-prone battery, and made several technical improvements. The ground software controlling Hubble was just ready by the 1990 launch.

Once in space, the first images were not as sharp as expected and demonstrated a defect in the primary mirror curvature. This flaw was mainly impairing the observation of faint objects and the cosmology program. The origin of the flaw was clearly identified and a corrective instrument was designed. Awaiting the repair by the shuttle mission in December 1993, HST performed many valuable observations for astronomers.

Since then and with the following four maintenance flights, the HST has delivered unprecedented results in all fields of astronomy. The overall US expenditure for the HST is estimated at between \$4.5 and \$6 billion, with Europe's financial contribution at about €600 million.

HST, Fig. 1 The Hubble Space Telescope imaged by the shuttle during the last servicing mission in 2009 (Credit NASA)



Overview

The Hubble Space Telescope was sent into orbit on April 24, 1990, by the Space Shuttle Discovery. This 11,000-kg telescope was serviced five times by the space shuttle in its working orbit at an altitude of about 575 km. The telescope was built by NASA with a significant contribution from ESA. It is operated by NASA and the data are archived at the Space Telescope Science Institute in Baltimore, USA. The Hubble's spectral range extends from the ultraviolet, through the visible, and into the near-infrared. Hubble's primary mirror is 2.4 m in diameter, which is not large by ground-based standards. The instruments as well as the avionics and hardware were upgraded and exchanged during the five successive servicing missions. Now, and up to the end of the mission, the HST is equipped with five instruments. The Advanced Camera for Surveys (ACS) was installed in 2002, improving the field of view and the light sensitivity. It is working with the newly installed Wide Field Camera (WFC3). The Cosmic Origins Spectrograph (COS) instrument is an ultraviolet spectrograph optimized for observing faint point sources with moderate spectral resolution. The Near-Infrared Camera and Multi-object Spectrometer (NICMOS) is the infrared instrument able to see through interstellar gas and dust. Finally, the Space Telescope Imaging Spectrograph (STIS) separates light into component wavelengths, acting much like a prism. All these instruments are placed at the focal plane of the telescope.

Key Research Findings

The HST was built and designed to image far, faint galaxies. This fossil light reveals how the Universe looked in the remote past and how it may have evolved with time. The Hubble Deep Fields gave a clear glance back to the time when galaxies were forming. Deep field observations require long-lasting pointing accuracy to a selected region of the sky. Deeper observation requires a longer exposure time, while the fainter objects become visible on the images. The first deep fields gave new insight about the early Universe, revolutionizing modern astronomy. The HST has harvested outstanding results in many fields of astronomy, like the calculation of the Hubble constant, the evaluation of the age of the Universe, and the astrophysics of objects such as quasars and super-massive black holes in the centers of galaxies. The systematic surveys were also used to detect gravitational lenses and map the distribution of dark matter in some portions of the Universe. For astrobiology, the Hubble Space Telescope has contributed to the imaging of the clouds of gas and dust where new stars are forming. Data collected from the Orion Nebula are giving new insight into these processes. The detected dust disks around newborn stars could be the beginning of planetary systems. Hubble performed the first detection of an atmosphere around an extra-solar giant planet, which orbits a Sunlike star (► [HD 209458b](#)) located 150 light-years away in the constellation Pegasus.

Hubble made also unique, repeatable observations of the surfaces of the planets and objects of our Solar System: imaging the dust storms on Mars, preparing for the flyby of asteroids like Vesta by the Dawn mission, or recording “live” the diving of the comet Shoemaker-Levy into the atmosphere of Jupiter (see Fig. 2).

For astrobiology, HST observations of several celestial bodies of the Solar System in all the wavelengths available evidenced auroras and rings for the large gaseous planets, complemented the observations from the orbit to decipher the weather system on Mars, discovered new moons of Pluto and other dwarf planets, performed numerous discoveries of Kuiper belt objects. HST also witnessed volcanic emission from Jupiter’s moon Io and revealed water plumes from Europa and another Jovian moon.

HST is also designed to dig in-depth into the origin of the universe and of the planetary systems. The high spatial resolution images for the Orion Nebula demonstrated that protoplanetary disk systems are commonly formed around stars. HST contributed to the discovery of some extra-solar planets through transits. The spectroscopic observations with Hubble of extrasolar planets



HST, Fig. 2 This natural-color image of Jupiter displays at the bottom right debris from a comet or asteroid that plunged into Jupiter’s atmosphere and disintegrated (Credit: NASA, ESA, Michael Wong [Space Telescope Science Institute, Baltimore, MD], H. B. Hammel [Space Science Institute, Boulder, CO], and the Jupiter Impact Team)

and their parent stars characterized some planetary atmospheres, evidenced of the presence of clouds, and identified for some a few planets, major atmospheric compounds such as methane, titanium oxide, and water.

Future Directions

The James Webb Space Telescope (► [JWST](#)), launched on December 25th, 2021, is placed in a halo orbit at the Lagrangian point L2. It is considered as the successor of the HST while it will operate instruments using different wavelengths.

Cross-References

- [Aeronautics and Space Agency of FFG](#)
- [Comet Shoemaker-Levy 9](#)
- [European Space Agency](#)
- [HD 209458b](#)
- [JWST](#)

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Space Telescope Science institute : <https://www.stsci.edu/>

Hubble Space Telescope

- [HST](#)

Hubble, Edwin

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Edwin Powell Hubble (1889–1953) was an American astronomer known by his works on galactic and extragalactic astronomy. His works provided

the first persuasive observational evidence that the Universe is expanding.

In 1929, with data collected from the best telescope of that time, the 100-in. telescope of the Mount Wilson Observatory, he showed that galaxies are moving away from Earth with a speed proportional to their distance according to the law, $v = H_0 \times d$, where v is the recession velocity of a galaxy at a distance d and H_0 is the value for the Universe expansion rate at the current epoch. Hubble's initial value for H_0 (now called the Hubble constant) was calculated to be approximately $500 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The Hubble Space Telescope, a satellite observatory orbiting Earth, launched by NASA's Space Shuttle mission STS-31 on April 24, 1990, is continuing the work begun by Hubble himself to study and map our Universe and helping to determine the Hubble constant to an accuracy of $\pm 10\%$; the actual H_0 value is $72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Hungarian-Made Automatic Telescope Network

► [HATNet](#)

Huronian Glaciation

Andrey Bekker

Department of Earth Sciences, University of California, Riverside, Riverside, CA, USA

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Keywords

Paleoproterozoic · Ice ages · Snowball earth · Rise of atmospheric oxygen

Synonyms

[Paleoproterozoic ice ages](#); [Paleoproterozoic Snowball Earth](#)

Definition

The Huronian glaciation is the oldest series of protracted climatic refrigeration events that extensively affected Earth. It occurred between 2.45 and 2.22 Ga in association with the rise of atmospheric oxygen. Three glaciations of that series, the classical Huronian ice ages, are bracketed in time between ~ 2.45 and 2.32 Ga, with the oldest glaciation at ~ 2.43 Ga (Gumsley et al. [2017](#)); the fourth event, recognized so far only in South Africa, is ~ 2.22 Ga in age. During these events, glaciers covered continents, extended to low latitudes, and reached to sea level. The ice ages were followed by a protracted time interval with greenhouse (warm and humid) conditions. The name is derived from the Huronian Supergroup exposed on the north shore of Lake Huron in Ontario, Canada, between Sault Ste. Marie, Sudbury, and Cobalt.

History

The Huronian glacial deposits were first recognized by Coleman ([1907](#)) in the northeastern part of the Huronian Basin in Ontario, Canada; just a year after a poorly sorted conglomerate with scattered pebbles and cobbles, some striated and faceted, was described in the Northern Cape Province of South Africa by Rogers ([1906](#)), who interpreted it to be glacial in origin. Blackwelder in 1926 inferred glacial origin for the Headquarter Formation of the Snowy Pass Supergroup in the Medicine Bow Mountains, SE Wyoming, which he correlated to the Huronian Supergroup of Ontario, Canada. Almost 20 years later, Pettijohn ([1943](#)) described tillite in a correlative to the Huronian Supergroup succession of Michigan, USA. Young ([1970](#)) synthesized all available by that time data and inferred glacial influence on Paleoproterozoic successions in Wyoming, Michigan, Quebec, and Nunavut. Shortly thereafter, Paleoproterozoic glacial deposits were for the first time recognized in Western Australia (Trendall [1976](#)), described in more details in South Africa (Visser [1971](#)), and inferred in the Dead River Storage Basin of Marquette County,

MI, USA (Puffett 1969). Although the presence of Paleoproterozoic glacial deposits in Fennoscandia was originally discussed by Eskola (1919), they were not described and documented in detail until recently (Marmo and Ojakangas 1984; Strand and Laajoki 1993). In Antarctica, the 2.50–2.45 Ga Ruker Series contains diamictite above thick banded iron formation associated with mafic volcanics (Mikhalsky et al. 2006; Phillips et al. 2006), offering a comparison with the Meteorite Bore Member of the Turee Creek Group in the Hamersley Province of Western Australia (see below). All other reported cases of Paleoproterozoic glacial deposits were either not confirmed by subsequent sedimentologic studies or turned out to be significantly younger and not correlative with the Huronian glaciations (e.g., Sausar Group, India: Mohanty 2006 vs. Mukhopadhyay et al.

2020; Hutuo Group, China: Chen et al. 2019 vs. Chen et al. 2018 and Du et al. 2011).

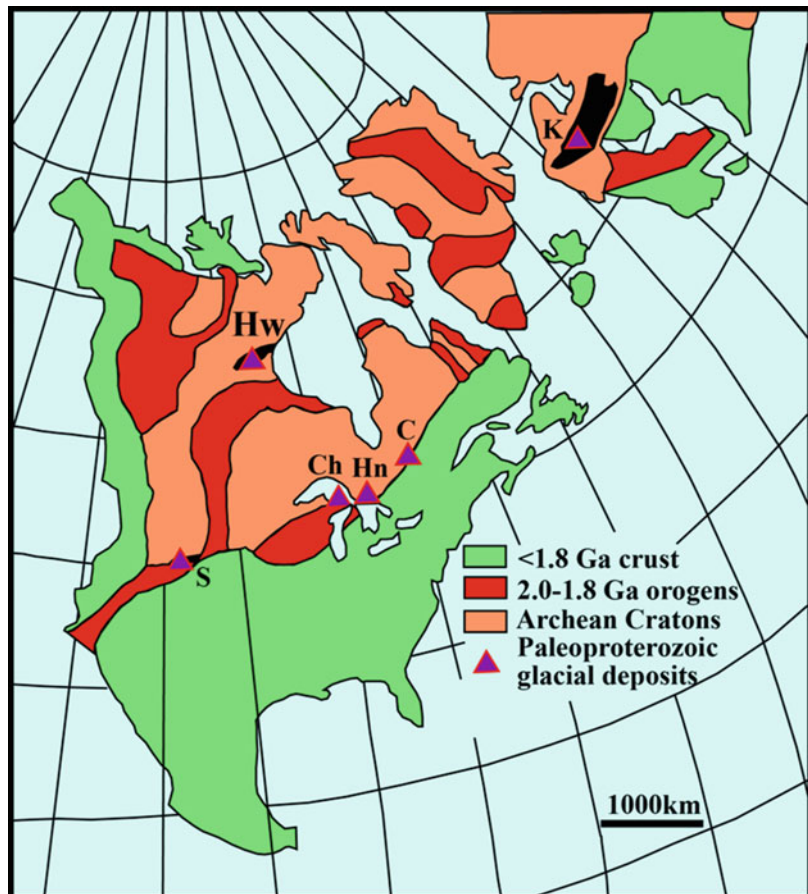
Overview

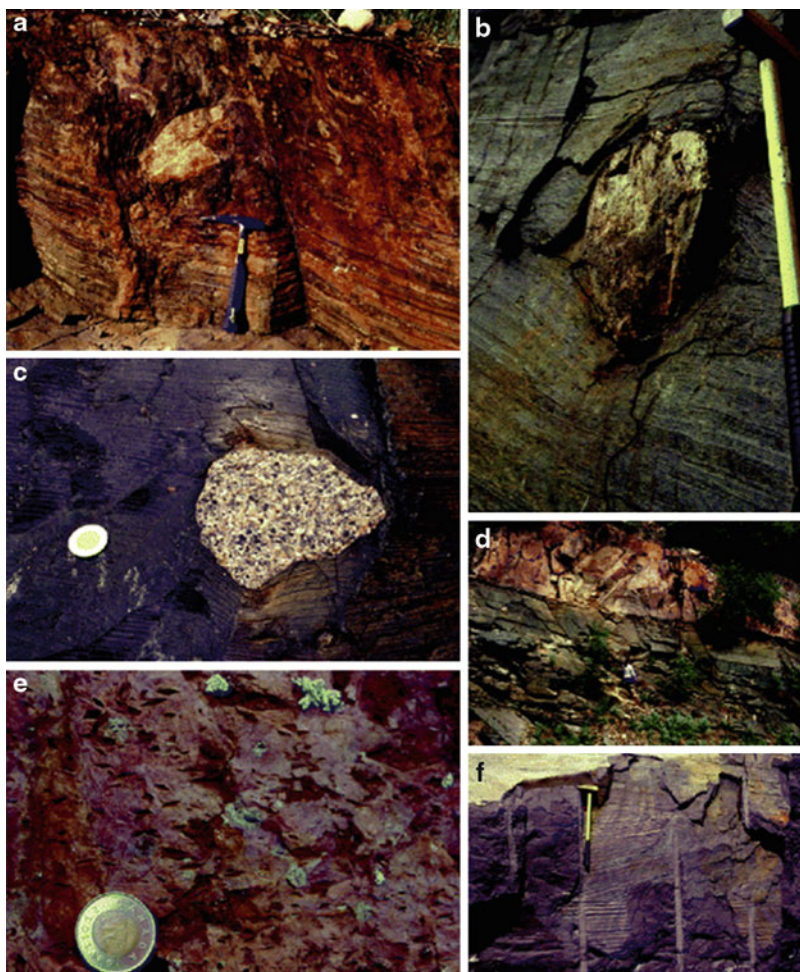
Paleoproterozoic glacial deposits are now confirmed in a number of basins in North America (Figs. 1 and 3), Western Australia (Meteorite Bore Member of the Turee Creek Group), South Africa (Pretoria and Postmasburg groups), and Fennoscandia (Sarioli informal group in Finland and in Karelia and Kola Peninsula, Russia). Evidence for glaciation is plentiful in these successions and includes varves with dropstones; striated, flat-iron-shaped, and faceted pebbles; striations in the underlying basement; exotic stones in diamictite (Fig. 2); extensive

H

Huronian Glaciation,

Fig. 1 Location of Paleoproterozoic glacial deposits in North America and Fennoscandia. (Modified after Young 2004). Abbreviations represent stratigraphic units, which contain glacial deposits. *S* Snowy Pass Supergroup, Medicine Bow Mountains, Wyoming, *Ch* Chocoy Group, Michigan, *Hn* Huronian Supergroup, Ontario, *C* Chibougamau Formation, Quebec, *Hw* Hurwitz Group, Nunavut, *K* Karelian Supergroup, Fennoscandia



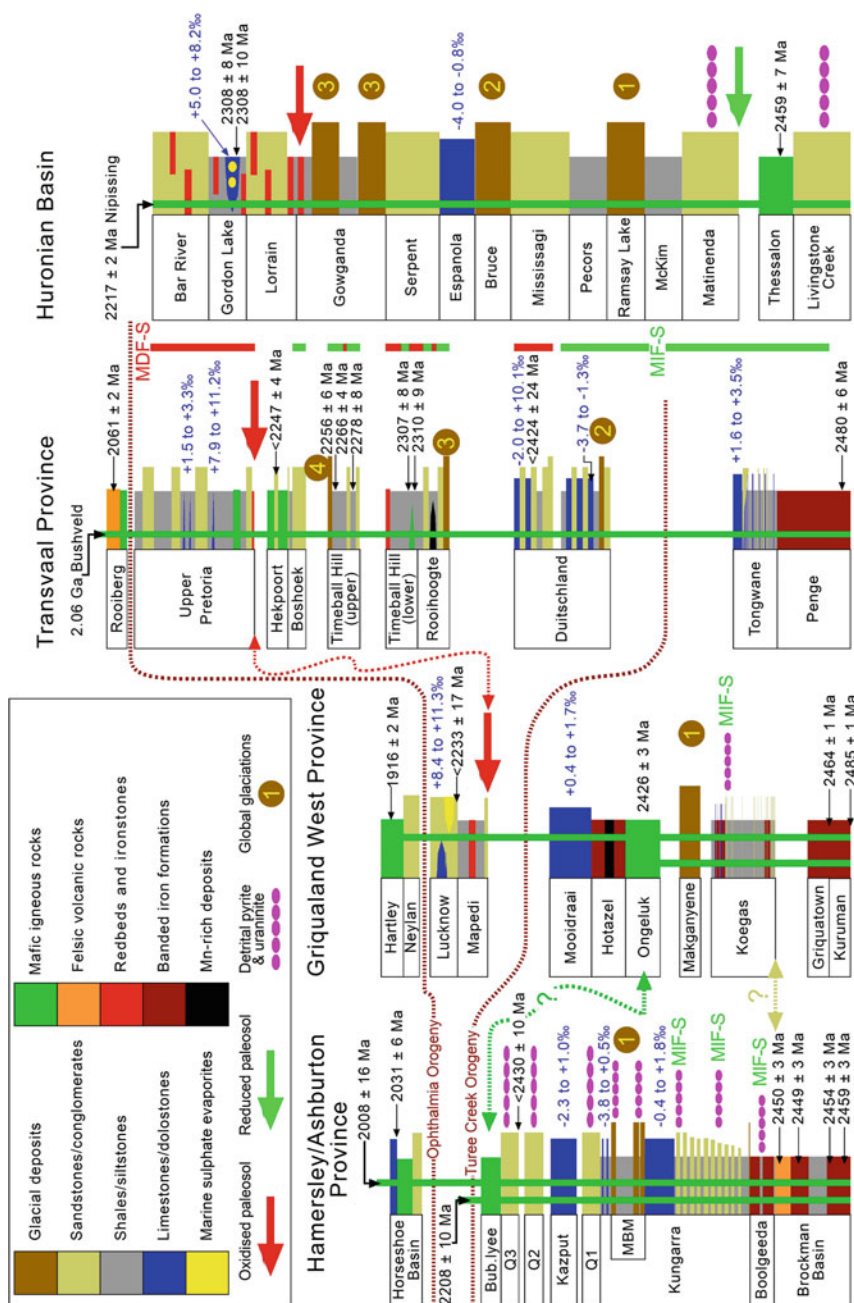


Huronian Glaciation, Fig. 2 Sedimentary features of Paleoproterozoic successions indicating glacial influence and postglacial warm and humid climate associated with oxygenated atmosphere. (a) Dropstone in finely laminated mudstone of the Pecors Formation, Huronian Supergroup, north of Quirke Lake; hammer for scale is 40 cm long. (b) Large dropstone in laminated matrix of the Gowganda Formation in Cobalt area; hammer is 70 cm long. (c) Dropstone of granite in finely laminated matrix of the Gowganda Formation, north of Elliott Lake; coin is

2.8 cm in diameter. (d) Red sandstone sandwiched between glacial diamictites of the Gowganda Formation, north of Elliott Lake, person for scale. (e) Molds of gypsum in red-colored siltstone from postglacial succession in Michigan (HW 480; Kona Dolomite); coin is 2.8 cm in diameter for scale. (f) Cross-bedded red-colored mudstone-siltstone in the upper part of the Gowganda Formation deposited in oxygenated deltaic setting, Cobalt area; hammer for scale is 70 cm long

development of diamictite not controlled by syn-sedimentary faults; till pellets; and chemical and mineralogical immaturity of conglomerate matrix (cf. Young 1970). The Huronian Supergroup contains three glacial units (Fig. 3), whereas other successions, except for the Snowy Pass Supergroup and Snowy Pass Group in Wyoming, USA, contain only one or two, making intra- and

intercontinental lithostratigraphic correlations difficult. It seems likely that four glacial events occurred in the Paleoproterozoic, but their regional or global extent is not well constrained. Paleomagnetic data are as yet scarce; however, they suggest low-latitude position of glaciated landmasses (e.g., Evans et al. 1997; Gumsley et al. 2017), whereas sedimentologic data



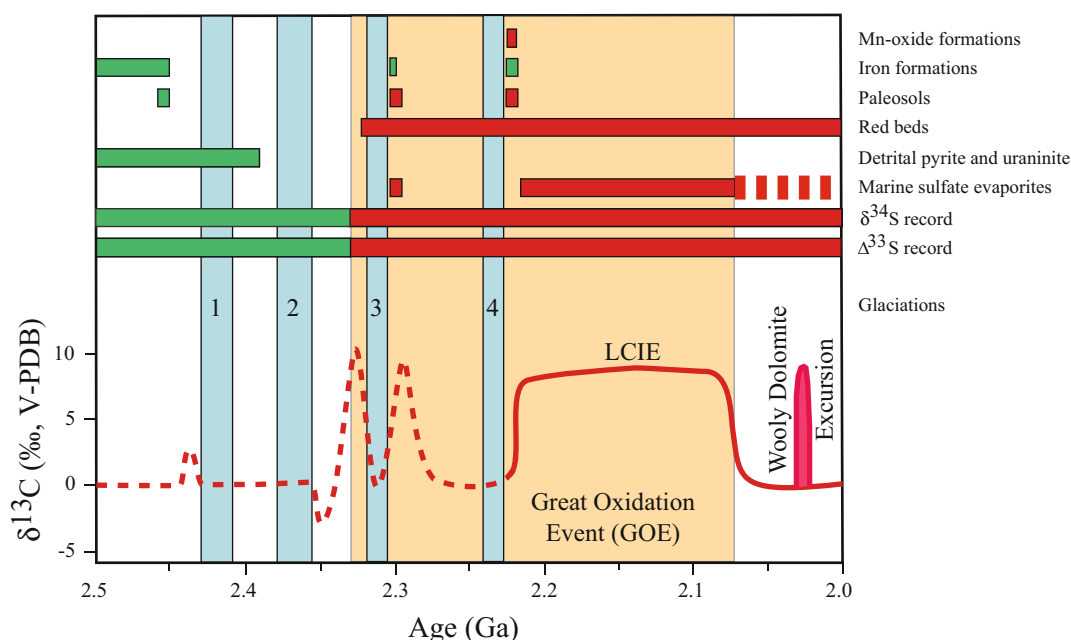
Huronian Glaciation, Fig. 3 Generalized stratigraphic sections of the Pilbara, Griqualand West/Transvaal and Huronian successions, highlighting the stratigraphic disposition of Paleoproterozoic global glaciations, C- and S-isotope chemostratigraphy, and published geochronology (after Bekker et al. 2020, 2021 with additional information on mass-independent fractionation of sulfur (MIF-S) and mass-dependent fractionation of sulfur (MDF-S) from Poulton et al. 2021). Neither stratigraphic thickness nor

absolute age are implied by the thickness of units in stratigraphic columns, whereas gaps along stratigraphic sections are hiatuses on unconformities. Bubblee is the Bubhawalaye Formation; Q1, Q2, and Q3 are respectively Quartzite 1, 2 and 3; MBM is the Meteorite Bore Member. The exact stratigraphic position of the transition from MIF-S to MDF-S is uncertain for the Huronian Supergroup and therefore not shown

indicates that ice extended to sea level in these regions (e.g., Young 2004), inviting a comparison with the Neoproterozoic Snowball Earth glaciations.

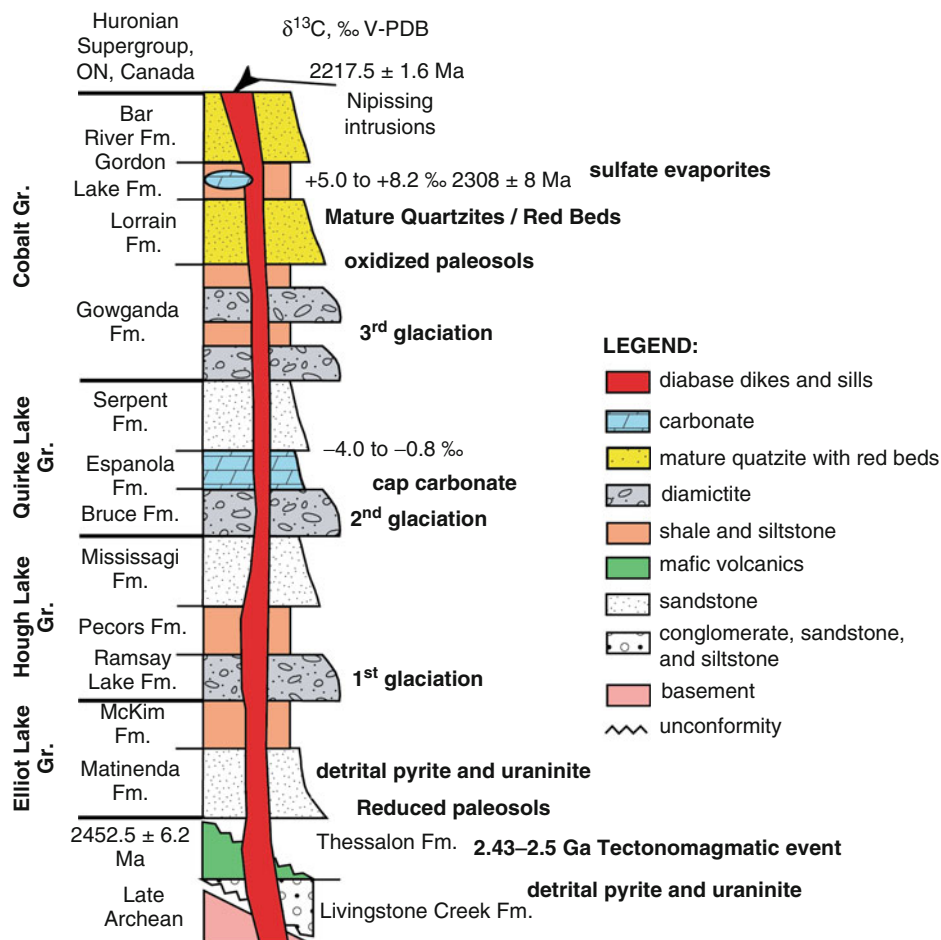
Large igneous provinces were extensively emplaced before (2.5–2.45 Ga) and after (~2.22 Ga) the Huronian glaciations, but with the exception of the ~2.32 Ga mantle plume and few locally developed orogenic events (e.g., Arrowsmith Orogeny), the 2.45–2.22 Ga time interval is largely devoid of magmatic activity (cf. Partin et al. 2014). Tuff beds dated in the Huronian Supergroup, Canada, and the Pretoria Group, South Africa (Rasmussen et al. 2013), have finally bracketed the age of the Paleoproterozoic ice ages (Fig. 3). Three Huronian glaciations are all between ca. 2.45 and 2.32 Ga in age, whereas the youngest glaciation recorded by the upper Pretoria Group is ca. 2.22 Ga in age. These

data allow two tantalizing implications: (1) The Huronian ice ages lasted long; (2) there was a glacial event at ca. 2.22 Ga in South Africa, which, based on geochronological constraints, might correlate with glacial units of the Chocoday Group in Michigan, USA (Vallini et al. 2006). The Makganyene Diamictite of the Postmasburg Group of the Griqualand West basin (paleomagnetically pinned to low paleolatitudes; Evans et al. 1997) was recently geochronologically bracketed between ~2.46 and 2.43 Ga in age (see Fig. 3; Gumsley et al. 2017), potentially providing the best age constraint for the beginning of the GOE. Correlation of the glacial diamictite of the Meteorite Bore Member of the Turee Creek Group with the Huronian glacials remains uncertain; considering that the retro-arc setting of the Turee Creek Group evolved from a conformably underlying back-arc basin containing 2.5–2.45 Ga



Huronian Glaciation, Fig. 4 Secular carbon isotope variations in seawater and redox indicators for the oxidation state of the early Paleoproterozoic atmosphere-ocean system (Modified from Bekker and Holland 2012). Four blue vertical bars mark Paleoproterozoic glacial events; the dashed secular carbon isotope curve between 2.5 and 2.22 Ga emphasizes the uncertainty in this part of the curve; red filled shape is the Woolly Dolomite excursion (Bekker et al. 2016); the dashed bar for marine sulfate

evaporites after ~2.06 Ga indicates that sulfate evaporites again became rare in the Paleoproterozoic and Mesoproterozoic records after that time. Deposition of iron formations and Mn-rich deposits indicates anoxic conditions in deep waters. While deposition of iron formations does not necessarily require atmospheric oxygen and can be mediated by anoxygenic photosynthetic bacteria, Mn oxidation requires significant levels of atmospheric oxygen



Huronian Glaciation, Fig. 5 Stratigraphic column of the Huronian Supergroup in Ontario, Canada, that contains three glacial horizons and overlying units indicating extreme degree of weathering. Also shown are atmospheric

redox indicators, age constraints, and environmental and tectonic changes. (Modified from Bekker et al. 2006; Rasmussen et al. 2013)

banded iron formations (e.g., Krapež 1996), the most parsimonious interpretation is that it represents the oldest Huronian ice age.

In contrast to Neoproterozoic glacially influenced successions, carbonates with negative carbon isotope values directly overlying glacial diamictite are present only above the second glacial diamictite of the Huronian Supergroup and correlative glacially influenced successions elsewhere. There are carbonates with negative carbon isotope values stratigraphically immediately below the glacial diamictite of the Polisarka Sedimentary Formation on the Kola Peninsula of Russia (Brasier et al. 2013), which is considered

to correlate to the oldest Huronian glaciation (Bekker et al. 2020). Sequences immediately underlying Paleoproterozoic glacial diamictites include banded iron formations in Western Australia and South Africa and conglomerates with detrital pyrites and uraninites in North America and ► *Fennoscandia*, whereas overlying units contain red beds and sulfate evaporites (Figs. 2 and 4). Combined, these and other proxies for atmospheric and ocean redox state indicate a transition from the reduced to an oxygenated atmosphere and ocean during the Huronian glaciations (Bekker et al. 2004). It is generally accepted that the atmosphere before ~2.45 Ga was reducing and

contained significant (≥ 1000 ppm) levels of methane, an effective greenhouse gas. Rise of atmospheric oxygen in the early Paleoproterozoic decreased methane levels in the atmosphere and initiated climatic cooling leading to glaciation (Bekker et al. 2005). If this interpretation is correct, the Huronian glaciations represent a response of Earth system to the rise of atmospheric oxygen in association with carbon dioxide replacing methane as a main greenhouse gas (Bekker and Kaufman 2007). Lithologies overlying Paleoproterozoic glacial deposits suggest an extended period of enhanced chemical weathering in the aftermath of the Huronian glaciations (Young 1973), which could reflect warm and humid climate and acidic groundwaters during the Great Oxidation Event and Lomagundi Carbon Isotope Excursion (Konhauser et al. 2011; Bekker and Holland 2012) (Fig. 5).

Cross-References

- Cap Carbonates
- Diamictite/Diamicton
- Glaciation
- Great Oxidation Event
- Lomagundi Carbon Isotope Excursion
- Oxygenation of the Earth's Atmosphere
- Paleosols
- Precambrian
- Proterozoic Eon
- Pyrite
- Red Beds
- Sedimentary Rock
- Shale
- Snowball Earth
- Stratigraphy
- Transvaal Supergroup, South Africa

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Huxley's Conception on Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

History

Thomas Huxley (1825–1895) was a British biologist who endorsed Charles Darwin's theory of evolution. As a zoologist, physiologist, and evolutionist, Huxley explained his conceptions on nature of living matter in two important lectures: *The Physical Basis of Life* (1868) and *Biogenesis and Abiogenesis* (1870). In the first lecture, he described and analyzed the importance of the

protoplasm as the main constituent of cells. He wrote that the protoplasm, simple or with a nucleus, is the formal basis of all life, and he insisted on the fact that materialism is the best way to understand life. In the second text, he strictly rejected the spontaneous generation and described the debate on this matter. He suggested distinguishing two terms: *biogenis*, when living matter comes from living matter, and *abiobenesis*, synonymous of spontaneous generation, when living matter comes from inert matter.

Cross-References

- ▶ [Cellular Theory, History of](#)
- ▶ [Darwin's Conception of the Origins of Life](#)
- ▶ [Haeckel's Conception of Origins of Life](#)
- ▶ [Protoplasmic Theory of Life](#)

Huygens

Therese Encrenaz
LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Christiaan Huygens (1629–1695) was born in The Hague (Netherlands). He studied law and mathematics in Leiden and then studied and built microscopes and telescopes. With his own telescope, he discovered ▶ [Titan](#), ▶ [Saturn's](#) biggest satellite, in 1655. In 1659, he found the explanation of the changing appearance of Saturn, due to its rings, which he published in *Systema Saturnium*. In 1656, he built the first pendulum clock with the objective of determining longitudes at sea. He developed in his *Traité de la Lumière* the first wave theory of light. His posthumous work, *Cosmotheoros*, published in 1698, deals with the nature of the universe and the habitability of other worlds. The probe of the Cassini-Huygens mission, which landed on Titan's surface on January 14, 2005, was named after him.

Cross-References

- ▶ [Saturn](#)
- ▶ [Titan](#)

Huygens Probe

François Raulin
Faculté des Sciences et Technologie, Université Paris Est Créteil et Paris Diderot, LISA – UMR CNRS 7583, Creteil, France

Keywords

ACP · Atmospheric probe · Cassini-Huygens · DISR · DWE · GC-MS · HASI · SSP · Titan · Titan's atmosphere · Titan's surface

Synonyms

[Cassini Titan's probe](#); [Huygens spacecraft](#); [Titan's atmosphere module](#); [Titan's atmosphere probe](#)

Definition

The Huygens probe was an atmospheric probe supplied by the European Space Agency (ESA) and part of the Cassini-Huygens mission to the ▶ [Saturn](#) system. The probe was named after the Dutch astronomer Christiaan Huygens who discovered ▶ [Titan](#), the largest satellite of Saturn, in 1655. It was designed to explore the environment of Titan, mainly its atmosphere, which makes Titan so unique. It was carried by the ▶ [Cassini](#) spacecraft. It entered Titan's atmosphere on January 14, 2005, and studied Titan for several hours during its descent and after its touchdown with the six instruments of its scientific payload (Table 1).

History

As early as 1982, an ambitious and international mission to explore the Saturn system was

Huygens Probe, Table 1 The Huygens probe’s scientific investigations and their expected astrobiological return

Huygens instruments and interdisciplinary programs	P.I., team leader or IDS		Astrobiological return
Scientific instruments			
Gas chromatograph-mass spectrometer (GC-MS)	H. Niemann	USA	+++
Aerosol collector and pyrolyzer (ACP)	G. Israël	France	+++
Huygens atmospheric structure instrument (HASI)	M. Fulchignoni	Italy	++
Descent imager and spectral radiometer (DISR)	M. Tomasko	USA	+++
Doppler wind experiment (DWE)	M. Bird	Germany	+
Surface science package (SSP)	J. Zarnecki	U.K.	+++
Interdisciplinary scientists			
Aeronomy	D. Gautier	France	++
Atmosphere/surface interactions	J.I. Lunine	USA	+++
Chemistry and exobiology	F. Raulin	France	+++

initially proposed to ► [NASA](#) and ESA by a team of European and US scientists. A probe to specifically study Titan was identified very early in the study phase of the mission as a potential contribution of ESA. After a Phase A study, the Titan’s probe was selected in 1988 by the Science Programme Committee of ESA and named “Huygens” at that time. The selection of the ESA Huygens probe investigations, as that of the NASA Cassini orbiter, was done jointly by ESA and NASA and announced in the fall of 1990.

Overview

The Huygens probe (Lebreton and Matson [2002](#)) was one of the key elements of the Cassini-Huygens mission. It was provided by ESA and constructed by an industrial consortium, with Aerospatiale, Cannes, France (currently Thales Alenia Space), as the prime contractor (Clausen et al. [2002](#)). It was carried by the Cassini spacecraft from its launch, on October 15, 1997, to its release, on December 25, 2004. It separated from Cassini that day at 2:00 UTC with a relative speed of ~0.35 m/s. It entered Titan’s atmosphere on January 14, 2005, targeted to land on a southern-latitude site on Titan’s dayside. Protected by its heat shield (Fig. [1](#)), it experienced a strong aerobraking, with a velocity decreasing from 21,600 km/h during entry to less than

1400 km/h at 180 km altitude and only 290 km/h at 160 km. There the main parachute (8.3 m in diameter) opened and then discarded at about 110 km altitude and replaced by a small one (3 m in diameter). This last parachute allowed the probe to reach Titan’s surface before the Cassini spacecraft passed below the horizon of the ► [landing site](#). However, it was efficient enough to allow a low-velocity landing (5 m/s). The descent time in the atmosphere was close to 2 h and 30 min. The probe continued operating after landing on the surface for about 3 h. The first 1 h and 12 min of surface data was collected by Cassini, before it went out of the field of view of Huygens (Fig. [2](#)). The total mass of the probe was about 350 kg including the probe structure, support equipments, and 48 kg of scientific instruments. The probe was developed to explore Titan’s atmosphere, mainly from ~150 km altitude, down to the surface, and to, eventually, carry out some surface measurements, although it was not conceived to survive the surface impact. Huygens included six scientific experiments (Table [1](#)) to study the physical and chemical properties of the atmosphere and surface of Titan.

Huygens included a CD-ROM with about 100,000 messages collected by ESA between December 1996 and February 1997. Those messages included texts, drawings, audio messages, and signatures from tens of thousands of citizens from the planet Earth (Fig. [3](#)).

Huygens Probe,

Fig. 1 The back cover of the probe, with its gold-colored blanket, is attached to the Huygens probe, already inside its front shield (covered by heat-resistant tiles) (Credit: ESA (ID number: SEMJRJ2VQUD))

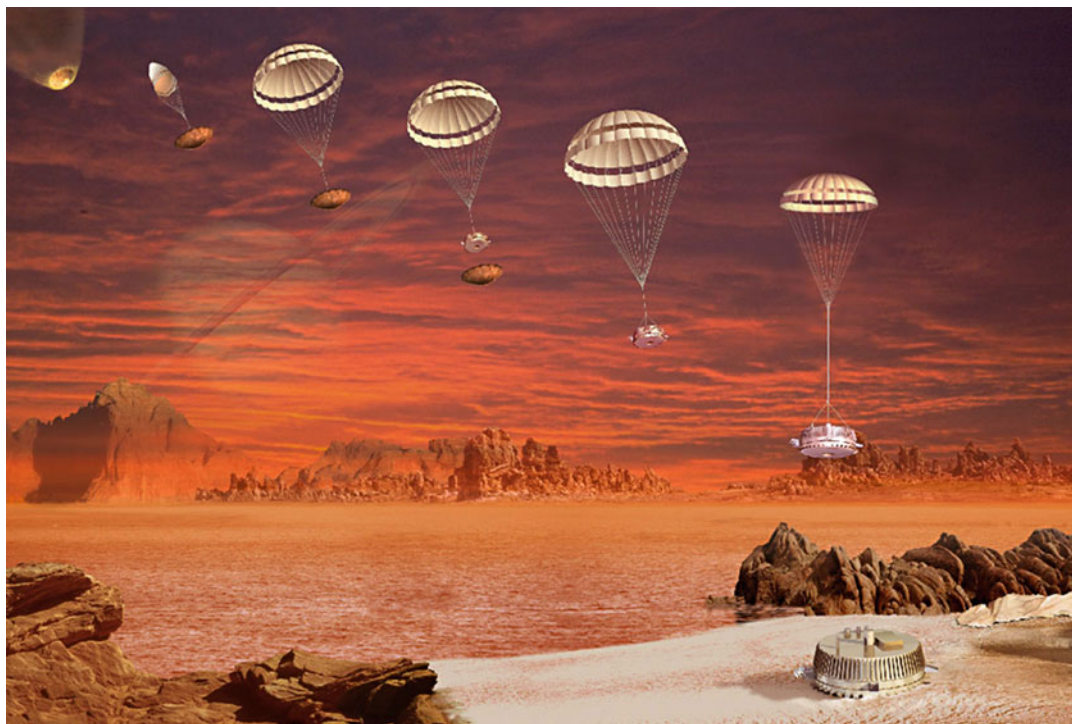
**Basic Methodology**

The energy on Huygens was delivered by five LiSO_2 batteries, capable of delivering more than 2 KWh. The data (housekeeping and scientific) were processed by a Command and Data Management Unit, which included a 16-bit microprocessor (running at 10 MHz). They were then sent to the Cassini orbiter in its solid-state memory with the Probe Data Relay Subsystem, which included S-band transmitters and circularly polarized transmitting antennas. The data were transmitted from Huygens to Cassini on two nearly redundant channels.

The ► [gas chromatograph-mass spectrometer \(GC-MS\)](#) (Niemann et al. 2002) included three GC columns, using dihydrogen as carrier gas, linked to a quadrupole mass spectrometer and a gas sampling system. The GC achieved the

separation of the different constituents of complex mixtures (atmospheric gases and heated or pyrolyzed aerosols from aerosol collector and pyrolyzer [ACP]). The MS allowed their detection and identification, with a mass range extending from 2 to 141 Da. The instrument was equipped with five ion sources feeding the mass analyzer sequentially. It also included an enrichment cell to concentrate trace gases and increase the limit of detection.

The ACP (Israel et al. 2002) was devoted to the in situ study of Titan's aerosols: their chemical composition and their distribution. It included a sampling system with a filter to collect atmospheric aerosols and an oven to heat the collected particles at different temperatures. Once the collecting phase was over, the filter was retracted inside the probe in the oven. Then the oven was isolated and the filter heated at different



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Huygens Probe, Fig. 2 Artist's picture of the descent and landing of the Huygens probe on Titan on January 14, 2005 (Credit: ESA-D. Ducros (ID number: SEMF4XULWFE))

temperatures. The produced gases were then analyzed by the GC-MS instrument. Two samplings were carried out in the 130–35 km altitude and the 25–20 km altitude, respectively.

The Descent Imager and Spectral Radiometer (DISR; Tomasko et al. 2002), the only optical remote sensing experiment aboard Huygens, operated in the 0.3–1.7 μm wavelength range. It included photometers to look upward and downward, solar visible and infrared spectrometers, and several imagers. Its scientific objectives were to study the thermal balance, dynamics, and main composition of the atmosphere, as well as the distribution and properties of the aerosols. It was also able to provide many images and information on nature of the surface.

The Huygens Atmospheric Structure Instrument (HASI; Fulchignoni et al. 2002) was composed of several sensors to measure physical properties of the atmosphere: accelerometer, temperature and pressure sensors, a microphone, and an electric field sensor. One of the main goals of the HASI was to measure the vertical temperature/

pressure atmospheric profile from the mid-stratosphere to the surface of Titan.

The Surface Science Package (SSP; Zarnecki et al. 2002) was also a multisensor experiment to measure surface properties: temperature, thermal conductivity, heat capacity, speed of sound, dielectric constant, and index of refraction (if liquid). It included a force transducer to measure the impact deceleration.

The Doppler Wind Experiment (DWE; Bird et al. 2002) was designed to determine the direction and strength of the zonal winds in Titan's atmosphere. It was composed of a transmitter on the Huygens probe and a receiver on the Cassini orbiter, allowing Doppler tracking of the probe from the orbiter.

Key Research Findings

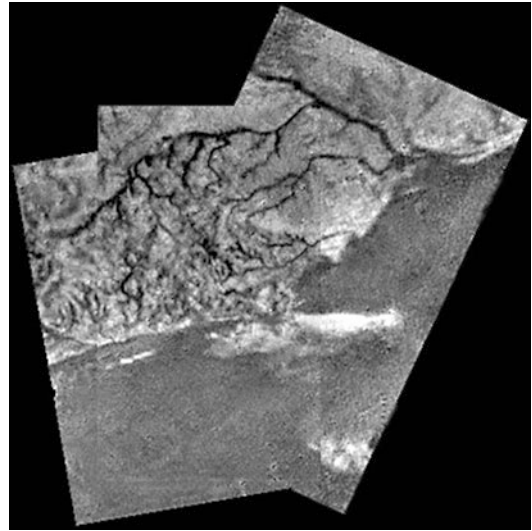
The whole Huygens operations worked perfectly, from the pre-entry in Titan's atmosphere to the landing (Lebreton et al. 2005, 2009; Owen 2005).



Huygens Probe, Fig. 3 The Huygens CD-ROM: front cover and CD (Courtesy of NASA/JPL/Caltech/ESA)

The latter was much smoother than expected, and the probe survived the impact and its instruments continued working for several hours on the surface. Only one problem was experienced: the loss of one of the two channels because of a programming error in its receiver. Consequently, no data were collected from this channel, which affected mainly the DWE experiment, but finally most of the data were recovered, thanks to Earth-based radio telescopes that were able to receive the weak radio signal from Huygens.

The scientific results of the Huygens instruments were first published in *Nature* in 2005 and then in two special issues of *Planetary and Space Science* (Raulin et al. 2007, 2008). They are also presented together with the Cassini data in a book devoted to Titan (Brown et al. 2009). The DISR (Tomasko et al. 2005) provided more than



Huygens Probe, Fig. 4 Channel networks, highlands, and dark-bright interface on the surface of Titan as seen by the DISR instrument on Huygens at 6.5 km altitude (Credit: ESA/NASA/JPL/University of Arizona – PIA07236)



Huygens Probe, Fig. 5 Image of Titan's surface where the Huygens probe landed taken by the DISR instrument on January 14, 2005. It shows pebble-sized objects, likely to be made of water ice (Credits: ESA/NASA/JPL/University of Arizona (PIA07232))

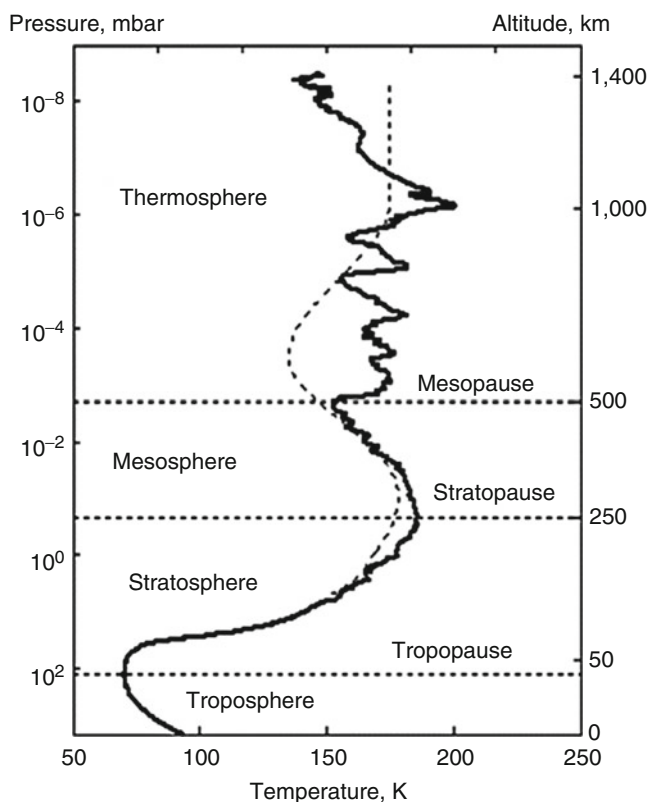
350 images and many spectra of Titan. Its images did not show any liquid ► [hydrocarbon](#) pool on Titan's surface, but dendritic structures formed by liquid which flowed in the past. It goes from brighter highland regions down to dark and flat lowlands (Fig. 4). They also showed that the Huygens landing site looked like a dry riverbed strewn with pebbles probably made of ► [water](#) ice (Fig. 5). The DISR infrared spectra of the surface suggested a mixture of water ice and organic compounds, including Titan tholin-like material. The DISR data also showed that haze particles in the atmosphere seemed continuously distributed from 150 km altitude to the surface, where the ► [methane](#) relative humidity reaches 50%. The HASI (Fulchignoni et al. 2005) determined the temperature, pressure, and density profiles of the atmosphere from 1400 km to the surface (Fig. 6). It detected an ionospheric layer in the low atmosphere, between 140 and 40 km, with a potential lightning signal. The SSP (Zarnecki et al. 2005) performed physical measurements just above and on Titan's surface. It evidenced a relatively soft

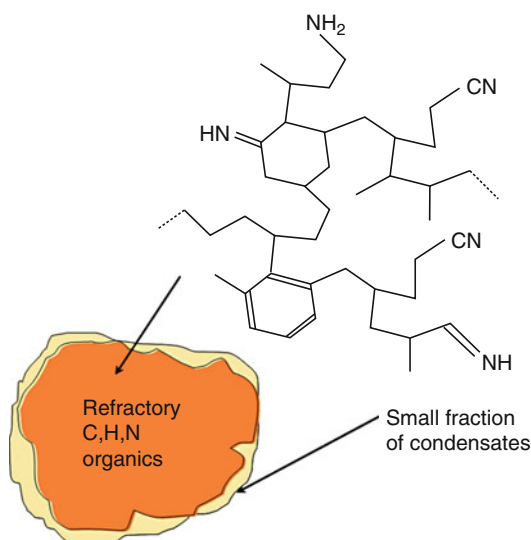
solid surface. The DWE team (Bird et al. 2005) was able to determine a high-resolution profile of the winds, including evidence for low-velocity winds below 5 km altitude, and to confirm the super-rotation of Titan. The GC-MS (Niemann et al. 2005) carried out a direct MS analysis of Titan's atmosphere from 146 km altitude down to the surface. It determined the concentration profiles of several atmospheric gases as a function of altitude and measured ► [isotopic ratios](#) and trace species. It detected ^{40}Ar as the main noble gas, with an abundance more than 100 times higher than that of ^{36}Ar . It measured $^{14}\text{N}/^{15}\text{N}$ and $^{12}\text{C}/^{13}\text{C}$ and D/H in the atmosphere and found values close to but smaller than the terrestrial values, except for D/H. It detected organic species on the surface, including ethane, cyanogen, and benzene. It also observed the presence of methane degassing on the surface. The ACP (Israel et al. 2005), using GC-MS as an analytical tool, was able to collect and pyrolyze atmospheric aerosols in the low stratosphere and mid-troposphere regions. It showed that the collected particles release NH_3

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Huygens Probe,

Fig. 6 Vertical temperature and pressure profile (*dotted line*) of Titan's atmosphere from HASI data. (Credit: ESA/ASI/UPD/OU/FMI)





Huygens Probe, Fig. 7 Elemental composition, structure, and example of the possible molecular composition of Titan's aerosols derived from the Cassini-Huygens ACP data

and HCN when heated at 600 °C, indicating that they are made of refractory organics, including ► **carbon** (C), ► **hydrogen** (H), and ► **nitrogen** (N) atoms (Fig. 7).

Applications

The Huygens probe was the first object launched by mankind that was able to softly land on a planetary object of the outer solar system. The Huygens landing site is now named the Hubert Curien Memorial Station, in recognition of one of the founders of ESA. The technical and scientific achievement of Huygens shows our capability to land on faraway worlds. It marks the beginning of the systematic exploration of outer solar system objects.

Future Directions

The lessons learnt from Huygens will be used in future to return to Titan and explore in details its surface in many locations. This was already envisaged with an international mission such as the Titan Saturn System Mission (TSSM). The TSSM, jointly studied by NASA and ESA,

planned to send a lander to explore one of Titan's lake and a Montgolfier to study for several months Titan's atmosphere and surface.

Cross-References

- [Aerosols](#)
- [Atmosphere, Structure](#)
- [Cassini](#)
- [Cassini Mission](#)
- [Cassini-Huygens Space Mission](#)
- [Chromatography](#)
- [Doppler Shift](#)
- [GC/MS](#)
- [Hydrocarbons](#)
- [Hydrogen](#)
- [Hydrogen Cyanide](#)
- [Landing Site](#)
- [Methane](#)
- [Nitrogen](#)
- [Pyrolysis GC/MS](#)
- [Refractory Molecule](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Spectroscopy](#)
- [Tholins](#)
- [Titan](#)
- [Volatile](#)
- [Water](#)

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Huygens Spacecraft

- [Huygens Probe](#)

Hybridization

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

In ► [genetics](#), hybridization is the process by which two genetically unrelated parents –

belonging to different strains, varieties, ► [species](#), or even genera – are crossed or mated to originate a hybrid organism. For example, a mule is a hybrid animal produced by crossing a female horse with a male donkey, whereas the grapefruit is a hybrid between a sweet orange and a pomelo. In turn, in molecular biology, hybridization is the process by which two biomolecules or fragments of them interact specifically with each other. ► [Nucleic acid](#) hybridization is the process of annealing two single-stranded (ss) DNA or ssRNA molecules of different origin to form a double-stranded (ds) DNA, a dsRNA, or a DNA-RNA duplex. Both nucleic acid strands must bear some sequence similarity in order to form stable hybrids by complementary base pairing. The process can be induced in the test tube or, alternatively, used for detection and identification of complementary sequences in ex vivo samples. Different hybridization techniques have been implemented in molecular biology and biotechnology, including membrane-based blot methods and microarray technology.

Cross-References

- [Base Pair](#)
- [Double Helix](#)
- [Genetics](#)
- [Nucleic Acids](#)
- [Primer](#)
- [Sequence](#)
- [Species](#)

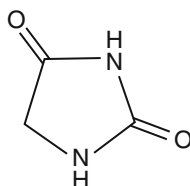
Hydantoin

Louis d'Hendecourt
Institut d'Astrophysique Spatiale, Université Paris-Sud 11, Orsay Cedex, France

Synonyms

[2, 4-Imidazolelidinedione](#); [Glycolyurea](#)

Hydantoin,
Fig. 1 Hydantoin



Definition

Hydantoin ($C_3H_4N_2O_2$) is an organic compound whose structure is shown in Fig. 1. It is a saturated heterocyclic molecule related to imidazole which contains two lactam, or cyclic amide, functions. From an astrobiological point of view, it could be important for two main reasons: (1) it is formed from condensation of ► [urea](#) and ► [glycolic acid](#), or cyanate and ► [glycine](#), likely common prebiotic molecules which have also been detected in two meteorites, including Murchison, and, more importantly, (2) it is a precursor in the formation of N-carbamoyl amino acid (NCA) or hydantoic acid, which may be an important intermediate in the formation of oligopeptides. More generally, hydantoins are cyclic molecules formed from N-carbamoyl-amino acids.

Hydantoin Formation

► [Bücherer-Bergs Synthesis](#)

Hydrocarbons

Koichiro Matsuno
Nagaoka University of Technology, Nagaoka,
Japan

Keywords

Carbonaceous meteorites · Fatty acids ·
Fischer-Tropsch-type reactions · Interstellar
grains · Pyruvate · Ultraviolet photon

Definition

Hydrocarbons are organic compounds consisting entirely of carbon and hydrogen. They may be synthesized from primary carbon sources such as carbon monoxide. The major source of prebiotic hydrocarbons on Earth might have been carbonaceous meteoritic infalls. Prebiotic significance of hydrocarbons could be found in their derivatives including the carbonyl group.

Overview

A major source of hydrocarbons for prebiotic evolution on Earth may be extraterrestrial material. Hydrocarbon derivatives constitute several percent of the total mass of carbonaceous meteoritic infalls, in contrast to amino acids that are present only in trace amounts in carbonaceous meteorites. The meteoritic infalls are in the form of interstellar grains composed largely of silicate minerals coated by thin layers of ice and frozen gases of such as carbon dioxide, carbon monoxide, ammonia, and methanol as well as a variety of small organic compounds including hydrocarbons as a principal ingredient. The synthesis of hydrocarbon derivatives in the icy mantles of interstellar grains could be initiated by irradiation by ultraviolet photons from a remote star.

The hydrocarbon derivatives of meteoritic origin, once they were delivered to Earth, would mostly be buried in the ocean. A smaller fraction would eventually be released into the periphery regions of hydrothermal environments and not necessarily right in the vicinity of black smokers, which are full of sulfur-containing chemicals. Insofar as small hydrocarbon derivatives such as formic acid or oxalic acid or their precursors are available in the periphery of hydrothermal environments at temperatures even less than 200 °C, Fischer-Tropsch-type reactions with the aid of metallic catalysts can work without being disturbed by the destructive interference from sulfur (McCollom et al. 1999). If the reaction solution is maintained at appropriately high pressures and temperatures, elongation of the alkyl chain can occur. A consequence is the synthesis of saturated

fatty acids such as decanoic acid. Once fatty acids are synthesized in aqueous environments where ionic strength is not sufficiently high, fatty acid vesicles are likely to be formed because of their amphiphilic nature. The presence of the vesicles can provide a means of encapsulating smaller monomers, enhancing the likelihood of further synthetic reactions to proceed in the vesicles.

Hydrocarbon derivatives have also been synthesized from pyruvate in prebiotic evolution experiments. Pyruvate itself has been synthesized from carbon monoxide using iron sulfide working as a reducing agent at 250 °C in experiments simulating black smokers (Cody et al. 2000).

Cross-References

- [Black Smoker, Organic Chemistry](#)
- [Fischer-Tropsch-Type Reaction](#)
- [Hydrothermal Reaction](#)

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Hydrodynamic Escape

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

The term *hydrodynamic escape* refers to the removal of gas from the atmosphere of a planet possessing a strong gravity field by the viscous drag of an escaping lighter gas, typically hydrogen. This phenomenon may explain why some planetary atmospheres are depleted in oxygen, nitrogen, and heavier noble gases, such as xenon.

Overview

When atmospheric temperature is high enough, the thermal agitation of gas molecules may be strong enough for some gaseous species to leave the gravity field of the planet. For a planetary body with radius R_p , Jean's escape velocity is obtained by equating the kinetic and potential energy and is equal to $\sqrt{2GM/R_p}$, with G being the universal gravitational constant and M the mass of the planet. For the Earth, escape velocity is 11.2 km s⁻¹. The mean thermal (translational) velocity of atoms in a gas is $\sqrt{8RT/\pi m}$, where m is the atomic mass of the gas and R is the gas constant (8.314×10^{-3} amu (km/s⁻¹)). For monatomic hydrogen, $m = 1$ g/mol⁻¹ and the thermal velocity is 2.5 km s⁻¹ at ambient temperature (298 K). Although this value is less than the escape velocity, a tiny fraction of hydrogen leaves the upper terrestrial atmosphere. In contrast, the thermal velocity of monatomic nitrogen is 700 m s⁻¹, and nitrogen remains in the atmosphere.

For a dense atmosphere, gas molecules collide with each other very frequently, and the distance between successive collisions (mean free path) is short. Let us imagine traces of monatomic nitrogen in an atmosphere of monatomic hydrogen. Collision with hydrogen, which on average tends to expand and leave the gravity field, imparts momentum to nitrogen atoms. Although thermal agitation would not be sufficient to remove this species from an atmosphere of pure nitrogen, the hydrogen viscous drag adds extra velocity to other species and may remove them to space. Hydrogen loss from early planetary atmosphere results in the loss of other species. This phenomenon, which is known as hydrodynamic escape, was elucidated by Hunten et al. (1987). There are some suggestions that Mars and Venus may have lost nitrogen and water in this way (e.g., Pepin 1991).

Cross-References

- [Earth's Atmosphere, Origin and Evolution of](#)

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Hydrodynamic Flow

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

The term hydrodynamic flow describes a dynamical approximation for the bulk motion of matter in which it is treated as a fluid (gas or liquid), rather than as a collection of particles.

Hydrogen

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science, Washington, DC, USA
Georgia Institute of Technology, Center for Chemical Evolution, Atlanta, GA, USA

Definition

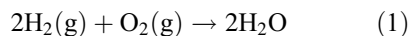
Hydrogen (chemical symbol H) is a chemical element with atomic number 1. It has an atomic weight of 1.00794 u (or Da) (1.007825 u for the isotope ^1H containing no neutrons). It is the lightest and most abundant element, making up ~75% of the Universe's detectable mass and ~90% of its detectable atoms.

Main sequence stars are mostly composed of ionized hydrogen in plasmas, which play a vital role in powering stars through proton-proton

reactions and the CNO nuclear fusion cycle. Hydrogen has three naturally occurring isotopes: ^1H , ^2H , and ^3H , which all contain 1 proton and 0, 1, or 2 neutrons, respectively. While hydrogen gas is rare in the Earth's atmosphere (~1 ppm by volume) because it escapes from the Earth's gravity field more easily than heavier gases, it is the third most abundant element on the Earth's surface, mainly as a component of water.

Its most common isotope is ^1H (protium), which contains a single proton. In ionic compounds, hydrogen can take a negative charge (forming an anion known as hydride and written as H^-), or as a positively charged species H^+ , also known as a proton. Hydrogen forms molecular compounds with most elements. It plays an important role in Bronsted-Lowry acid-base chemistry with many reactions exchanging protons between soluble molecules.

Molecular hydrogen (H_2), which is a gas at room temperature and pressure, was first produced artificially in the sixteenth century by Paracelsus by mixing metals with strong acids. In 1766–1781, Cavendish was the first to recognize hydrogen gas as a discrete substance, and that it produces water when burned in air. This property led to it receiving its name, which is from the Greek meaning “water-former.” Molecular hydrogen is highly inflammable and burns readily in air:



The energy levels of hydrogen can be calculated fairly accurately using the Bohr model of the atom. However, a more accurate description of the hydrogen atom comes from a purely quantum mechanical treatment that uses the Schrödinger equation, which allows the calculation of the probability of the electron density around the proton.

Protonated molecular hydrogen, or H_3^+ , is found in the interstellar medium, where it is generated by ionization of molecular hydrogen by cosmic rays. H_3^+ is relatively stable in outer space due to the low temperature and matter density. H_3^+ is thus one of the most abundant ions in the universe, and plays an important role in the chemistry of the interstellar medium.

Hydrogen in the ► [interstellar medium](#) can exist as neutral atomic hydrogen (referred to by

astronomers as HI), as ionized atomic hydrogen (protons, called HII), or as molecular hydrogen (H₂). Atomic hydrogen is typically observed by its hyperfine transition at a wavelength of 21 cm, accurately predicted by Dutch graduate student Hendrik van de Hulst in 1944. Regions of ionized hydrogen, produced by ultraviolet radiation from hot stars, are detected from recombination lines such as those in the Balmer series. Molecular hydrogen has no transitions in the visible portion of the spectrum, and was first observed by G. Carruthers in the ultraviolet, using a rocket-borne spectrograph.

Hydrogen forms millions of known molecular compounds with other elements, in particular carbon. Hydrogen forms molecular compounds with elements that are more electronegative than it is, such as the halogens. In these compounds, hydrogen has a partial positive charge. Hydrogen also forms molecular compounds with less electronegative elements, such as the metals and metalloids, in which case it takes on a partial negative charge. These compounds are called hydrides.

Large quantities of hydrogen gas are produced by reaction of water with mantle minerals (such as olivine), notably on the sea floor. It is widely believed that this process, called serpentinization, may have created a reduced environment favorable for the origin of life.

Cross-References

- ▶ [Hydrogen Isotopes](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Interstellar Medium](#)
- ▶ [Serpentinization](#)

Hydrogen Bond

Gilles Bruylants
Engineering of Molecular NanoSystems,
Universt  Libre de Bruxelles, Brussels, Belgium

Keywords

Molecular interactions · Noncovalent interactions

Synonyms

[H bond](#)

Overview

A hydrogen bond (H bond) is the attractive non-covalent interaction between a hydrogen atom covalently bonded to an electronegative atom (hydrogen bond donor) and another electronegative atom (hydrogen bond acceptor), such as nitrogen, oxygen, or fluorine.

The hydrogen bond has some features of covalent bonding: it is directional, produces interatomic distances shorter than the sum of the van der Waals radii, and usually involves a limited number of interacting partners, which can be interpreted as a type of valence. These covalent features are more substantial when the hydrogen atom is bonded to a more electronegative atom. The hydrogen bond is relatively strong (usually between 5 and 30 kJ/mol but extremely strong values such as 155 kJ/mol in the HF₂[−] molecule are observed, in which case the term Low Barrier Hydrogen Bond is frequently used) compared to other non-covalent interactions, such as van der Waals interactions, but weaker than covalent or ionic bonds. The bond strength depends on its length, the bond angle, the local dielectric constant, the electronegativity of the non-hydrogen atoms, temperature, and pressure.

Hydrogen bonds can occur between molecules (intermolecular hydrogen bond) or within different parts of a single molecule (intramolecular hydrogen bond).

The most ubiquitous example of an intermolecular hydrogen bond is the one found between water molecules. The water molecule is composed of two hydrogen atoms which can form a hydrogen bond (as donors) and one oxygen atom which has two lone pairs of electrons, each of which can be involved in a hydrogen bond (as acceptors). In liquid water, every water molecule can consequently be hydrogen bonded with up to four other molecules.

Hydrogen bonding also plays an important role in determining the three-dimensional structure adopted by larger molecules including macromolecules such as ▶ [proteins](#) and ▶ [nucleic acids](#). The double helical structure of DNA is due largely to

hydrogen bonding between the ► [base pairs](#), which link one complementary strand to the other. In proteins, hydrogen bonds between the backbone oxygen atoms and amide hydrogen atoms contribute to the formation of secondary structure elements, such as alpha helices and beta sheets. In addition, many proteins have hydrogen bonds between side chains. Taken together, these interactions contribute to folding proteins into specific shapes that determine their biological function. However, the importance of this contribution to stability of the folded state still remains controversial, as both donors and acceptors of hydrogen bonds can form hydrogen bonds with water when unfolded in aqueous solution.

Cross-References

- [Base Pair](#)
- [Covalent Bonds](#)
- [Nucleic Acids](#)
- [Protein](#)
- [Van der Waals Forces](#)
- [Water, Solvent of Life](#)
- [Watson-Crick Pairing](#)
- [Weak Bonds](#)

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Hydrogen Chloride

- [Chlorine Hydrides in the Interstellar Medium](#)

Hydrogen Chloride (HCl)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[HCl](#)

Definition

Hydrogen chloride is a colorless gas under standard conditions, consisting of diatomic molecules containing hydrogen and chlorine. Two isotopologues have been detected by astronomers.

History

Interstellar HCl was first detected in 1985 from the Kuiper Airborne Observatory by G. Blake and colleagues (Blake et al. [1985](#)). Although it is detected in the gas phase in interstellar molecular clouds (Schilke et al. [1995](#)), the majority of the chlorine in these regions appears to be sequestered in the ► [interstellar dust](#) grains (Cernicharo et al. [2010a](#)). The two isotopic species, H^{35}Cl and H^{37}Cl , have been detected with the Herschel satellite toward evolved stars (Cernicharo et al. [2010b, c](#)). More recently, the cations HCl^+ and H_2Cl^+ have also been detected in molecular clouds (e.g., De Luca et al. [2012](#); Neufeld et al. [2012](#)). HCl has also been detected in Comet 67P/Churyumov-Gerasimenko (De Keyser et al. [2017](#)).

Cross-References

- [Interstellar Dust](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

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Hydrogen Cyanamide

► [Cyanamide](#)

Hydrogen Cyanide

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Synonyms

[Formonitrile](#)

Definition

Due to its dual reactivity, as both a nucleophile and an electrophile, hydrogen cyanide, HCN, plays an important role in many synthetic processes potentially related to the origin of life. At room temperature, it is a colorless and extremely poisonous gas, with a bitter odor reminiscent of almonds that some people are unable to perceive for genetic reasons. It has been found in molecular clouds (Snyder and Buhl 1971), evolved stars (Wilson et al. 1973), and comets (Huebner et al. 1974; Despois et al. 1986). It is one of the most abundant triatomic species in

space. Its less stable isomer ► [hydrogen isocyanide](#), HNC, has also been found in space (Snyder and Buhl 1971; Saykally et al. 1976). In molecular clouds, both isomers form from the dissociative electronic recombination of HCNH^+ . In cold molecular clouds, the abundance ratio HCN/HNC is of order unity (Sarrasin et al. 2010). HCN plays an important role in chemical reactions thought to have been important on the primitive Earth, for example, in Miller-Urey-type experiments (via its involvement in the Strecker amino acid synthesis) and in its self-condensation reactions that produce both amino acids and nucleic acid bases (Oró 1961).

Cross-References

- [HCN Polymer](#)
- [Hydrogen Isocyanide \(HNC\)](#)
- [Miller, Stanley](#)
- [Strecker Synthesis](#)

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Hydrogen Cyanide Polymer

► [HCN Polymer](#)

Hydrogen Ion Concentration Index

► [pH](#)

Hydrogen Isocyanide (HNC)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[HNC](#)

Definition

Hydrogen isocyanide (HNC) is a linear triatomic molecule that is an isomer of HCN, hydrogen cyanide, the latter being a key intermediary in several possible pathways for the production of important biological molecules. HNC itself is one of the more abundant triatomic molecular species in interstellar clouds, where the abundance ratio HNC/HCN appears to be sensitive to temperature. Because of its relatively large electric dipole moment (and hence rapid transitions to lower energy states) and since higher energy levels are populated by collisions with molecular hydrogen (the most abundant cloud species), the intensity of HNC rotational transitions can be used to estimate density in molecular clouds. Hydrogen isocyanide is also observed in cometary comae.

History

Hydrogen isocyanide was initially detected in the interstellar medium in 1971 by L. Snyder and D. Buhl. Because HNC is considerably higher in energy than its isomer HCN, at thermal equilibrium its abundance in the interstellar medium

would be essentially zero. Instead, in cold clouds, its abundance can equal or even exceed that of HCN. This evidence for the kinetic control of isomerization pathways was one of the strongest early observational supports for ion-molecule models of interstellar chemistry (Herbst 1987). Hydrogen isocyanide was first observed in a comet in Comet Hyakutake in 1996, but there is evidence that it may be primarily produced in the coma rather than being a constituent of the icy nucleus (Irvine et al. 1998; Cordiner et al. 2017)

Cross-References

- [Comet](#)
- [Hydrogen Cyanide](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

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Hydrogen Isotopes

Daniele L. Pinti
Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, Qc, Canada

Synonyms

[Protium](#); [Deuterium](#); [Tritium](#)

Definition

Hydrogen (symbol, H; atomic mass, 1.00794) has three isotopes. Two are stable in the environment and are denoted as ^1H (protium) and ^2H (deuterium or D). The third isotope, ^3H (tritium or T), is unstable and decays to ^3He with a ► [half-life](#) of 12.32 ± 0.02 years. Being hydrogen one of the ► [water](#)-forming elements, the ratio of the stable isotopes D/H has been used for identifying the origin of water within the Solar system. The D/H ratio measured in carbonaceous chondrites and Antarctic micrometeorites ($143\text{--}170 \times 10^{-6}$; Robert 2001; Engrand et al. 1999) is closer to the value of the present-day ocean (155.7×10^{-6}) than that measured in long-period and Jupiter family comets ($298\text{--}530 \times 10^{-6}$; e.g., Bockelée-Morvan et al. 1998; Altwegg et al. 2015).

Cross-References

- [Delta, Isotopic](#)
- [Deuterium/Hydrogen Ratio](#)
- [Micrometeorites](#)
- [Oceans, Origin of](#)
- [Oxygen Isotopes](#)
- [Ultra-carbonaceous Antarctic Micrometeorites](#)
- [Water, Delivery to Earth](#)

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Hydrogen Oxide

- [Water, Solvent of Life](#)

Hydrogen Phosphide

- [Phosphine](#)

Hydrogen Sulfide

Nicholas Arndt
ISterre, University Grenoble Alpes, Grenoble, France

Synonyms

[Sewer gas](#); [Swamp gas](#); [Stink damp](#); [Sour damp](#)

Chemical Formula

H_2S

Definition

Hydrogen sulfide is a colorless and poisonous gas with a strong odor of rotten eggs and the chemical formula H_2S . It occurs in volcanic gases and natural gases. It is produced by breakdown of organic matter, as a product of microbial sulfate reduction (when bacteria use sulfate as the terminal electron acceptor during growth under anoxic conditions), and by liberation from sulfide minerals. Being abundant in the prebiotic Earth, the H_2S figures out in many “[origin of life](#)” models (e.g., Olson and Straub 2015), especially those positing an origin near black smoker-type hydrothermal vents. It is found both in interstellar molecular clouds and in comets. The sulfanyl radical, SH, and

the corresponding cation sulfaniumylidene (sulfanylium), SH^+ , have also recently been detected in the interstellar medium.

Cross-References

- ▶ [Black Smoker](#)
- ▶ [Molecules in Space](#)
- ▶ [Origin of Life](#)
- ▶ [Sulfate Reduction](#)
- ▶ [Sulfate Reducers](#)
- ▶ [Sulfur Hydrides in the Interstellar Medium](#)

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Hydrogenated Amorphous Carbon

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[HAC](#)

Definition

Amorphous carbon is composed of randomly arranged clusters of hexagonal rings (the carbon portion of benzene). When hydrogen atoms are attached at surface sites, the substance is referred to as hydrogenated amorphous carbon or HAC. At various times, hydrogenated amorphous carbon has been proposed as the carrier of the infrared emission features commonly associated with ▶ [polycyclic aromatic hydrocarbons](#).

Cross-References

- ▶ [Polycyclic Aromatic Hydrocarbon](#)
- ▶ [Unidentified Infrared Emission Bands](#)

Hydrogenated Fullerene

- ▶ [Fullerane](#)

Hydrogenosomes

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Hydrogenosomes are organelles present in certain anaerobic eukaryotic microorganisms in which ▶ [fermentation](#) reaction takes place to generate ▶ [ATP](#). Some anaerobic eukaryotes lack mitochondria and contain instead hydrogenosomes. The major biochemical reactions in the hydrogenosomes are those associated to the oxidation of pyruvate producing H_2 , CO_2 , and acetate as final products. In some anaerobic ▶ [eukaryotes](#), intracellular symbiotic H_2 consumers, such as ▶ [methanogens](#), can be found.

Cross-References

- ▶ [ATP](#)
- ▶ [Endosymbiosis](#)
- ▶ [Energy Conservation](#)
- ▶ [Eukaryote](#)
- ▶ [Fermentation](#)
- ▶ [Methanogens](#)

Hydrolysis

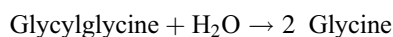
Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, hydrolysis refers to a chemical reaction in which molecules are split by the addition of a molecule of water. One fragment of the parent molecule gains a hydrogen ion (H^+), while the other group receives a hydroxyl group (OH^-).

Hydrolytic reactions catalyzed by both acid and base are common, for example, the hydrolysis of ► [amides](#) or esters. Their hydrolysis occurs when a nucleophile (water or a hydroxyl anion) attacks the ► [carbonyl](#) group of the ester or amide. In water, hydroxyl ions are better nucleophiles than water itself. In acid, the carbonyl group becomes protonated, and this leads to easier nucleophilic attack. The products of the hydrolysis of amides and esters are a carboxylic acid and an amine, and a carboxylic acid and an alcohol, respectively.

Under physiological conditions, in which the concentrations of a hydrolysable reactant and its products are low (on the order of 10^{-3} – 10^{-6} molar), the hydrolysis reaction, such as the hydrolysis of a peptide to amino acids, is essentially thermodynamically irreversible. For example:



Here the ΔG for the reaction is ~ -3.5 kcal/mole, and the spontaneous reassembly of amino acids to ► [peptides](#) is negligible.

Cross-References

- [Amide](#)
- [Amine](#)
- [Carbonyl](#)
- [Carboxylic Acid](#)
- [Peptide](#)

Hydromagnetics

- [Magnetohydrodynamics](#)

Hydrophobic Effect

Lawrence Pratt
Tulane University, New Orleans, LA, USA

Keywords

Hydrophobicity · Hydrophobic interactions · Hydrophobic bonds

Definition

Hydrophobic effects are phenomena of aqueous solutions involving hydrophobic species or molecular groups, which are recognized by contrast to hydrophilic species or groups. Hydrophilic species typically have simply recognized chemical interactions with water molecules, e.g., ammonia (NH_3) or perhaps have electrostatic interactions with water, e.g., ions such as Na^+ . Hydrophilic species typically have substantial solubility in liquid water. In contrast, hydrophobic species, e.g., methane (CH_4) or hydrocarbons broadly, have less favorable interactions with water molecules, and predominantly interactions of van der Waals type. Hydrophobic species typically have low solubilities in water. Hydrophobic groups can be combined with hydrophilic groups

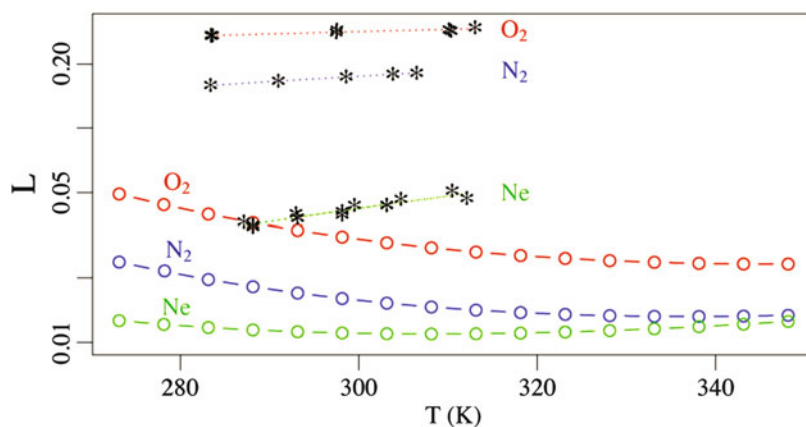
in larger molecules, and this vastly extends the functionality of molecules like that. Molecules that combine hydrophobic and hydrophilic groups are called amphiphilic. Sodium dodecylsulfate ($\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}$), a simple surfactant, is an example. The characteristic functionality of amphiphilic molecules is to coat aqueous solution interfaces, satisfying the tendency of hydrophilic groups for contact with water while also satisfying the tendency of hydrophobic groups to avoid contact with water. In fact, the appellation “surfactant” indicates that behavior.

The extended functionality of amphiphilic species can lead to self-assembled possibilities for organization of larger solution structures, including micelles, bilayer membranes, and specifically structured macromolecules such as folded water-soluble protein molecules. The balance of hydrophobic and hydrophilic effects can make the solution thermodynamic characterization of these solutions tricky. Since hydrophilic effects are typically more simply recognized and modeled, hydrophobic effects are associated with the additional complications exhibited by amphiphilic species. Those complications are typically unfavorable entropy change for dissolution, and

substantial temperature dependences for those entropy changes. Figure 1 gives examples of distinctions between solubilities of simple gases in water and cyclohexane, and distinctions in T -dependences. Distinctive T -dependences are often required for identification of hydrophobic effects for specific study.

History

Tanford's (1997) expansive discussion (Further Reading) gives an entertaining history of the genesis of the concepts and names associated with hydrophobic effects in the context of understanding soluble proteins. That historical discussion culminates with the watershed review article of Kauzmann (1959) (Further Reading), which marks an opening of the modern era in study of hydrophobic effects. Since the mid-1970s, analysis of the underlying molecular description of hydrophobic effects has extensively exploited the development of molecular-scale simulation with rapidly advancing computational tools. Ashbaugh and Pratt (2006) presented a modern perspective on the interplay between computer



Hydrophobic Effect, Fig. 1 Ostwald coefficient L for some simple gases in water (circles) and cyclohexane (stars). The Ostwald coefficient is the fractional amount of the gas in the solution relative to the amount in a coexisting dilute vapor phase. Thus $L = 0.05$ for O_2 at the lower temperatures here means that the concentration

of O_2 in the water is 5% of the concentration of O_2 in coexisting vapor. All results are for low (Earth) ambient pressures. Notice that this plot utilizes a logarithmic vertical axis. These gases are less soluble in water than in cyclohexane, and the T dependences display opposite trends. (Redrawn after Ashbaugh and Pratt 2006)

simulation work, molecular theory, and classic physical chemistry. A broader range of applications is considered in the review of Pratt and Pohorille (2002).

Overview

A striking feature of observed biophysical structures is that spatial organization is achieved by competing interactions, hydrophilic and hydrophobic interactions. The most primitive conceptualization of hydrophobic effects is just that water and oil can demix. Those phase equilibria, together with molecular-scale hydrophobic-hydrophilic amphiphilicity, can then result in spatially segregated mesoscopic structures (Further Reading: Tanford 1978). The driving force for oil-water phase separation is customarily viewed as a sticky interaction operating between hydrophobic species, but not as specifically as suggested by the old-fashioned term “hydrophobic bond”.

Phase separation is not the only interesting aspect of hydrophobic effects. Standard solution thermodynamic studies establish that the suggested hydrophobic stickiness becomes stronger as the temperature increases through a physiological range. This is experimentally clear in the phenomenon of cold-denaturation of proteins wherein cool, unfolded soluble proteins fold upon heating. That protein globules become more highly ordered with increasing T may seem counter-intuitive. But if the contacting aqueous solution becomes sufficiently disordered with T -increase, expectations from ordinary thermodynamics are restored. This suggests that the refolding of a cold-denatured protein is driven by the participation of the solution. Participation of the solution in stabilizing functional biomolecular structures is an aspect of hydrophobic effects.

Molecular theories and explanations of hydrophobic effects range from appeal to and parameterization of simple intuition to aggressive statistical mechanical theory of

solutions. Because these are problems of acknowledged importance and sometimes challenging to molecular-scale intuition, agreement on molecular theories and mechanisms has been imperfect. Ashbaugh and Pratt (2006) give a glimpse of the range molecular theories advanced for these phenomena.

An important aspect to hydrophobic effects is that the solvent water itself behaves unlike common organic solvents. Liquid water is typically a chemically active medium. It is stable over comparatively wide temperature range, and exhibits a large heat capacity that helps to moderate temperature excursions for the terrestrial biosphere. The Pohorille and Pratt (2012) discussion considered thermodynamic characteristics of solvents that might be compared to water. That survey identified non-water liquids glycerol, diethylene glycol, ethylene glycol, formamide, 2-aminoethanol, 1–4 butanediol, and 1–5 pentanediol, and mixtures of such solvents, as cases worthy of further study for comparison with liquid water in supporting a solvophobic/solvophilic dichotomy and perhaps leading to interesting self-assembly of functional larger-scale solution structures.

Cross-References

- [Lipid Bilayer](#)
- [Protein](#)
- [Water](#)

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Hydrophobicity

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Hydrophobicity refers to the property of a molecule to resist dissolution in water. Organic compounds with ionizable or polarizable groups tend to be hydrophilic, as opposed to hydrophobic, as those groups may be favorably solvated by polar water molecules via hydrogen bonds and other mechanisms. On the other hand, organic compounds without polarizable groups are generally hydrophobic and thus show low solubility in water. Alkanes are typical hydrophobic molecules. When hydrophobic molecules are placed in water, water tends to exclude them. This is called the hydrophobic effect. Molecules with both hydrophilic groups and hydrophobic groups are called amphiphilic molecules. Hydrophobicity and amphiphilicity are important in the self-assembly of organic molecules which may have been important in the origin of biological membranes.

Amino acids show a variety of hydrophobicities due to their variable side chains. Phenylalanine and leucine have large hydrocarbon groups and show high hydrophobicity, while aspartic acid and lysine show low hydrophobicity (high hydrophilicity) due to ionizable groups in their side chains. Various hydrophobic scales are sometimes used to evaluate the hydrophobicity of amino acids and other compounds.

Cross-References

- [Amino Acid](#)
- [Amphiphilicity](#)
- [Hydrogen Bond](#)
- [Self-Assembly](#)

Hydrosphere

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

The *hydrosphere* is the combined mass of water in the atmosphere, at the surface, and in the interior of the Earth and of other planetary bodies. About 97% of the total volume of the Earth's hydrosphere ($1.335 \times 10^9 \text{ km}^3$) is in the oceans; the remaining $\sim 3\%$ is in the continental ice caps ($\sim 1.7\%$), groundwater ($\sim 1.3\%$), lakes and rivers ($\sim 0.013\%$), and the atmosphere ($\sim 0.0009\%$). Up to five times the surface volume of the oceans may be present in the mantle, fixed in the structure of nominally anhydrous minerals. Mars appears to have had a small liquid hydrosphere early in its history and retains water in ice caps and in the subsurface. A thick hydrosphere covers the Jovian moons Europa (ca. $3.8 \times 10^9 \text{ km}^3$) and perhaps Ganymede and the Saturnian moon Enceladus.

Cross-References

- [Mars](#)
- [Oceans, Chemical Evolution of](#)
- [Ocean Planet](#)
- [Oceans, Origin of](#)
- [Water, Delivery to Earth](#)

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Hydrostatic Balance

- [Hydrostatic Equilibrium](#)

Hydrostatic Equilibrium

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Hydrostatic balance](#)

Definition

Hydrostatic equilibrium designates a stable state of a fluid where there is a condition of balance between gravitational force and pressure gradient. In a planetary atmosphere, under simplifying assumptions (perfect gas, isothermal), the hydrostatic equilibrium condition leads to a law of pressure (p) variation with altitude (z) that is exponential: $p = p_0 \exp(-z/z_0)$, where z_0 is the scale height (8 km on Earth). In a star, the radiation pressure creates an additional outward force that participates in the hydrostatic equilibrium equation. Note that hydrostatic equilibrium implies that the star's or planet's shape is a sphere in the simplest case and an oblate spheroid for a rotating body.

Cross-References

► [Gravitation](#)

Hydrothermal Alteration

Michel Jébrak
Département des Sciences de la Terre et de
l'Atmosphère, Université du Québec à Montréal,
Montreal, QC, Canada

Keywords

Hydrothermal system · Mars

Synonyms

[Metasomatism](#)

Definition

Hydrothermal alteration is defined as any change in the mineralogic composition of a rock due to the action (by either physical or chemical means) of hydrothermal fluids in an open system.

History

Hydrothermal alteration has been recognized on Earth since the onset of geology. It is a very common process, and it is often associated with mineral deposits. Hydrothermal alteration was suspected on Mars from observations carried out by early ► [Viking](#) landers (Newton and Hagerty 1997), and it was discovered on the ground by the Mars Science Laboratory rover "Curiosity."

Overview

Hydrothermal alteration marks the disequilibrium between fluids, usually aqueous, and rocks, usually silicate-rich. Hydrothermal alteration has been observed on Mars and is presumed to exist on other small ocean planets (Pirajno 2009). Smaller planets show rock porosity to a greater depth than the Earth, allowing deeper hydrothermal fluid circulation and exchange to exist.

On ► [Mars](#), alteration mineralogy can be determined from the composition of impact craters, which provide natural probes into the subsurface. Alteration minerals occur as large unsaturated, partially altered zone, without contact with the atmosphere. Mud volcanoes reflect the importance of such clay formation at depth. Two styles of alteration have been recorded: low-pH alteration, marked by sulfate deposits, and neutral to high-pH alteration, marked by crystallization of chlorite, nontronite, saponite, serpentine, and carbonates. Such alteration could be produced by hydrothermal systems related to impacts, high-temperature geothermal systems related to plume

volcanism (Tharsis), and zones of high geothermal gradient (Ehlmann et al. 2011). Impact activity induced localized hydrothermal system near the borders of the craters, and such activity may last several million years after the impact. The subsurface alteration peaked in the early stage of Mars' evolution, in the Noachian (>4.1 Gyr ago) and into the Early Hesperian (3.7–4.1 Gyr ago). Serpentine is uncommon but has been found in *mélange* terrains, impact craters, and within a regional olivine unit near the Isidis basin.

In other small ocean planets (► [Titan](#), ► [Ganymede](#), ► [Callisto](#), ► [Europa](#), ► [Enceladus](#)), hydrothermal alteration is assumed due to the probable onset of hydrothermal systems and the formation of liquid water at the contact within the cryosphere (Vance et al. 2007).

Zones of hydrothermal alteration may impact the topography by facilitating collapse of hydrothermal zones. Increase of porosity, higher temperature, and presence of water in hydrated minerals may have facilitated the establishment of subsurface biota. Carbon monoxide-bearing fluids infiltrated from the surface could have reacted with the hydrogen from serpentinization to form methane, which could have fuelled ► [methanotrophs](#) and been mediated by ► [methanogens](#) (Michalski et al. 2013). Alteration of basaltic rocks releases Fe and Mg cations which can fuel iron respiration and facilitate the formation of complex organic molecules.

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Hydrothermal Environments

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Keywords

Black smoker · White smoker · Hydrothermal fluid · Oceanic crust · Origin of life · Serpentinization

Definition

A *hydrothermal environment* is a setting dominated by the circulation of hot, mainly aqueous fluids. In a mid-ocean ridge setting, seawater penetrates the oceanic crust, becomes heated, interacts with the oceanic crust so that its chemical composition changes, and then exits at a hydrothermal vent (black and/or white smoker) on the ocean floor. The environment surrounding the vent sustains rich, anoxic chemotrophic ecology. This environment is a possible setting for the emergence of life on Earth.

Overview

The simple definition of a hydrothermal fluid is a hot water-rich fluid in the Earth's crust. The origin of the fluid is diverse, ranging from seawater that penetrates down into the oceanic crust or fills pore space in sedimentary basins to magmatic fluid released from crystallizing igneous intrusions. These fluids are heated as they descend into the oceanic and/or continental crust or encounter magmas. Hot fluids can transport large volume of materials derived from the parent magma or leached from surrounding rocks, and many of the world's greatest ore deposits form as metals such as Cu, Zn, Au, or U precipitate from hydrothermal fluids.

In astrobiology, the most important hydrothermal environment is close to the surface of the oceanic crust, at or near a mid-ocean ridge. As

seawater penetrates the oceanic crust, it becomes heated and interacts with the crust so that its chemical composition changes (Humphris et al. 1995; Alt and Teagle 2000; Früh-Green et al. 2007). It then may exit at a hydrothermal vent on the ocean floor. Components leached from basaltic rocks of the crust – sulfide or sulfate, silica, oxides, and carbonates – precipitate as the fluid is cooled and becomes diluted as it mixes with seawater. These components are initially dispersed in the plume that ascends from the vent, or they flocculate around the vent to form chimneys (black and white smokers) whose height might reach 60 m. Particles raining out from the plume produce a layer of sediment, to which the relicts of chimneys (which topple when they become too tall and unstable) are added. The product is a lens of “exhalative” sulfide, which, if accreted to the continent, can be mined for metals such as Cu, Zn, and Pb (Tivey 2007).

Fluids that circulate at a mid-ocean ridge become strongly heated and acidic as they interact with basaltic crustal rock. Such fluids dissolve large quantities of Fe-Cu-Zn sulfides that precipitate as small particles within the fluid as it exits the vent, imparting a black color to the hydrothermal plume and giving rise to the term “black smoker.” Such fluids interact with very hot rock adjacent to magma chambers beneath the ocean ridge; their temperatures may reach 400 °C. In environments off the mid-ocean ridge axis, reactions between seawater and ultramafic rocks (through process called serpentinization) produce methane- and hydrogen-rich fluids that are highly alkaline, with lower temperatures ranging from about 40 °C to 90 °C. These fluids are rich in dissolved carbonate and sulfate; when they exit from the ocean floor, they form “white smokers.”

The areas around hydrothermal vents often host complex communities of archaea, bacteria, and larger, more diverse organisms, including giant tubeworms, clams, limpets, and shrimps. These deep-sea organisms have no access to sunlight and depend on the hydrothermal fluids for nutrients and energy. The archaea and bacteria use sulfur compounds, particularly hydrogen sulfide, to produce organic matter via chemosynthesis. The bacteria surround the hydrothermal vent

area with a thick mat that attracts other organisms such as amphipods and copepods that graze on the bacteria. Larger animals complete the food chain. The main families found around seafloor vents are annelids, pogonophorans (marine wormlike animals), gastropods, bivalves, and crustaceans, together with the famous tubeworms that epitomize the vent community.

Corliss et al. (1981) and Wächtershäuser (1990), a German chemist turned patent lawyer, suggested that life might have originated at hydrothermal vents early in the Archean. It is well established that organic compounds are produced by inorganic, ► **Fischer-Tropsch-type** reactions deep in the oceanic crust when hot aqueous fluids react with minerals like olivine or pyroxene. These compounds were transported in hydrothermal fluids to the seafloor where they interacted with seawater. The presence of clay minerals provided templates that foster the formation of peptides and protocells. Martin and Russell (2007) proposed that as hydrothermal fluid emerged at the ocean floor, it reacted inside small metal sulfide cavities within hydrothermal vent chimneys. Large chemical and thermal gradients between the interior and exterior of the chimney provided the microenvironment for life-forming chemical reactions to take place.

Active hydrothermal vents may exist on Jupiter’s moon Europa, and alteration minerals that might have resulted from the circulation of hydrothermal fluids have been found on Mars.

Basic Methodology

Active hydrothermal vent systems are observed from submersibles – small submarines that can descend to the great depths of the ocean floor. Scientists record the activity of the vents, register the flux and the physical characteristics of the fluids, and take samples of the fluids, of the chimneys, and of surrounding sedimentary deposits and eventually organisms. These are analyzed in the laboratory – the fluids for their composition and other characteristics (acidity and oxidation state), the rock samples for their mineralogy, and geochemical composition. Several vents have

been sampled by scientific drilling as part of the Integrated Oceanic Drilling Program (IODP). Fossil hydrothermal vents are studied in sections that have been obducted onto, or accreted to, the continental crust. Notable examples are in Cyprus and in mining areas such as the Abitibi greenstone belt in Canada and the Urals.

- [Hydrothermal Reaction](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Mid-Ocean Ridge](#)
- [Origin of Life](#)
- [Serpentine](#)
- [Serpentinization](#)
- [White Smoker](#)

Key Research Findings

Hydrothermal circulation plays an important role in cooling the oceanic crust; hydration of basalts strongly affects its composition; and release of fluids in subduction zones controls island arc magmatism and contributes directly to the growth of continental crust. Hydrothermal fluids form accumulations of Cu, Zn, and Pb sulfides, which are mined when the deposits are found on the continents. Unusual bacterial and animal communities surround active hydrothermal events. Hydrothermal vents in the early Archean may have been the site of the emergence and early evolution of life.

Future Directions

Investigation of hydrothermal vents is continuing as part of the Integrated Ocean Drilling Program and other oceanographic programs. The biological community is involved through their research on the ecology of hydrothermal vents. The search for a better understanding of the reactions that produced prebiotic compounds continues. Companies and government organizations are investigating how active submarine hydrothermal systems might be mined as a source of metals such as Cu, Zn, and Au.

Cross-References

- [Black Smoker](#)
- [Chemoautotroph](#)
- [Chemolithoautotroph](#)
- [Chemolithotroph](#)
- [Chemotroph](#)
- [Hydrothermal Alteration](#)

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Hydrothermal Reaction

Koichiro Matsuno
Nagaoka University of Technology, Nagaoka,
Japan

Keywords

Exergonic reactions · Heating · Hot vents · Hydrolysis · Hydrothermal circulation · Quenching · Selective retention

Definition

Hydrothermal reactions are chemical reactions that take place in or near hydrothermal vents. Of importance from the perspective of prebiotic chemistry is the fact that the two processes, heating and quenching, are separated due to the repeated hydrothermal circulation of seawater around the hot vents. Heating is indispensable for activating the reactants for a wide variety of synthetic reactions, while quenching is crucial for selectively retaining some of those species that are synthesized. Heating and quenching experienced sequentially during hydrothermal circulation of seawater can make prebiotic chemistry evolutionary without being entrapped in thermal equilibrium in which both heating and quenching remain inseparable.

Overview

Hydrothermal reactions are classified into two distinct groups. One is for the reactions in thermal equilibrium, and the other is for those off thermal equilibrium.

Experimental examination of synthetic chemical reactions in thermal equilibrium starts from the reactants supplied externally to an environment initially prepared in thermal equilibrium and specifies the character of the final synthetic products precipitated under the imposed equilibrium conditions. An advantage of hydrothermal reactions examined under the present methodology is in the appraisal of exergonic reactions at higher temperatures compared to endergonic ones expected at lower temperatures, though it may look counterintuitive at first sight. A case in point is an estimate of the thermodynamic likelihood of synthesizing amino acids from their precursors in moderately reducing hydrothermal environments. Thermodynamic evaluation in terms of the Gibbs free energy reveals that the synthesis of many amino acids is exergonic when synthesized from their component smaller molecules at temperature 100 °C, whereas the synthesis is endergonic at 18 °C (Amend and Shock 1998).

That synthesizing organic molecules such as amino acids in hydrothermal environments is exergonic implies the synthetic reactions be energetically downhill and is quite welcome from the perspective of prebiotic synthesis at least until finally reaching thermal equilibrium. Evolutionary relevance of chemical reactions in thermal equilibrium is thus sought in how the initial reactants could be prepared and how the reaction products could be removed. In fact, equilibrium prebiotic chemistry can provide a wide variety of reaction products depending upon the choice of the initial reactants. Some products might indeed catalyze reactions that have some prebiotic utility, but other products may well inhibit such catalysis or catalyze adverse reactions. An example of this sort is seen in the clay-catalyzed condensation of nucleotides, which could work best if only one type of enantiomer of the starting material is present, while if both types were present, catalytic condensation of one enantiomer could be disturbed and inhibited by the presence of the other enantiomer (Joyce and Orgel 1999).

Instrumental to making prebiotic chemistry evolutionary must therefore be naturalization of the coordination of both supplying the initial reactants to and removing the products from reaction sites in an integrated manner. One natural candidate for meeting this challenge is constant circulation of seawater through the periphery or the vicinity of hydrothermal vents, the latter of which could work as reaction sites because of the availability of heat energy for activating various reactions. Both reactants and products are carried by the circulating flow of seawater and visit the hot reaction sites occasionally, while the flow stays in the vast cold ocean during most of the time. Chemical reactions proceeding within the circulating flow are undoubtedly not in thermal equilibrium due to crossing the temperature gradients generated around the vents repeatedly as dismissing the occurrence of stationary chemical reactions anchored at thermal equilibrium.

When one tries to figure out the average frequency of an arbitrary tiny droplet of seawater in the ocean visiting one hydrothermal ridge system, its modest estimate would give about once every 30 million years upon the conjecture that the

weight of the total seawater on the surface of Earth is of the order of 10^{18} t and the water issued from a single ridge system is about 1000 t per second. If there are about 1000 independent hydrothermal ridge systems in the ocean even prior to the emergence of the major continents, the frequency of a tiny droplet visiting any one of the ridge systems could be raised to about once every 30 thousand years. This numerical exercise simply gives a possible lower limit to the actual visiting frequency. The actual visiting can however be made far more frequent locally because of the participation of a wide variety of shortcuts.

Geology-assisted hydrothermal circulation of seawater is peculiar in converting the preceding reaction products in the solution into the succeeding reactants when visiting hot spots again and again, after being subject to rapid quenching every time. This hydrothermal conversion from products to reactants can have a natural tendency to enhance the synthesis of products of a specific kind. The underlying chemistry is pretty simple. Suppose one starts with a solution of monomers of a single kind to be circulated. Elongation of oligomers out of the initial monomers could be expected when both precursor oligomers and monomers are visiting hot spots, while those products that could be hydrolyzed back into the original monomers are released into the cold surroundings. Only those derivatives that could survive the preceding period of hydrolysis even partially may participate in the further elongation when they visit the hot spots the next time. The elongated products are thus inclined to selectively maintain only those oligomers of the kind that could be evolutionary in keeping the preceding memory of synthesis even partially.

There is nothing special with both thermal synthesis of products and their hydrolysis in prebiotic chemistry. However, if one conceives of both within the homogeneous scheme of chemical reactions in thermal equilibrium, a formidable obstacle would come up. No separation between synthesis and hydrolysis is possible there. Synthesis and hydrolysis would produce a homogenized mixture in thermal equilibrium, with ending up with a mere mixture of complex products and no chemical evolution.

What is specific to hydrothermal circulation of seawater around the hot vents in the ocean is its natural capacity of separating between synthetic production and selective retention of the products. As a matter of fact, one may be able to observe how products would be synthesized in the hot spots and how those products could subsequently survive their possible hydrolysis when transferred into the cold surroundings by following the streamline of the circulating fluid sequentially. What remains to be seen is to address the tractable issue of whether the present picture of separating synthetic production from selective retention of the products could experimentally be testable.

One relevant experiment is the synthesis of oligopeptides from monomeric glycine in a flow reactor simulating hydrothermal circulation of seawater in the ocean, while setting the frequency of visiting a hot spot (225 °C) to be once every 30–80 s instead of every 30,000 years (Imai et al. 1999). When the frequency of visiting the hot spot was raised from once every 78 s to every 34 s, the yields of oligomeric products were found to increase accordingly. The increase of the yields demonstrates the cumulative nature of synthetic production in the sense that the yields increased exponentially with the increase in the frequency of visiting the hot spot.

Unless the synthetic production and selective retention of the products are forcibly homogenized as in theoretical chemical reactions in thermal equilibrium, prebiotic chemistry proceeding in inhomogeneous thermodynamic conditions (such as those applied to hydrothermal circulation of seawater) could already be selective in retaining only a specific set of synthetic products. Unique to the selective retention of the products associated with the hydrothermal reactions is the built-in selective sieve for those products surviving rapid quenching that takes place soon after the products leave the hot spots and enter into the cold environments. In particular, there are at least two distinct fates waiting for the product entering into the cold. One is to lower the temperature of the product with the aid of its hydrolysis, and the other is to lower the temperature of the product by storing the acquired heat energy internally in the form of chemical bonds without suffering

hydrolysis. Which will win depends entirely upon which is faster. This is the situation of winner takes all. Those that could not survive rapid quenching would necessarily be pruned off.

Prebiotic chemistry aimed at addressing the origins of life has to face two different tasks in an integrated manner at the same time. One task is to prepare the chemistry that could be sufficiently synthetic and versatile enough to be amenable to evolutionary adaptation. And another one is to secure the chemistry that could be sufficiently fine tuned and specific enough to maintain a well-orchestrated self-organization. At first sight, these two tasks would seem contradictory. Despite that, chemical reactions riding on hydrothermal circulation of seawater may suggest to us a loop-hole for reaching out to a meaningful integration of the seemingly contradictory tasks by letting the circulating flow serve as a unifying thread. One likely means of examining the present objective experimentally might be to try to run the overall exergonic reactions of the oxidative citric acid cycle within the paradigm of hydrothermal reactions under the premise that pyruvate as the energy and carbon source is already available (Matsuno and Nemoto 2005).

Cross-References

- [Black Smoker, Organic Chemistry](#)
- [Hydrocarbons](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Polymer](#)

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Hydrothermal Vent Microbiology

- [Hot Vent Microbiology](#)

Hydrothermal Vent Origin of Life Models

Koichiro Matsuno and Eiichi Imai
Nagaoka University of Technology, Nagaoka, Japan

Keywords

Amino acids · Black smoker · Carboxylic acids · Concentration problem · Hydrothermal vent · Membranous structures · Nucleotides · White smoker

Definition

- [Hydrothermal environments](#) are places where hot water comes into contact with mineral surfaces.

History

Perhaps the first specific proposal (aside from Darwin's offhand reference to a warm little pond (Calvin 1961), which is in some ways a hydrothermal model) for the involvement of hydrothermal environments in the ► [origin of life](#) was that of Harvey in 1924 (Harvey 1924), who suggested that terrestrial thermal springs such as those found in Yellowstone National Park in Wyoming might have been ideal sites for chemical evolution. The idea was resurrected after the 1979 discovery of black smoker submarine hydrothermal sites associated with mid-ocean spreading centers (Corliss et al. 1981). Since its modern resurrection, a wealth of theoretical and experimental studies have examined the idea from various perspectives; nevertheless, the idea remains contentious.

Overview

The resurgence of the hydrothermal model in the late 1970s offered a counterpoint to the long-prevalent Oparin-Haldane heterotrophic model, which had attracted several criticisms. Among them were the notion that the early atmosphere may not have been reducing (in which case the yield of organics from atmospheric synthesis would have been greatly reduced (Schlesinger and Miller 1983)), the possibility that large meteorite impacts might have repeatedly sterilized the surface of the Earth (Maher and Stevenson 1988), and the possible detrimental effects of UV radiation on surface chemistry in the absence of an ozone layer (Berkner and Marshall 1965). Among the proposed benefits of hydrothermal vent environments for the origin of life are thus (1) protection from harsh surface conditions (such as the aforementioned UV radiation and ocean sterilizing meteorite impacts); (2) an abundance of chemical potential in the form of reduced dissolved gases and metals; (3) mineral surfaces to serve as catalysts, adsorbents, and cavities for the production and entrapment of organic compounds; and (4) thermal energy to overcome kinetic barriers to reaction.

It is likely that the geothermal heat flux was greater near the time of the origin of life than at present (Holm 1992); thus, hydrothermal sites were likely more abundant on the early Earth, and they may be more abundant in the modern solar system, for example, in the interiors of Mars and Europa, than are favorable surface environments (CIBA 1996). Furthermore, it has also been suggested that hyperthermophilic archaeobacteria, of the sort typically associated with submarine vents, cluster near the roots of phylogenetic trees (Stetter 2006), supporting the idea that life originated at high temperature, or at least passed through an early high-temperature bottleneck (Arrhenius et al. 1999).

There are a number of potential geochemical settings which are compatible with hydrothermal origin of life models; among them are ► **black smoker** type vents, off-axis type vents, and terrestrial hot spring environments. Black smoker hydrothermal environments have typically very

high temperature ($\sim 350^\circ\text{C}$) and are acidic, reducing, and sulfide rich. Significant amounts of metal sulfides may be deposited in these environments. The eponymous black chimneys are largely composed of metal sulfides which precipitate as the reducing, hot, acidic metal, and sulfide-rich hydrothermal fluids meet the cold ($\sim 2^\circ\text{C}$) oxidizing ambient seawater.

Not long after the discovery of these sites, Wächtershäuser (1988) proposed a pyrite surface model for the origin of life, which suggested life arose based on the attachment of negatively charged molecules such as organophosphates and carboxylic acids (which are ubiquitous in modern biochemistry) to positively charged pyrite surfaces. A series of carbon-fixing reactions were proposed to be catalyzed by these surfaces which allowed for the duplication of the catalytic surface reaction system, which subsequently spread across the mineral surface and complexified over time. This model was not initially explicitly proposed in the context of submarine hydrothermal vents, but the ubiquity of sulfide minerals in such environments quickly led to its being considered in that manner.

Debate soon focused on the extremely high temperatures and low pH values found in such systems, conditions under which most organic compounds are rather unstable (White 1984), which led many to doubt their appropriateness as sites for the accumulation and complexification of organics. After this debate had subsided somewhat, a second type of submarine vent was discovered, the so-called Lost City or peridotite-hosted hydrothermal vent system (Kelley et al. 2001). These environments have typically much lower temperature ($\sim 40\text{--}90^\circ\text{C}$), and the fluid emanating from them is basic (pH 9–11) and quite reducing. Hydrothermal origin of life models has arisen over time to accommodate the conditions more typically found in these environments (see, e.g., Martin and Russell (2007)).

Laboratory simulations of the stability and reactivity of organic compounds under hydrothermal vent type conditions are complicated by the fact that the conditions in these environments range so widely (i.e., from highly reducing to highly oxidizing, from ~ 2 to 350°C , from pH

2 to pH 11, and as fluids are in contact with diverse and variegated mineral surfaces for periods of time ranging from seconds to tens of thousands of years (Holm 1992)).

Some problems which need to be overcome in hydrothermal vent origin of life models include concentrating reactants, synthesizing small organic molecules from dilute solutions under conditions that many organic molecules are unstable, and the polymerization of those monomers into more complex molecules such as peptides, oligonucleotides, and membranes (with the types of molecules specific to the particular model of the proposer).

While many have proposed that complex organic chemistry may occur in deep-sea hydrothermal vent environments, there are a number of obstacles to this. First, the notion that the atmosphere was not particularly reducing stems from the idea that the upper mantle had already released most of its volatiles and its reducing equivalents (largely in the form of metallic and reduced iron) had already segregated into the lower mantle and core (Delano 2001). Thus, although [serpentinization](#) may have been the source of reducing equivalents in hydrothermal systems, their reducing nature was not likely much greater than it is now. Presently, there is some debate over how much of the reduced gases (which consist predominantly of H₂, CH₄, and lesser amounts of ethane, ethane, propene, and propane (Proskurowski et al. 2008)), and this does appear to be in line with equilibration under the reducing environment of the system. However, although the organic molecules detected thus far are extremely depleted in ¹⁴C, suggesting the source of the carbon in them is the mantle derived, the confirmation of the presence of more complex abiotic organic or reduced nitrogen compounds is frustrated by contaminating biological material which becomes entrained as water is drawn into the vent system from neighboring pore sediment water. Thus, it remains uncertain whether even simple organics can be generated in these systems. There is certainly room for further investigation of this possibility.

One suggested the advantage of synthesizing organic compounds in the vicinity of

hydrothermal vents is that many synthetic reactions are calculated to be exergonic at elevated temperatures and pressures. The syntheses of 11 of the 20 protein-forming amino acids were calculated to be exergonic at 100 °C (Amend and Shock 1998). However, Bada et al. (1995), among others, have shown that amino acids are extremely unstable at elevated temperature. Even simple molecules such as glycine have short half-lives at temperatures above 150 °C, and the abundance of such molecules would depend on the balance between their synthesis and degradation. The experimental verification of such syntheses under conditions comparable to those found in natural environments is thus far lacking.

The synthesis of more complex molecules such as nucleotides, oligonucleotides, lipids, or peptides requires that several precursor molecules be brought together. As these reactions are at the very least kinetically second order, they require some concentration mechanism to occur appreciably. One proposed mechanism for solving the concentration problem is thermophoresis in hydrothermal pore systems. Baaske et al. (2007) have theoretically and experimentally discovered model laboratory systems that suggest pore systems inside rocks in the vicinity of ocean hydrothermal vents could enhance the concentration of reactants in pore water with the aid of the marked temperature gradients available there. The enhancement of the concentration is due to the interplay between convective and diffusive flow of solutions in the presence of temperature gradients. Another proposed solution is surface adsorption; however, mineral surfaces are also known to act as catalysts for breaking molecular bonds (Marshall-Bowman et al. 2010), and surface adsorption typically becomes weaker at high temperature; thus, most organics would likely tend to migrate to lower-temperature environments (Cohn et al. 2001), and the residence time of molecules in the high-temperature portion of the systems also requires some experimental verification.

Provided significant starting concentrations of amino acids, peptides can be formed at elevated temperature in water, both with and without condensing agents, as long as the reactions are not

heated for very long. For example, tripeptides of phenylalanine, tyrosine, and glycine have been synthesized at 100 °C in slurries of FeS and NiS as a catalyst in the presence of hydrogen sulfide or methanethiol as a condensing agent (Huber and Wächtershäuser 1998). However, peptides are thermally unstable in water. Below mM concentrations of amino acids, peptides do not form appreciably (Cleaves et al. 2009). Peptides are considerably more stable than oligonucleotides; thus, these sorts of considerations are likely more severe for molecules such as RNA, presenting a disconnect between hydrothermal vent models and RNA World models.

Cycling could overcome some of these problems. For example, molecules could be synthesized during residence in a high-temperature milieu and then quickly quenched into a lower-temperature region. Imai et al. (1999) observed that the synthesis of hexamer of glycine was possible from the cyclic reaction of fairly concentrated solutions of glycine in simulated hydrothermal circulation between 250 and 0 °C. For deep-sea environments, this may be problematic, as the bulk ocean would likely have had a very low concentration of organic compounds (Aubrey et al. 2009). Terrestrial thermal pools may be more favorable in this regard.

There are thus several problems for hydrothermal vent models with respect to organic chemistry. Nevertheless, several lines of evidence point toward an early high-temperature period for life, and there also remain numerous unknown aspects of the types of chemistry which might occur in such environments which warrant further study.

Cross-References

- [Amino Acid](#)
- [Black Smoker](#)
- [Black Smoker, Organic Chemistry](#)
- [Earth, Formation, and Early Evolution](#)
- [Hot Vent Microbiology](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Reaction](#)
- [Oligopeptide](#)
- [Origin of Life](#)

- [Polymer](#)
- [Serpentinization](#)
- [White Smoker](#)

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Hydroxy Acid

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Hydroxy acids are organic compounds containing both hydroxyl and carboxylic acid functional groups. α -Hydroxy acids are a particularly important class of carboxylic acids which have a hydroxyl group on the carbon adjacent to the carboxylic acid group or α -carbon. They may be either naturally occurring or synthetic. Commonly occurring biological α -hydroxy acids include lactic (CH₃CHOHCOOH), glyceric (HOCH₂CHOHCOOH), glycolic (HOCH₂COOH),

and malic (HOOCCH₂CHOHCOOH) acids. α -Hydroxy acids are important metabolic products of the biological transamination of ► [amino acids](#). Several α -hydroxy acids and α -hydroxy acid polyols have been identified in the Murchison meteorite. Some interpret the presence of α -hydroxy acids in this body as evidence for the Strecker-cyanohydrin mechanism for the synthesis of the amino acids also found in it.

Cross-References

- [Amino acid](#)
- [Carboxylic acid](#)
- [Hydroxyl group](#)
- [Strecker synthesis](#)

Hydroxyacetaldehyde

- [Glycolaldehyde \(HOCH₂CHO\)](#)

2-Hydroxyethanoic Acid

- [Glycolic Acid](#)

Hydroxyl Group

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

The term hydroxyl group is used to describe the -OH functional group in an organic compound.

Organic molecules containing hydroxyl groups are known as alcohols. Hydroxyl groups are especially important in biochemistry due to their tendency to form hydrogen bonds, as they contain both lone pairs of electrons and a weakly acidic proton. Hydroxyl groups are also able to form hydrogen bonds with water, a property that increases the hydrophilicity and solubility of molecules containing them. The carbohydrates are an example of a group of molecules that are extremely soluble due to hydroxyl functional groups.

Cross-References

- ▶ [Alcohol](#)
- ▶ [Carbohydrate](#)

Hydroxyl Radical (OH)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[OH](#)

Definition

The hydroxyl radical, containing single oxygen and hydrogen atoms, is highly reactive. In the terrestrial troposphere, it interacts with and removes a number of pollutants as well as the greenhouse gases methane and ozone. It can damage typical biological macromolecules. As a free diatomic molecule, it is widespread in the ▶ [interstellar medium](#) of our Milky Way galaxy and other galaxies, where it is frequently observed in maser emission. Some external galaxies contain so-called OH megamasers, with luminosity orders of magnitude greater than masers in our Galaxy. In the solar system, OH is a major constituent of cometary comae and an indirect measure of their water content.

History

The OH radical was the first interstellar molecule detected by radio astronomers, in 1963 by Weinreb et al. Measurements of the Zeeman effect for OH transitions have subsequently been used to estimate the magnetic field in the interstellar medium. In 1981, the pure rotational lines of OH were observed at far-infrared wavelengths in absorption against the continuum emission from a background molecular cloud. Cometary OH has been detected both in the ultraviolet and, in 1973, at radio wavelengths; this led to the correct prediction that H₂O ice was present in cometary nuclei and was the source of the hydroxyl radical (through photodissociation by the solar ultraviolet photons).

Cross-References

- ▶ [Atmosphere, Structure](#)
- ▶ [Comet](#)
- ▶ [Interstellar Medium](#)
- ▶ [Maser](#)
- ▶ [Molecules in Space](#)

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4-Hydroxyphenylalanine

- ▶ [Tyrosine](#)

\$16-Hydroxypurine

- ▶ [Hypoxanthine](#)

Hygiea

Hervé Cottin

Univ Paris Est Creteil and Université Paris Cité,
CNRS, LISA, F-94010 Créteil, France

Definition

(10) Hygiea is the fourth largest object of the asteroid main belt, after (1) Ceres, (4) Vesta, and (2) Pallas, the number between brackets being the historical order of discovery of each object. Its mass is 8.7×10^{19} kg, with a density of 2.06 g/cm³, and its size is 450 km × 430 km × 424 km, which makes it a relatively spherical object and considered by some astronomers as a candidate to be recognized as a dwarf planet. Its orbit around the Sun is completed in 5.57 years and is quite eccentric (eccentricity = 0.119) with perihelion at 2.8 ua and aphelion at 3.5 ua. With an albedo of 0.063, Hygiea's surface spectral characteristics are similar to those of the dwarf planet Ceres and match carbon-rich C-type asteroid properties. Due to this spectral proximity and similar densities, it has been proposed that Ceres and Hygiea could share a common origin.

History

(10) Hygiea was discovered in 1849 by Annibale de Gasparis. This first observation occurred rather late compared with other large asteroids such as (2) Pallas or (3) Juno, respectively, discovered in 1802 and 1804. This is due to the relatively low albedo of (10) Hygiea combined with its large distance from the Sun.

Cross-References

- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [C-Asteroid](#)
- [Ceres](#)
- [Meteorites](#)

Hypercycle

Peter Schuster

Institut für Theoretische Chemie der Universität
Wien, Wien, Austria

Keywords

Autocatalytic network · Hyperbolic growth ·
Major transitions · Dynamical systems ·
Oscillations · Symbiosis

Synonyms

[Cyclic replicator equation](#)

Definition

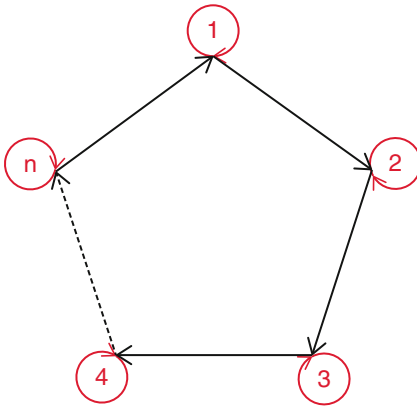
A hypercycle is a catalytic network of autocatalysts (I_k) that are functionally coupled in a dynamical cycle: $\Rightarrow I_1 \Rightarrow I_2 \Rightarrow \dots \Rightarrow I_n \Rightarrow I_1 \Rightarrow$. Hypercycle dynamics are described by means of nonlinear differential equations of replicator equation type (Fig. 1).

History

The hypercycle was invented in the 1960s (Eigen 1971) as a model for cooperation of otherwise competing elements that are capable of self-replication. Hypercycles were postulated as mechanisms for major transitions in evolution (Eigen and Schuster 1977, 1978a, b; Maynard Smith and Szathmáry 1995; Schuster 1996; Phillipson and Schuster 2009).

Overview

Several replicators ($X_1, X_2, \dots, X_n$) – entities capable of self-replication – form a cyclic catalytic network in which the replication is catalyzed by the precursor element: X_1 catalyzes the formation of X_2 and so on until X_n catalyzes the formation of X_1 . Thereby, the catalytic interactions form



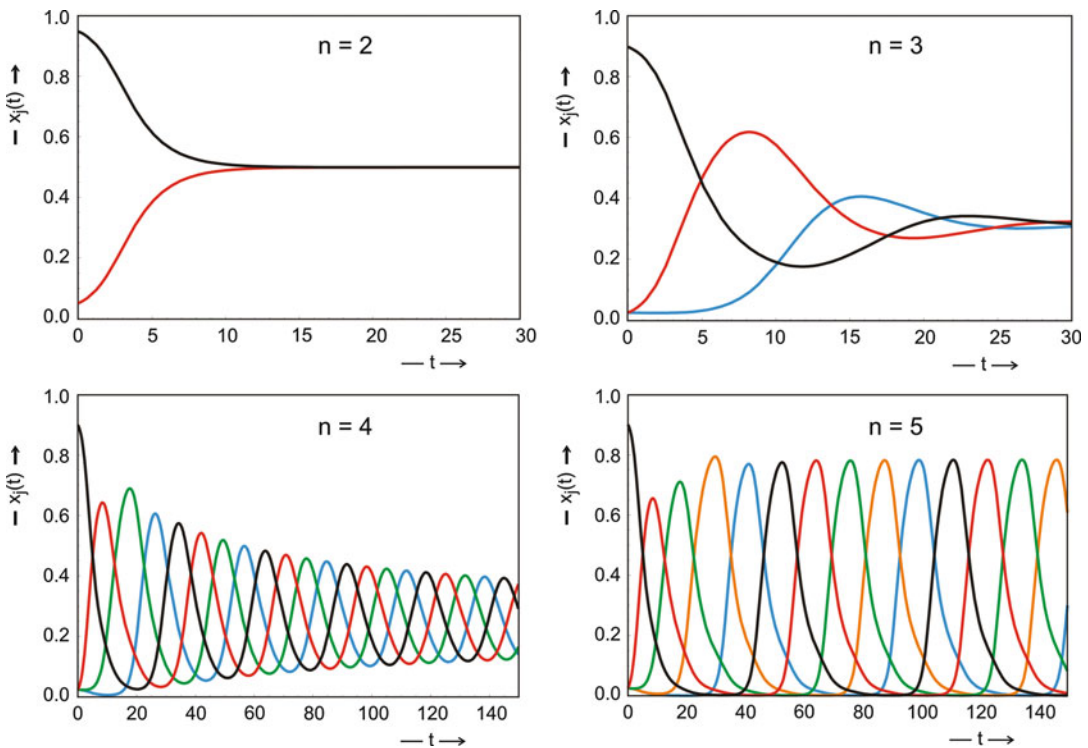
Hypercycle, Fig. 1 The catalytic interactions in a hypercycle with n members. The individual elements, 1, 2, 3, 4, ..., n , are coupled by cyclic catalysis (black arrows): $1 \rightarrow 2$, $2 \rightarrow 3$, $3 \rightarrow 4$, $4 \rightarrow n$, $n \rightarrow 1$. Every member is an autocatalyst as indicated by cycles (small circular arrows)

a closed loop: $1 \rightarrow 2 \rightarrow 3 \rightarrow \dots \rightarrow n \rightarrow 1$. The simplest theoretical example is the *elementary hypercycle*, which in mathematical terms is described by the differential equation

$$\frac{dx_j}{dt} = x_j \left(f_j x_{j-1} - \sum_{i=1}^n f_i x_{i-1} x_i \right); \quad (1)$$

$$i, j = 1, 2, \dots, n \text{ and } i, j = \text{mod } n$$

which is a special case of replicator equations (Hofbauer and Sigmund 1998; Nowak 2006). The variables are normalized concentrations of replicators, $[X_j] = N_j$ and $x_j = N_j / \sum_{i=1}^n N_i$ with $\sum_{j=1}^n x_j = 1$. The parameters f_j are rate parameters of the catalyzed replication reactions, $(A) + X_j + X_{j-1} \rightarrow 2X_j + X_{j-1}$, where (A) stands for the building blocks for the synthesis.



Hypercycle, Fig. 2 Hypercycle dynamics visualized in form of solution curves of Eq. 1. Normalized concentrations of the members of hypercycles $x_j(t)$ are plotted as functions of time t for different sizes of the cycle. Individual members (different colors) cooperate in the reproduction of the entire cycle. Different dynamics is observed for different sizes: $n = 2$, the concentrations approach their stationary values monotonously; $n = 3$, the concentrations approach the stationary values with strongly damped oscillations; $n = 4$, the

concentrations approach the stationary values with weakly damped oscillations; and $n = 5$, the concentrations oscillate without damping. For $n > 5$, hypercycle dynamics shows oscillations without damping as illustrated here for the $n = 5$ case. The following parameter values were chosen: $f_1 = f_2 = f_3 = f_4 = f_5 = 1$; initial conditions, $x_1(0) = 0.95$ and $x_2(0) = 0.05$ for $n = 2$ and $x_1(0) = 0.9$ and $x_k(0) = 0.1/(n-1)$ for $n = 3, 4, 5$

The qualitative features of solutions of Eq. 1 do not depend on particular values f_j (as long as they are strictly positive, $f_j > 0$, Hofbauer and Sigmund 1998). Without losing generality, all f_j values are chosen to be equal, and the dynamical system has a stationary point in the middle of concentration space: $x_1 = x_2 = x_3 = \dots = x_n = 1/n$. The solution curves $x_j(t)$ show characteristic dependence on the size of the hypercycle (Fig. 2):

1. For $n = 2$, the dynamical system converges monotonously to a unique and asymptotically stationary state at which both replicators X_1 and X_2 are present.
2. For $n = 3$ and $n = 4$, the stationary state is unique and asymptotically stable. The solution curves $x_j(t)$ show strongly damped oscillations $n = 3$ and weak damping for $n = 4$.
3. For $n \geq 5$, the stationary state is unstable and the concentrations $x_j(t)$ oscillate.

Independently of internal dynamics, the total concentrations of hypercycles as integral units, $C(t) = \sum_{i=1}^n N_i(t)$, grow stronger than exponential for unlimited resources. This *hyperbolic growth* is observed for a class of systems in which the population size has an enhancing effect on the growth rate. Examples of hyperbolic growth were observed in virology, in demography (growth of human population), and in economics (*increasing returns*). Systems with hyperbolic growth outgrow exponentially growing systems, since in theory a hyperbolically growing population can reach infinity in finite times. Once a hypercycle has been established, it is very hard to replace it by another system: hypercycles are candidates for *once-and-forever* decisions. Examples for hypercycles in the real world are symbioses and other forms of cooperation within and between species. Formation of hypercycle-like networks among cooperative RNA replicators has been reported (Vaidya et al. 2012).

Cross-References

- Endosymbiosis
- Evolution, Biological
- Evolution, Molecular

- Quasispecies
- Self-Replication
- Symbiosis

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Hypersaline Environment

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Hypersaline environment is an extreme habitat dominated by high salt concentration. Associated to this extreme condition, other extreme conditions can be found like low oxygen concentration and alkaline conditions. The inhabitants of these environments are microorganisms that are called

“halophiles.” Halophiles have to solve the problem of the osmotic pressure generated in the cell membrane. To do that, they can use compatible solutes. Different groups can be distinguished on the basis of their physiological responses to salt. Several classifications have been proposed; one considers the optimum growth of the microorganisms at different salt concentrations: non-halophiles are those that grow best in media containing less than 0.2 M NaCl, halotolerant microorganisms that can tolerate high salt concentrations, moderate halophiles growing between 0.2 and 2.5 M NaCl, and extreme halophiles growing in optimal conditions at high salt concentration (2.5–5.2 M NaCl).

Hypersaline Lake

► [Soda Lake](#)

Hypertelescope

► [Interferometry](#)

Hyperthermophile

Jose Berenguer
Centro de Biología Molecular Severo Ochoa,
UAM-CSIC, Madrid, Spain

Keywords

High temperature · Hot springs · Hydrothermal vents · Origin of life · Thermal environment

Definition

The word hyperthermophile (literally extremely heat loving) refers to a microorganism that has

an optimum temperature for growth above 80 °C. Most hyperthermophiles belong to the Archaea domain, with only few exceptions belonging to Bacteria.

History

Thomas D. Brock (1978) isolated the archaeal genus *Sulfolobus* at Yellowstone National Park and showed that it grew optimally at 75 °C with an upper temperature limit for growth at 85 °C. Previous reports by the same author described prokaryotic microorganisms that were able to grow on microscopy slides inside boiling (92 °C) hot springs. These organisms probably were true hyperthermophiles. However, the first hyperthermophiles isolated and characterized in the laboratory (*Methanothermus fervidus* and the *Thermoproteus* spp.) were isolated from hot springs in Iceland and described simultaneously in 1981 in two articles coauthored by Karl O. Stetter and Wolfram Zillig (Zillig et al. 1981; Stetter et al. 1981). In the following two decades, further work led mainly by K. O. Stetter focused on submarine or subterranean thermal environments. This work allowed the isolation and description of more than 50 species of hyperthermophilic Archaea and a few Bacteria, some requiring temperatures above 90 °C to grow, with optimum temperatures above 100 °C. Phylogenetic analysis based on 16S RNA revealed that all of them are slowly evolving groups, supporting an ancient origin for this type of microorganisms.

Overview

Since the first descriptions of hyperthermophiles in 1981 (Zillig et al. 1981; Stetter et al. 1981), about 90 species of hyperthermophilic Archaea and Bacteria have been described from different terrestrial and marine thermal environments. Taxonomically and despite the existence of yet unassigned isolates, most are grouped in ten orders (Archaea: Thermoproteales,

Desulfurococcales, Pyrodictiales, Thermococcales, Archaeoglobales, Methanococcales, Methanobacteriales, Methanopyrales; Bacteria, *Aquificales* and *Thermotogales*). A few hyperthermophilic isolates are even unable to grow below 80–90 °C. Despite this, it has been possible to isolate hyperthermophiles far from the nearest known thermal effluent, probably because they remain viable for years at low temperatures. At the upper part of the temperature range, there are hyperthermophiles that can tolerate temperatures normally used in sterilization processes (121 °C) for 1 h (*Pyrodictium occultum*). Kashefi and Lovley (2003) reported residual growth of a hyperthermophilic isolate under such conditions.

The use of different phylogenetic markers assigns the hyperthermophiles to the root of the corresponding evolutionary trees, leading to the hypothesis that this kind of microorganism is very ancient. Despite this generally accepted view of the phylogenetic tree, the slow-evolving character of hyperthermophiles has been challenged by different studies in the last decade based on other phylogenetic approaches (Ciccarelli et al. 2006). According to this view, hyperthermophilic character could be an adaptation of moderate **thermophiles** to superheated environments, in some cases through lateral gene transfer.

Adaptation to hyperthermophilic conditions is the result of a series of specific modifications of the structures and macromolecules of the cell, as simple metabolites and cofactors are basically the same as those of mesophiles. Membrane adaptation results from an increase in the hydrophobic lateral interactions between the major lipids, esters of glycerol and two fatty acids in Bacteria, and ethers of glycerol and two isoprenol-derived alcohols in Archaea. In hyperthermophilic Archaea, bipolar tetraether lipids form membrane monolayers in which C40 isoprenols are frequently cyclized as a further thermal adaptation. A low DNA content (1.8–3 Mbp) and the presence of histone-like proteins have been described in some hyperthermophilic Archaea. The presence of type I topoisomerase that introduces positive coils (reverse gyrase) into DNA is the only trait common

to hyperthermophilic Bacteria and Archaea, leading to the hypothesis that DNA stability is an important factor for life at high temperatures. However, *Thermococcus kodakaraensis* mutants lacking this activity show only a slight decrease in growth rate above 90 °C, so it has been proposed that this enzyme could help to rewind ssDNA regions separated by thermal stress (Sandman 2008). Enzymes from hyperthermophiles usually have an activity profile that fits the temperature growth range of the organism of origin as the result of a higher number of intra- and intermolecular interactions (Vieille and Zeikus 2001).

Most hyperthermophiles grow as obligate or facultative chemolithotrophs by using either hydrogen or sulfides (e.g., pyrite) as electron donors and nitrate, CO₂, sulfur, sulfate, or ferric iron as electron acceptors to gain energy. Low concentrations of oxygen are also used by some isolates, but for most hyperthermophiles oxygen is highly toxic at or near their temperature of growth. Carbon assimilation by hyperthermophiles growing chemolithotrophically takes place on CO₂ or CO mainly through the reductive acetyl coenzyme A cycle (acetyl-CoA or Wood-Ljungdahl pathway), like in many anaerobic Gram-positive bacteria, or through the reductive tricarboxylic acid cycle (rTCA or Arnon cycle), as in green sulfur bacteria, although alternative modified pathways also exist. These cycles usually generate acetyl coenzyme A, from which gluconeogenesis must start. The presence of an irreversible condensing fructose biphosphate aldolase/phosphatase is a generalized trait within autotrophic hyperthermophiles that appears to be an essential step to guide these pathways toward gluconeogenesis (Say and Fuchs 2010). Facultative and obligate chemoorganotrophs also exist among hyperthermophiles that grow by anaerobic respiration, essentially with elemental sulfur (S⁰) as electron acceptors or, more rarely, by fermentation (i.e., *Thermoproteus uzonensis*). Data obtained from the analysis of thermophilic environments using molecular ecology methods (Pagé et al. 2008) suggests that the biodiversity of chemoorganotrophic hyperthermophiles is underestimated.

Basic Methodology

The high sensitivity to oxygen of hyperthermophiles at their growth temperatures is an important challenge for their isolation. Environmental samples to be used for the isolation of hyperthermophiles (water, soil, rock, etc.) have to be taken under reducing conditions to prevent any contact of microorganisms with oxygen at least at high temperature, when its toxic effect is more severe. For terrestrial surface environments, taking samples does not require sophisticated equipment. In the absence of N_2 gas, reductants such as sodium sulfide/sodium dithionite and an appropriate redox indicator such as resazurin can be added to sample glass containers, which have to be tightly closed with gas-impermeable butyl rubber stoppers. Samples can then be transported to the laboratory at room temperature. For under-sea hot environments, perforation drills, water samplers, piston corers, grab samplers, and dredge samplers or even deep submergence vehicles (DSVs) and remotely operative vehicles (ROVs) are required. Numbers of whole microbial communities in different submarine hydrothermal samples range from 10^4 to 10^9 cells per gram at the surface of ► [black smoker](#) chimneys, sediments, and hydrothermal plumes. Superheated vent fluids can range from undetectable numbers up to 10^6 cells per ml (Nakagawa and Takai 2006).

Once at the laboratory, isolation of new hyperthermophiles requires enrichment cultures subjected to conditions mimicking those of the environment at the sampling site regarding temperature, putative electron donors and acceptors, and carbon sources. Growth rate is a limiting factor for successful enrichment, and periods of days are usually required before attempting the isolation of individual cells. Due to obvious difficulties in keeping solid media under the prescribed conditions, most isolation procedures require liquid medium and use either dilution or physical methods such as optical tweezers. For high scale production, special fermenters have been designed to withstand the harsh growth conditions that most hyperthermophiles require,

which in some case combine high temperatures and pressure in acidic media (Stetter 2006).

Key Research Findings

The main interest of hyperthermophiles is based on two key observations. On the one hand, they were and still are regarded as ancestral organisms, giving an opportunity to analyze what are most likely “living fossils” from the Archaean era. This view is still the most accepted hypothesis, although an alternative hypothesis has been proposed. On the other hand, a search for the temperature limits for life has driven the search quest for more thermophilic microorganisms. Today, the upper temperature limit for growth of a well-established and described microorganism is 113 °C for *Pyrolobus fumarii* (Blöchl et al. 1997), whereas description of an isolate able to grow at 121 °C is still under discussion (Kashefi and Lovley 2003). A further area of research on hyperthermophiles is focused on the impressive thermostability of their enzymes and their possible use in industrial processes. This thermostability is also responsible for the ease with which their proteins and macromolecular complexes crystallize under laboratory conditions, raising additional interest that led to develop large structural genomics projects (Jenney and Adams 2008).

Applications

The high stability of enzymes under high temperatures (there are enzymes active above 125 °C) is associated with an increase in compactness that results in increased resistance to additional stresses such as the presence in the reaction of detergents or organic solvents (Vieille and Zeikus 2001). Such combination of resistances fits specific applications in different fields. For example, DNA polymerases from hyperthermophiles (*Pyrococcus* sp., *Thermococcus* sp.) are commonly used to amplify DNA sequences with high fidelity. Other enzymes from hyperthermophiles are or have

the potential to be used in industrial processes for which high temperatures represent an added value, such as starch and cellulose hydrolysis and further sugar modification (endoglucanases, glucosidases, xylanases, amylases, glucoamylases, pullulanases, etc.), proteases for detergents, lipases and esterases for biocatalysis, oxidoreductases like alcohol or glutamate dehydrogenases for biotransformations, C-C bonding enzymes (aldolases, transketolases), nitrile-degrading enzymes, etc. (Antranikian 2008). Additional applications in specific but robust biosensor devices or for nanotechnology are also in development. In addition to the enzymes, hyperthermophiles produce special kinds of compatible solutes such as mannosyl glycerate, cyclic 2,3-biphosphoglycerate, and diglycerol phosphate in relevant amounts, some of which have been shown to confer thermoprotection and protection against desiccation to mesophilic enzymes (Santos et al. 2008).

Future Directions

Given the biological and applied interest of hyperthermophiles, future research in the field will develop several lines of interest. Their ancient nature and extreme form of living require a comprehensive physiological study of at least a pair of model organisms, for which a reliable system for genetic manipulation should be developed. Present developments on *Thermococcus kodakaraensis* and *Sulfolobus solfataricus* are at the front lines of this effort. The construction of efficient systems for the overexpression of genes in such models will widen the number of hyperthermophilic enzymes available for applications that at present are hidden because of the inability to produce them in mesophilic hosts. Such expression systems will also be required to crystallize some of these proteins and complexes. Also, the metagenomic approaches on hyperthermophilic environments will open up a new world of enzymes having biotechnological potential to help to optimize existing processes and develop new

ones. Finally, molecular ecology methods in such environments will likely unveil the presence of new non-cultivable hyperthermophiles that could uncover some phylogenetic surprises. Hyperthermophiles are of special interest for astrobiology because high-temperature processes are important factors in the development of planetary bodies; thus, the scenarios in which life can develop in the universe increase correspondingly.

Cross-References

- ▶ [Autotroph](#)
- ▶ [Autotrophy](#)
- ▶ [Black Smoker](#)
- ▶ [Chemolithoautotroph](#)
- ▶ [Deep-Sea Microbiology](#)
- ▶ [Deep Subsurface Microbiology](#)
- ▶ [Hot Spring Microbiology](#)
- ▶ [Hot Vent Microbiology](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Hydrothermal Vent Origin of Life Models](#)
- ▶ [Osmolite](#)
- ▶ [Thermophile](#)

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Hypolithic

Charles S. Cockell
Geomicrobiology Research Group, PSSRI,
Open University, Milton Keynes, UK

Keywords

Communities · Cyanobacteria ·
Extremophiles · Lithic habitats

Synonyms

Subliths

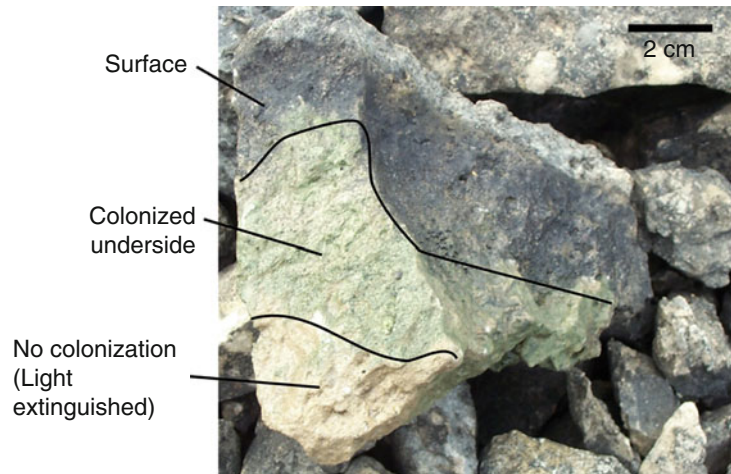
Definition

Hypoliths are organisms or communities of organisms that live on the underside of rocks or at the rock-soil interface.

Overview

In hot and cold deserts, the underside of rocks can provide a refugium for microorganisms, both photosynthetic (cyanobacteria and algae) and non-photosynthetic (Cameron and Blank 1965; Schlesinger et al. 2003). The organisms are referred to as “hypoliths.” The community is termed “hypolithon” (following the terminology for endoliths by Golubic et al. 1981). The photosynthetic components of hypoliths include organisms adapted to extreme rock habitats including *Chroococcidiopsis* and *Gloeocapsa* species. Hypoliths often display well-defined “bands” of growth on the underside of rocks or in the case of thin rocks, complete colonization of their underside. As photosynthetic microorganisms provide a source of carbon for heterotrophic microorganisms, the hypolithic colonization of translucent rocks by photosynthetic microorganisms can indirectly benefit non-photosynthetic microorganisms (Smith et al. 2000). Hypolithic colonization of quartz stones has now been documented in many locations, for example, the Vestfold Hills, Antarctica (Smith et al. 2000); the Mojave Desert, USA (Schlesinger et al. 2003); the Negev desert, Israel (Berner and Evenari 1978); the Namib Desert, Africa (Budel and Wessels 1991); and the deserts of China (Warren-Rhodes et al. 2007). On the underside of rocks, organisms gain a range of advantages compared to surface organisms, such as protection from UV radiation (Cockell et al. 2003). In the Antarctic polar desert, the stones warm the hypolithic biota and, during the summer, mitigate freeze-thaw (Broady 1981). Quartz stones in the Vestfold Hills, Antarctica, could provide temperatures 10° in excess of ambient air temperatures (Smith et al. 2000). For photosynthetic organisms, the limiting factor for the thickness of rocks under which photosynthetic microorganisms can grow is set by the thickness

Hypolithic, Fig. 1 An example of a community of photosynthetic hypoliths inhabiting the underside of opaque rocks in the Canadian High Arctic



H

that reduces light levels to below those required for ► [photosynthesis](#). Investigations on the colonization of the underside of translucent flint in the Negev desert showed that the more translucent flint types were colonized in a greater number of instances compared to less translucent flints (Berner and Evenari 1978). Less than 0.01% of incident light penetrated to below 40 mm in quartz rocks in the Negev (Berner and Evenari 1978), and light was reduced to 0.08% of incident under 25 mm of quartz rock from the Mojave desert (Schlesinger et al. 2003). At these depths colonization became limited. Broady found similarly large attenuations under Antarctic quartz rock (Broady 1981). The moisture availability in the hypolithic habitat is also an important determinant of which rocks are colonized and their ecological distribution in the environment (Warren-Rhodes et al. 2007). Hypoliths are also found under opaque rocks in polar deserts (Cockell and Stokes 2004). Greater than 90% of rocks examined were colonized. Periglacial processes can cause movements in rocks, which in turn create openings around the edges of rocks that allow the penetration of photosynthetically active radiation to the underside of rocks. These processes allow for the colonization of rocks with productivity of these communities potentially as high as the above-ground productivity accounted for by plants (see Fig. 1).

Cross-References

- [Cryptoendolithic](#)
- [Extremophiles](#)
- [Photosynthesis](#)

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Hypoxanthine

Shin Miyakawa
Kamagaya, Chiba, Japan

Synonyms

[\\$16-Hydroxypurine](#)

Definition

Hypoxanthine ($C_5H_4N_4O$, molecular weight: 136.11) is a naturally occurring purine base. It is occasionally found as a constituent of nucleic acids such as tRNA. The half-life of hypoxanthine to hydrolysis is 12 days at 100 °C and 5,000 years at 0 °C at pH 7. It has a UV absorption maximum at 249.5 nm (pH 7). It has been found in the Murchison meteorite and is synthesized by hydrolysis of ► [adenine](#), in HCN polymerizations, and in discharge experiments using gas mixtures such as CO–N₂–H₂O. The ribonucleoside of hypoxanthine is named inosine.

Cross-References

- [Adenine](#)
- [HCN Polymer](#)
- [Hydrogen Cyanide](#)
- [Meteorite, Murchison](#)
- [Nucleic Acids](#)
- [Purine Bases](#)

HZE Particle

Gerda Horneck
DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Synonyms

[Heavy charged particle](#); [Heavy ion](#); [Heavy nucleus](#); [Heavy primary](#)

Definition

HZE particles are a component of cosmic radiation consisting of energetic heavy nuclei (atomic number 3 or greater), so named for their high (H) atomic number (Z) and high energy (E). They contribute roughly 1% of the flux of galactic cosmic radiation and to an even lesser fraction to ► [solar particle events](#). Because of the difficulty of adequate shielding and the special nature of HZE particle-produced lesions, these particles are considered a major hazard to living beings in space, especially outside Earth's magnetosphere, that is, to human exploratory missions and interplanetary transfer of life by natural processes.

Cross-References

- [Biostack](#)
- [Cosmic Rays in the Heliosphere](#)
- [DNA Damage](#)
- [Linear Energy Transfer](#)
- [Lithopanspermia](#)
- [Panspermia](#)
- [Radiation Biology](#)
- [Solar Particle Events](#)

IAC, Colombia

Jorge Enrique Bueno Prieto
Instituto de Astrobiología de Colombia, Bogotá,
Colombia

- Developing research projects in Colombia's scientific centers
- Training teachers in the interdisciplinary methods of astrobiology
- Strengthening astrobiology in Latin America

Synonyms

[Instituto de Astrobiología de Colombia](#)

Definition

The Instituto de Astrobiología de Colombia (IAC) is an international partner of NASA Astrobiology Institute (NAI). The goals of the IAC are:

- Contributing to scientific excellence, creativity, and innovation for astrobiology education and research in Latin America
- Promoting interdisciplinarity in basic and engineering sciences
- Encouraging and inspiring students and teachers in STEM topics through astrobiology

The IAC approaches these goals by:

- Promoting education and research in astrobiology in schools and universities throughout Colombia

Cross-References

- ▶ [Biodiversity](#)
- ▶ [Ecosystem](#)
- ▶ [Evolution, Biological](#)
- ▶ [Extreme Environment](#)
- ▶ [Extremophiles](#)

References and Further Reading

www.astrobiologia.org

IAF

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[International Astronautical Federation](#)

Definition

In September 1950, Alexandre Ananoff from the “Groupement astronautique français” convened the first International Astronautical Congress (IAC). Eighteen representatives from the astronautical societies of eight countries (Argentina, Austria, Denmark, France, Germany, Spain, Sweden, and the UK) decided to set up an association to secure future international cooperation. The International Astronautical Federation (IAF) was formally established at the second IAC organized by the British Interplanetary Society (BIS), in London, in 1951.

Every year since then, the federation, together with the International Academy of Astronautics (IAA) and the International Institute of Space Law (IISL), has organized the International Astronautical Congress, which encourages the advancement of knowledge about space. It is held in connection with a major space exhibition. IAC is now recognized as the main international conference on space activities. More than 1600 technical papers on space programs and research activities around the world are presented in various sessions. The IAF maintains an online archive of past congress papers and presentations to provide members with a historical record of global space activities.

In 2020 the IAF had 407 members from 71 countries. The organizations involved include astronautical and other professional societies, space agencies and international organizations, companies from the space industry, universities and other research institutions, and nonprofit organizations interested in space matters.

lapetus

Therese Encrenaz
XLESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Iapetus was discovered in 1671 by Giovanni Domenico Cassini; it is the outermost mid-sized

icy satellite of ► [Saturn](#). Its distance to Saturn is 3,560,000 km (or 59 Saturnian radii), and its diameter is 1440 km. Its density is 1.02 g/cm³, indicating a very low rock/ice ratio. Iapetus is unique in its albedo distribution, which is very low on Iapetus’ leading side in its orbit around Saturn and ten times higher on the opposite side. It has been proposed that the dark material could be due to the permanent accretion of matter coming from the neighboring satellite ► [Phoebe](#), which is also very dark. Another possible explanation is that the low albedo of Iapetus could be a result of organic deposits formed from methane ice impacted by dust particles.

Cross-References

- [Phoebe](#)
- [Saturn](#)

IAU

William M. Irvine
Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Keywords

Astronomy · ICSU

Synonyms

[International Astronomical Union](#)

Definition

The International Astronomical Union (IAU) was founded in 1919 with the mission of promoting and safeguarding the science of astronomy in all its aspects through international cooperation. More than 12,000 professional astronomers (active in professional research and education) from all over the world, at the Ph.D. level and beyond, are IAU members. The IAU is financed

by academies or equivalent institutions of its 79 member countries.

Overview

The scientific and educational activities of the *IAU* are organized by its nine scientific divisions and some 35 specialized commissions (e.g., commissions devoted to Astrobiology, History of Astronomy, Stellar Evolution, The Local Universe) that cover the full spectrum of Astronomy. The long-term policy of the *IAU* is defined by the triennial General Assembly and implemented by the Executive Committee, while the day-to-day operations are directed by the *IAU* officers. The *IAU* Secretariat is hosted by the Institut d'Astrophysique de Paris, France.

The key activity of the *IAU* is the organization of scientific meetings, including nine international *IAU* Symposia every year, with additional symposia and other meetings every 3 years at the General Assembly. The *IAU* is also responsible for the definition of fundamental astronomical and physical constants, unambiguous astronomical nomenclature, promotion of educational activities in astronomy, and informal discussions on the possibilities for future international large-scale facilities. Furthermore, the *IAU* serves as the internationally recognized authority for assigning designations to celestial bodies and surface features on them. The *IAU* is a member of the International Council for Science (ICSU).

Ibn Battuta Desert

Gian Gabriele Ori and Kamal Taj-Eddine
Int'l Research School of Planetary Sciences, Univ.
d'Annunzio, Pescara, Italy
Ibn Battuta Centre, Université Cadi Ayyad,
Marrakech, Morocco

Keywords

Mud volcanos · Cold-seeps · Hydrothermal site · Sebkha · Evaporites · Travertines · Microbial communities

Definition

Ibn Battuta Desert is an informal term applied to the arid lands in Morocco extending from the Southern slope of the High Atlas to the North up to a desertic area rich of sebkhas (dry lakes) near Tarfaya to the South. The Ibn Battuta Desert stretches to the East from the Tafilalet (Erfoud, Rissani) up to the Atlantic Coast. Astrobiological field research have been performed in several locations, of which the most interesting are: (i) Hamar Laghdad -Kess Kess- (Tafilalet) near Erfoud (31°22'42"N 4°03'03"W); (ii) sebkhas in desert belt along the Atlantic coast South of the town of Tarfaya. (iii) the El Bordj carbonate body, Silurian in age, which represent the oldest chemosynthetic deposits so far recognized on Earth (33°03'58"N 5°36'41"W).

Overview

The Ibn Battuta Desert has been used by the Ibn Battuta Centre (www.ibnbattuta.org) for a large number of activities including rover mobility tests, entry, descent and landing (EDL), spacecraft operations, instrument testing for Martian mission, human Martian exploration, and geological features.

One of the main astrobiological setting in the informal Ibn Battuta Desert is the Hamar Laghdad located in Tafilalet near Erfoud, consisting of a ridge with cluster of mounds called Kess Kess (Fig. 1). These mounds, Middle Devonian in age, are interpreted as mud volcanoes produced by hydrothermal activity. They have been studied for several decades and recently, several authors suggested a strong astrobiological relevance due to the purported hydrothermal chemosynthetic origin. This unit has been firstly described by Roch (1934) whereas Brachert et al. (1992) provided a detailed sedimentological analysis. More recently, laboratory and paleontological evidence support a hydrothermal interpretation with a possible contribution by methane (Belka 1998; Joachimski et al. 1999; Cavalazzi et al. 2012; Guido et al. 2013; Franchi et al. 2015). A mound slightly younger than Kess Kess, the Hollard



Ibn Battuta Desert, Fig. 1 A panoramic view of the Kess Kess carbonatic mounds



Ibn Battuta Desert, Fig. 2 The Hollard Mound where it is possible to see a section of the internal structure: the internal core formed by a vertical chimney is surrounded

by inclined strata that represent the slope of the mound. The section shows clear evidence of a formation due to sedimentary volcanic processes



Ibn Battuta Desert, Fig. 3 A view of the Sabkha Oum Dbâ in foreground the steep wall of the margin of the depression and the central evaporites



Ibn Battuta Desert, Fig. 4 The travertine cascade at the Southern end of Sabkha Oum Dbâ. The smooth morphology is produced by calcareous layering, microbial/algal mats and vegetation

Mound (Fig. 2) (Hollard 1981), shows clearly evidence of a cold seep origin. The Kess Kess represent the most prominent examples of mud



Ibn Battuta Desert, Fig. 5 A sample from the bottom of creeks at the southern margin of Sabkha Oum Dbā. The top brown layer is an algal mat with diatoms and cyanobacteria. Immediately below there is a thin green layer mostly formed by cyanobacteria. The dark material below is a mixture of mud and cyanobacteria in an anoxic environment

volcanoes that have been active through the Devonian and Carboniferous in this area that was a shallow water embayment of the Paleozoic Ocean. They represent a quite unique case of this type of environments.

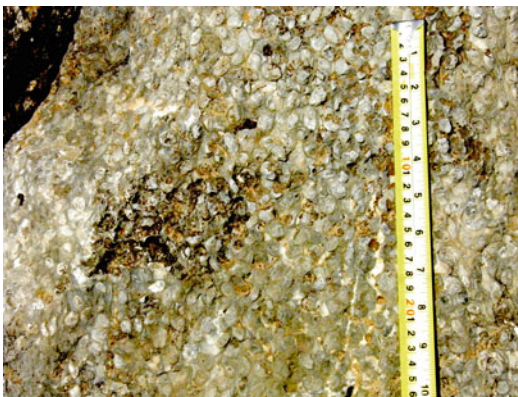
Another area with a strong astrobiological interest lies in the scattered sebkhas in the desert belt along the Atlantic coast South of the town of Tarfaya. The area is scattered by sabkhas (evaporitic dry lakes) that could be similar to the ones that may have produced evaporitic sediments on Mars. This area has attracted the attention of astrobiologists only recently (Barbieri and Cavalazzi 2018) with a program managed by the Ibn Battuta Centre. The area shows complex morphologies and environments. The sebkhas are localized inside depressions several tens of meter deep (Fig. 3). Evaporitic deposits are usually concentrated in the middle and the margins are covered by clastic, mostly, wind-blown deposits. Associated with the evaporites there are travertine deposits that, in one case, form an active travertine



Ibn Battuta Desert, Fig. 6 The slip face of a barchan dune near Tarfaya. The upper part of the dune slope consists of dark sand due to the presence of microbial elements



Ibn Battuta Desert, Fig. 7 The El Bordj body



Ibn Battuta Desert, Fig. 8 The brachiopod faces of the El Bordj body



Ibn Battuta Desert, Fig. 9 The three-dimensional morphologies of the stromatolite South of Ouarzazate

cascade (Fig. 4). Bacterial mats colonize the cascade itself and deposits downstream as well (Fig. 5).

In this area, geochemical research work has been carried on reg (deflation surfaces) deposits (Oberlin et al. 2018). Even the aeolian bed forms show evidence of biological activities in the

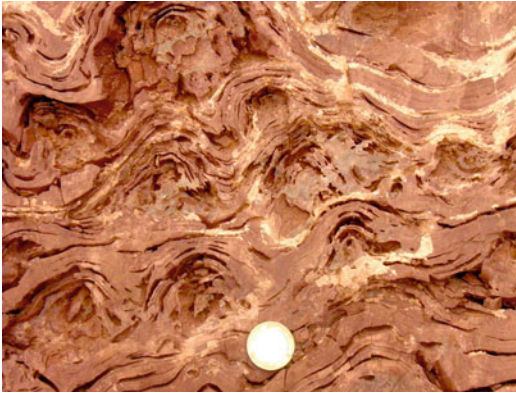
coastal area (near Tarfaya) with the formation of bacterial mats in the slip face of dunes. The effect is to “cement” the sand that is then eroded by the avalanching movement of the sand (Fig. 6).

A geological unit of strong astrobiological interest is the El Bordj carbonate body, Late

Silurian in age, which is the oldest chemosynthetic deposits so far recognized on Earth (Fig. 7). The El Bordj body is actually located outside the Ibn Battuta Desert at its border in the Middle Atlas. It was firstly described by Ager et al.

(1976), whereas Campbell and Bottjer (1995) suggested a possible chemosynthetic origin based on the presence of an extensive brachiopod community. Barbieri et al. (2004) with a compelling analysis have recognized this body as cold-seep in origin with methane mediation. Brachiopod accumulations (Fig. 8) form the bulk of the body that are matched also by stromatolites. Due to some agricultural work that has exposed a larger area of the body, Jakubowicz et al. (2017) have been able to recognize large modiomorphid bivalves associated with atrypid brachiopods. This finding confirms the chemosynthetic origin of these deposits.

The Ibn Battuta desert displays a number of other astrobiological sites and features such as the Cambrian stromatolites (Fig. 9), South of Ouarzazate where it is possible to see them in growing 3D position (Fig. 10).



Ibn Battuta Desert, Fig. 10 Section of the stromatolites



Ibn Battuta Desert, Fig. 11 A section of the travertine ridge near Shoura. The inclined stratifications dipping basinward

Quaternary travertine deposits crop out along the road linking Ouarzazate to Boumalne near Skoura. These travertines form a ridge marking to the margin of a lacustrine basin (Fig. 11). They exhibit a inclined stratification representing the margin of the basin.

Cross-References

- [Methane](#)
- [Microbialites](#)

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Ice

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In chemistry, ice refers to water in a solid crystalline phase, the common form of which encountered at normal terrestrial temperatures and pressures is known as Ice I *h*. There are 16 known crystalline phases of water ice, most of which are only known to occur at very high pressures, pressures which may be encountered in the interiors of large icy planets or moons, although one other phase, Ice XI, has been observed in some Antarctic glaciers. Ice I *h* is the only known nonmetallic substance which expands as it freezes, being some 9% less dense than liquid water at 273 K. This is due to hydrogen bonding in the crystal lattice which forces the molecules into positions farther apart than normally occurs in the liquid phase. This change in volume contributes to water's activity in the mechanical

weathering of minerals and also causes ice to float when frozen.

In planetary science, and more generally in astronomy, an ice refers to a volatile (a species with a low boiling point, such as N_2 , water, CO_2 , NH_3 , H_2 , CH_4 , and SO_2) with a melting point above ~ 100 K. The solid phases of these ices can be glasses (which are technically extremely viscous liquid phases) or crystalline solids, depending on the temperature, pressure, and rate at which the ice forms. Ices observed or expected to be present on the mantles of interstellar dust grains include, in addition to water, CO , CO_2 , CH_3OH , CH_4 , NH_3 , O_2 , and N_2 . Ices reported on the surfaces of satellites in the outer solar system and of Kuiper Belt Objects include H_2O , CH_4 , N_2 , CO , CH_3OH , and perhaps other volatile organics such as ethane.

Cross-References

- [Comet](#)
- [Enceladus](#)
- [Europa](#)
- [Hydrogen Bond](#)
- [Interstellar Ices](#)
- [Kuiper Belt](#)
- [Volatile](#)
- [Water](#)

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Ice Line

- [Snow Line](#)

Ice-Albedo Bifurcation

- [Snowball Earth](#)

Icy Moons Chamber

- [Simulation Chambers](#)

243 IDA

- [Ida](#)

Ida

Ivanka Pelivan
Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Synonyms

[243 IDA](#)

Definition

Ida is a main-belt asteroid of the Koronis family, originating from the breakup of a larger parent body. It orbits the sun between the orbits of Mars and Jupiter at an average distance of 2.86 AU with one orbit taking about 4.84 years. Ida has a rotation period of 4.63 h. Elongated in shape, its average diameter is about 32 km. It is accompanied by its moon Dactyl which has an average diameter of 1.2–1.6 km. Dactyl's orbit provided constraints for Ida's density to $2.6 \pm 0.5 \text{ g/cm}^3$. Ida's mass is estimated between 3.65 and $4.99 \times 10^{16} \text{ kg}$.

Ida has been classified as spectral S-type asteroid. The irregular surface of the asteroid is heavily cratered and covered by regolith composed of silicate minerals. Ida exhibits space weathering where older parts of the surface turn reddish. Based on cratering records, Ida's surface seems more than 1 billion years old, whereas the Ida-Dactyl system is estimated to be less than 100 million years of age considering the collisional life expectancy of Dactyl.

History

Ida was discovered in 1884 by the Austrian astronomer Johann Palisa in Vienna. It was visited and imaged in 1993 by the Galileo spacecraft. Ida’s moon Dactyl, the first confirmed satellite of an asteroid, was discovered in February 1994 by Ann Harch from Galileo’s imaging team.

Cross-References

- ▶ Asteroid
- ▶ Asteroid Belt, Main
- ▶ Galileo Galilei
- ▶ Regolith, Planetary

IDP

- ▶ Interplanetary Dust Particle

IEC

- ▶ Ion-Exchange Chromatography

IEP

- ▶ Isoelectric Point

Igneous Rock

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Synonyms

Magmatic rock

Definition

An igneous rock forms by crystallization of magma. There are two main types: *effusive*

volcanic rocks that crystallize or solidify from erupted lava or fragmental (pyroclastic) material that reaches the surface of the Earth, at contact with the atmosphere and/or the hydrosphere; *plutonic or intrusive rocks* which crystallize from magma that did not reach the surface. These two types are distinguished by their grain size: *effusive volcanic rocks* are fine-grained or even glassy because they cool rapidly following eruption at the Earth’s surface; rare crystals typically float in a fine-grained matrix; *intrusive plutonic rocks* are coarse-grained and typically show an interlocking fabric because they crystallize slowly in a thermally insulated environment. Common minerals in igneous rocks are ▶ *olivine*, pyroxene, amphibole, mica, plagioclase, feldspar, and quartz. Common intrusive rock types include ▶ *peridotite*, ▶ *gabbro*, granodiorite, and ▶ *granite*; their volcanic equivalents are ▶ *komatiite*, ▶ *basalt*, andesite, and rhyolite, respectively.

Cross-References

- ▶ Basalt
- ▶ Continental Crust
- ▶ Gabbro
- ▶ Granite
- ▶ Mafic and Felsic
- ▶ Mantle
- ▶ Mid-ocean Ridge
- ▶ MORB
- ▶ Oceanic Crust

Ikhwan al-Safa

Ahmed Ragab¹ and Allyssa Metzger²
¹Harvard Divinity School, Cambridge, MA, USA
²Harvard University, Cambridge, MA, USA

Keywords

Islam · Islamic astronomy · Isma’ili · Fatimid · Pythagorean · Celestial animal · Astrology

Synonyms

Brethren of purity

Overview

The Brethren of Purity (*Ikhwan al-Şafa'*) were a group of anonymous authors who composed a collection of 50–52 epistles (the last two may have been later additions by the same or other authors), which became well-known from the late ninth century. Contemporary Shiite Isma'ili scholars and authors claimed the epistles to be composed by Isma'ili missionaries – a claim that went uncontested by their contemporaries. This Isma'ili attribution combined with internal evidence suggest that the epistles were either fully or largely completed before the establishment of the Isma'ili Caliphate in 909.

As a collection, the Epistles attempted to encompass all branches of knowledge. The 52 Epistles were grouped into four sections, sometimes called books: “mathematical sciences” (14 epistles), “corporeal and natural sciences” (15 epistles), “sciences of the soul and intellect” (ten epistles), “Divine and legal sciences” (11 or 12 epistles). Ikhwān al-Şafā addressed astronomical and cosmological considerations in the second book, especially in its second epistle (16 overall). Ikhwān al-Şafā endorsed the concept of the celestial animal, which Ptolemy presented in his *Planetary Hypotheses*, and which had important Stoic roots. Similar to an animal or a human, the universe with its different orbs is animated by the universal soul, which leaves it at the end of times, much like the departure of a human or animal soul signals the end of life for that given being. Their discussion of the universal soul, and the end of the universe at the end of times, departed from Aristotelian views on the infinity of the universe which were common among philosophers at the time, and share the convictions of the theologians (*mutakallimīn*).

Although Ikhwān al-Şafā's writings betray strong Pythagorean and Neo-Platonic influences,

their cosmological and astronomical discussions largely accepted Aristotelian and Ptolemaic models that were dominant in the Greco-Islamic context of the time. They accepted the universal circular motion of planets as caused by the movement of the outer orb, which is moved by the Prime Mover. Motion was transferred downwards from outer to inner orbs, making lower planets slower than the upper planets. They unequivocally refused any notion of contradictory or retrograde motion, insisting that all planets moved in the same direction in perfect circles. They appeared to have objected to Ptolemy's eccentrics, although they fully endorsed epicycles as perfect explanations of the planets' retrograde motion and of apparent change in their size and brightness. Ikhwān al-Şafā accepted the Aristotelian notion of a different nature for celestial beings. However, they explained that this nature was limited only to their being incorruptible, and that they exhibited many of the other qualities of bodies in the sub-lunar sphere. These similarities appeared to provide enough justification for celestial influences on beings in the sublunar sphere, thus legitimizing astrology. They rejected the existence of empty space whether inside or outside the universe.

While the Epistles represented an encyclopedic collection that addressed all essential branches of knowledge at the time, they had a central goal of self-improvement that held through the entire collection. They also maintained a clear understanding of prophecy and the Imamate and their role as conduit of universal divine knowledge, the difference between the Select and the Commoners in relation to knowledge, and the role of knowledge as the central component of faith and pious living.

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The series “Epistles of the Brethren of Purity,” edited by Nader El-Bizri and published jointly by Oxford University Press and the Institute of Ismaili Studies since 2008, will be the first critical edition and annotated English translation of the entire corpus of the Rasāʾil, gradually replacing the three previous editions of the text (Bombay 1887–9, Cairo 1928, Beirut 1957)

Imaginary Voyages (from Antiquity to the Eighteenth Century)

David Dunér

Lund University, Lund, Sweden

Keywords

History of science · Literature · Philosophy of science · Science fiction

Synonyms

Science fiction; Space voyages

Definition

Imaginary voyages are fictional travel accounts or narratives, commonly expressing utopian ideas and satirical comments on the contemporaneous society.

History

A kind of imaginary voyage is the space travel narrative using current scientific knowledge, often in combination with satire, political critique, utopian dreams, and philosophical reflection. The dream of flying and leaving this Earth is archaic. The Chinese emperor Shun more than 4000 years ago, according to a legend, fled to safety in a parachute. The Old Testament tells of Elijah taken up to heaven by angels in a chariot of fire. In Greek myth, the inventor Daedalus designed wings of feathers and wax in order to escape, together with his son Icarus, from the labyrinths of King Minos. Icarus flew too close to the Sun, so that the wax melted and he soon fell into the sea.

Ancient cosmology did not give much scientific support for the existence of extraterrestrial life. Aristotelian physics and the Ptolemaic geocentric model made a sharp distinction between

IKI

Michel Viso

Innovaxiom, Paris, CX, France

Synonyms

Russian Space Research Institute

Definition

IKI, the Russian Space Research Institute (Russian: Институт космических исследований Российской Академии Наук), is an institute of the Russian Academy of Sciences that was founded in 1965 as the Space Research Institute of the USSR Academy of Sciences and renamed in 1992. It is the leading Russian organization for space research and has frequently collaborated on missions with ► [NASA](#), ► [ESA](#), and other national space agencies. IKI is located in Moscow and has a staff of some 290 scientists in the fields of astrophysics, planetary sciences, solar-terrestrial physics, cosmic plasma physics, and geophysics. Among its successes relevant to astrobiology was the ► [Vega](#) spacecraft to ► [Comet Halley](#).

Cross-References

► [Vega 1 and 2 Spacecraft](#)

the Earth and the heavens. Notwithstanding, imaginary space voyages exist in antique literature. The Roman author Marcus Tullius Cicero's *Somnium Scipionis* (The Dream of Scipio) from the first century BCE tells about a journey taking place in the dreams in which the soul is liberated from the body and travels into space.

What could be described as the first detailed space travel narrative is the Syrian satirist Lucian of Samosata's *Alēthē diēgēmata* (A True Story), written in the second century CE. *A True Story* is indeed a satire, a parody that alludes to the fantastic travelogues, fictional journeys, miracles, and fables told in the Greek archipelago. Lucian, however, admits that he is lying, but claims also that he is far more honest than other liars, because he tells us that he is lying. He and his crew travelled through the Pillars of Hercules – the Strait of Gibraltar – in curiosity and longing for adventure. A whirlwind pulled the ship into the air and they sailed for seven days and seven nights. On the eighth day, they came to a large land that resembled an island shining with a bright glow. The land was inhabited and cultivated. It was the Moon. Below them they saw another land with cities, rivers, seas, forests, and mountains. It was their own world. They then became entangled in a battle between the armies of the Moon and the Sun. Lucian seconded the Moon king against the Sun king. The Moon people, Lucian reports, are not born of women, but of men, and men marry there with men, and they carry their unborn children not in the belly, but in the calf. The Lunarians eat smoke and drink air. Lucian assures that anyone who does not believe him will realize, if one ever comes to the Moon, that he is telling the truth.

The scientific revolution in the sixteenth and seventeenth century changed the human view of the world, the universe, and humankind's place in the creation. Imaginary space voyages became a popular genre. There were basically three reasons that made space travel more conceivable and appealing: (i) new scientific explanations of the planetary motions, the heliocentric worldview making Earth a planet among other planets; (ii) new inventions, the telescope by which one could gaze at distant celestial bodies, finding a topography of the Moon similar to the geography

of Earth; and (iii) the discovery of new worlds and foreign people and cultures, such as the European rediscovery of America, the "New World" in 1492 and of the southern continent Australia in the seventeenth century.

The Aristotelian-Ptolemaic worldview was challenged in 1543 by the Polish astronomer, Nicolaus Copernicus. In his ground-breaking work, *De revolutionibus orbium coelestium* (On the Revolutions of the Celestial Spheres), Copernicus put forward a heliocentric model in which the Sun is at rest in the center of the universe, while the Earth orbits around the Sun together with the other planets. One could then ask oneself: If the living Earth is not a unique place, why would not then the other planets harbor life too? One of the first to draw the consequences of the Copernican-heliocentric worldview was the Italian Dominican friar and philosopher Giordano Bruno, who supposed that life might exist on planets in other solar systems.

The German astronomer Johannes Kepler, known for his laws of planetary motion, combined the new understanding of the universe with the idea of life on other planets. His posthumous work, *Somnium* (The Dream, 1634), can be said to be the first space voyage story based on scientific theories. The fictional framework let him convey the new astronomical worldview. *Somnium* is about a young Icelander, Duracotus, who travels to Denmark to hand over letters to Tycho Brahe. Later in the story, Duracotus travels in his dreams to the Moon. The weightlessness and the effect of gravity on the body are discussed, as well as the topography of the Moon. Kepler assumes that there is an atmosphere on the Moon and that it has conditions for life. Because the mountains are higher and the valleys deeper on the Moon, the lunar inhabitants are larger than us, have a greater appetite, grow faster, and die earlier. Duracotus meets animals such as large lizards and monsters, and *Somnium* becomes a nightmare, where everything is magnified.

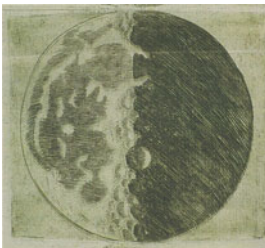
A turning point in the history of astrobiology took place in the autumn of 1609, when the Italian physicist and astronomer Galileo Galilei turned a telescope for the very first time towards the starry sky. He then studied the surface of the Moon, and

it turned out to be a rugged surface with mountains, valleys, and plains. His astonishing discoveries were published in *Sidereus nuncius* (Sidereal Messenger, 1610), which also included the very first images of the Moon seen through a telescope. Furthermore, with the same instrument, he found that the Sun had spots, that Jupiter had four moons, that Venus had phases like the Moon, and that the Milky Way consisted of innumerable stars. In the following decades, these discoveries sparked a debate and speculations concerning the presence of life on other planets. A convinced Copernican, the English natural philosopher John Wilkins, put forward 14 claims confirming the plurality of worlds. In the end he predicts that it is possible that some of our descendants will invent a way to get to this other world, and if there are inhabitants there, they will trade with them. One of Wilkins's critics, the Scottish writer Alexander Ross, answered with a book entitled *The New Planet, No Planet; or, the Earth No Wandering Star Except in the Wandering Heads of Galileans* (1646) (Fig. 1).

Imaginary space voyages commonly follow the narrative of the utopian genre, where the author uses foreign cultures and imaginary worlds in order to put forward a critique of the contemporary society or culture and to express alternative realities and possibilities. The order of things could be in a completely different way than it happens to be. In the middle of the seventeenth century, a number of Moon stories were published. The English author Francis Godwin's novel *The Man in the Moone: or A Discovrse of a Voyage Thither* (1638) tells about Domingo Gonsales, who travelled to the Moon with a

flock of trained wild swans or "gansas." The journey took twelve days. He stayed there a year, encountered the Lunarians, then returned to Earth and landed in China. The novel describes, among other things, the tones of the lunar language, which are reminiscent of the Chinese tonal system and musical cipher. From the same year is John Wilkins' *The Discovery of a World in the Moone* (1638). In *Itinerarium exstaticum* (Ecstatic Itinerary, 1656), by the German Jesuit Athanasius Kircher, the narrator Theodidactus takes a cosmic journey together with an angel as guide and tutor. The French satiric novelist Savinien de Cyrano de Bergerac wrote *L'Autre monde: où Les états et empires de la lune* (The Other World: Comical History of the States and Empires of the Moon, 1657). Cyrano travelled with bottles of dew attached to him which lifted him up with the heat of the Sun, but he eventually returned back to Earth and landed in Canada. A second time, he travelled with rockets to the Moon. He then met the lunar inhabitants, whom he tried to convince that their Moon was our world and was inhabited. In a later story from 1662, Cyrano also travelled to the Sun (Figs. 2 and 3).

The space travel stories were not only the unlimited means of imagination, but many used



Imaginary Voyages (from Antiquity to the Eighteenth Century), Fig. 1 The Moon seen through a telescope. Galileo Galilei, *Sidereus nuncius* (1610)



Imaginary Voyages (from Antiquity to the Eighteenth Century), Fig. 2 Domingo Gonsales travels to the Moon with a flock of trained wild swans, or "gansas." Francis Godwin, *The Man in the Moone: or A Discovrse of a Voyage Thither* (1638)



Imaginary Voyages (from Antiquity to the Eighteenth Century), Fig. 3 Cyrano travels up in the air with the dew. An English edition from 1687 of Savinien de Cyrano de Bergerac's *L'Autre monde: où Les états et empires de la lune* (1657)

the theme, like Kepler, as a way of presenting the new scientific worldview. An influential work, written by the French essayist Bernard Le Bovier de Fontenelle, *Entretiens sur la pluralité des mondes* (Conversations on the Plurality of Worlds, 1686), consists of six evening lectures that take place as a conversation between a philosopher and his aristocratic hostess in the gardens of a country chateau. All philosophy, he says, is based on two things: curiosity and poor eyesight. We want to know more than we can see. During the walks, they discussed the plurality of the worlds and the existence of intelligent beings on other planets. Maybe there is, says the philosopher, astronomers on Jupiter, and maybe we cause them scientific disputes, where some philosophers have to defend their opinion that we exist. The marchioness speculates, since the inhabitants of Venus are closer to the Sun, they might be small black creatures, scorched by the Sun, full of fire, and very amorous. . . (Fig. 4)

The Dutch physicist and astronomer Christiaan Huygens expresses in *Cosmotheoros* (1698) his thoughts on extraterrestrial life and claims that life on other planets would be similar to what we find on Earth. Among other things, he notes that water in liquid form is necessary for life. He also seemed to have detected darker and brighter spots on the surface of Mars and Jupiter, which must, according to him, be understood as water and ice. Beyond our solar system, there are stars of the same kind as our Sun – and why, he wonders,



Imaginary Voyages (from Antiquity to the Eighteenth Century), Fig. 4 An aristocratic lady and a philosopher discuss the plurality of worlds. An edition from 1687 of Bernard Le Bovier de Fontenelle, *Entretiens sur la pluralité des mondes* (1686)

could these not in turn have their planets with their own moons? Huygens's aliens are in many ways like Earthlings, they have mathematics, astronomy, and music, have similar gifts of understanding and moral perceptions.

In the eighteenth century, the idea of life on other planets became widely accepted, and a fashionable topic of discussion among scientists, philosophers, and theologians. The Swedish inventor Christopher Polhem tells in *Nyia tiender uthur månan* (News from the Moon) from the 1710s about a Sami who travels to the Moon. A Sami had been engaged by a couple of learned gentlemen in Uppsala to fly up in the air with the help of wings, but after several failed flight attempts, a Sami magician came up with a different idea of how to get to the Moon. With the help of his magic drum, he was able to travel there. He stayed on the Moon for seven months and meanwhile, learned the language of the lunar inhabitants. When he returned, he told about everything he had seen and heard.

Voyage to Cacklogallinia (1727), written under the pseudonym Samuel Brunt, begins in a land of birds. The story tells about an expedition to the Moon where they collect gold on the mountains of the Moon and take it back to Cacklogallinia. The lunar inhabitants turned out to be idealists and had no material desires. In the Norwegian-Danish author Ludvig Holberg's satirical story *Iter subterraneum* (Underground Journey, 1741), the

space travel goes into the Earth. During a mountain trip in Norway, the hero of the story, Niels Klim, tumbles into a hole and falls to the Earth's interior, which turns out to be hollow containing its own planetary system. After ending up in a circular orbit, he finally lands on the planet Nazar where he finds a land of trees, the Principality of Potu. Everything was different there – like a satire of terrestrial life. He attended dissertation defenses that took place as popular theatrical pleasures. The judgment was considered distorted and bad. It was thought that those who immediately grasped something must necessarily lack power in their judgment. This satirical genre of space travels also includes a story of the French Enlightenment philosopher François Marie Arouet de Voltaire, *Le Micromégas*, published in 1752. It tells about a 120,000-foot-long inhabitant of a planet belonging to Sirius who visits our solar system. He had been deported because he had claimed that there were inhabitants on planets other than his.

A book that stands out is *De telluribus in mundo nostro solari* (The Earths in our Solar System, 1758), written by the Swedish scientist and theologian Emanuel Swedenborg. He explicitly states, without irony, that he himself, on many occasions in the spiritual world, had conversed with beings from other planets. With Martians, Venusians, and inhabitants of planets in other solar systems, he had deep theological and scientific conversations. As a mechanic and scientist, Swedenborg had previously designed the first airplane with fixed wings. Before Kant and Laplace, he had also presented a nebular hypothesis explaining the formation of our solar system and its planets. In the same work, *Principia rerum naturalium* (The Principles of Natural Things, 1734), he also expressed the possibility of life on other planets in other solar systems.

The idea of life on other planets became an imaginative theme for poets and satirists, even plays and operas were written. In Joseph Haydn's opera *Il mondo della Luna* (World of the Moon, 1777), the old man Buonafede is tricked by his daughters' cavaliers into traveling to the Moon where he meets the emperor of the Moon, who causes him to consent to their marriage.

From being an impossibility during the Middle Ages, extraterrestrial life became a possibility at the end of eighteenth century, even a probability based on a new cosmology, new observations, and interpretations. The French Enlightenment philosophers Diderot, d'Alembert, and d'Holbach embraced the idea of the plurality of worlds. The existence of a multitude of worlds with rational beings was also assumed by the German philosopher Immanuel Kant to be very probable. The German-British astronomer William Herschel explained that his conclusion about the existence of other worlds was based on astronomical foundations, not on fantasy, theology, and poetry. He did not doubt that the Moon was inhabited, and in 1776 he even claimed that he had detected growing patterns on the Moon, which he interpreted as forests. "I am," he says two years later, "almost convinced that these numberless small Circuses we see on the Moon are the works of the Lunarians and may be called their Towns."

Overview

What these imaginary space voyages and stories about life on the Moon and other planets capture are questions about truth, how we can know what we know, how we gain knowledge about what we do not know, how we imagine the unknown, and where the limits of the imagination go. In general, it can be said that the conceptions of the unknown always have their beginning in the known. When humans try to think freely, fantasize, and speculate, they are limited by what they already know, their culture and way of life. It is, obviously, difficult to know so much about the unknown. Therefore, human conceptions and imaginations of life in space say a lot about the human being itself, human thinking, knowledge, and dreams.

Cross-References

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- [Copernican Principle](#)
- [Geocentric Worldview](#)
- [Heliocentric Worldview](#)
- [Herschel, William](#)

- [Huygens](#)
- [Kepler, Johannes](#)
- [Life in the Solar System \(History\)](#)
- [Plurality of Worlds](#)
- [Principle of Plenitude](#)

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Imaging

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Adaptive optics · CCD · Camera · Direct detection · Telescope

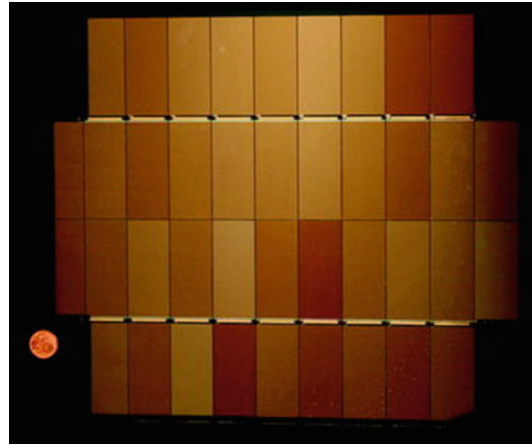
Definition

Imaging is the set of techniques used for obtaining images of one or several astronomical bodies or fields using a two-dimensional detector, computerized techniques, and smart optical techniques such as ► [adaptive optics](#).

Overview

In astronomy, imaging is in most cases the first observational approach to discovering a new object, the image being required to clarify structure and morphology, before using the more physical tool of ► [spectroscopy](#). Shape, size, decomposition into elements, arrangement of subparts, measurement of displacements, and discrimination of photometric variations belong to the set of information provided by the image. From the planets in the solar system to the identification of gigantic filamentary structures or sheets in the universe, the image has played a major role in astronomy. Improving the quality of the image has been and remains today more than ever a powerful drive in instrumental research: two-dimensional detectors, high angular resolution, ► [adaptive optics](#), high dynamical range, and post-processing techniques are fields of intense activity. One notes that the direct detection of exoplanets is certainly among the most demanding topics in terms of angular resolution and high contrast.

Detectors: In the last 40 years, the photographic technique has been largely replaced by digital sensors such as CCDs and now CMOS chips (complementary metal-oxide-semiconductor, a technology used for constructing integrated circuits). Giant cameras associating several tens of CCD chips can feature up to 500 Mpixels and cover extra-large fields on the sky, as demonstrated, for instance, by Megacam, a camera installed at the Canada-France-Hawaii Telescope (Fig. 1). CCDs provide numerical images, which can easily be processed by computers. They also offer a very good detection efficiency in a large domain of wavelength. Beyond $\lambda = 1 \mu\text{m}$, infrared arrays based on the CMOS technique have about the same

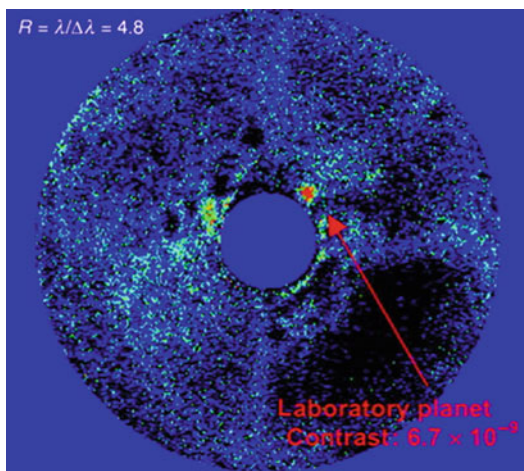


Imaging, Fig. 1 The Megacam camera developed by CEA-France and installed at the prime focus of the Canada-France-Hawaii Telescope, behind a wide field corrector. This huge camera includes 36 CCDs of $2,048 \times 4,612$ pixels each, arranged side by side, leading to a total of 340 Mpixels

advantages. Recently large arrays of infrared bolometers have been produced, allowing imaging in even the submillimeter domain.

A certain degree of computer correction for atmospheric and instrumental effects allows sharpening up the image and improving the contrast. Multiple digital images can also be combined to further enhance the signal-to-noise and suppress artifacts. Thanks to the ► [adaptive optics](#) technology that can negate to a large extent the atmospheric blurring, image quality can approach the theoretical resolution capability of the telescope, that is, angular details as small as $\theta = \lambda/D$, where D is the diameter of the telescope and λ the wavelength. For $\lambda = 2 \mu\text{m}$ and a $D = 8 \text{ m}$, this corresponds to a length of 10 km on Venus' surface or the orbit of Mercury seen around a star at 300 light-years. In space, almost perfect conditions also provide excellent angular resolution, despite a more moderate telescope size, as illustrated by the stunning images of the Hubble Space Telescope. The future James Webb Space Telescope with its 6.5 m diameter telescope will soon provide similar exquisite image quality but in the infrared domain.

As regards high contrast imaging, the recent pressure put by the search for exoplanets was the



Imaging, Fig. 2 High-contrast imaging. Thanks to the combination of dedicated optical devices (here a four-quadrant phase mask coronagraph) and imaging techniques (here differential rotation), it is possible to reach an extremely high contrast ratio at the laboratory: a fake *planet* 0.15 billion times fainter than an artificial star (behind the central occulted disk) is perfectly seen on this image obtained at LESIA, Observatoire de Paris

cause of an explosion of ideas and new concepts to mitigate the problem of the huge difference in brightness between a star and the planets orbiting it. New types of coronagraphs to hide the starlight, of wavefront control to reduce speckles, and of pupil shaping to suppress the wings of the point spread function produced by diffraction have been proposed and tested. Also, differential techniques based on chromatic differences, or on image rotation, or on polarization properties have been refined and greatly improve the detection capability. Today in the laboratory, a contrast of 10^{-9} is reached at an angular distance of a few λ/D only (Fig. 2). The past decade has seen those techniques implemented in ground-based or space instruments, such as SPHERE on the ESO-VLT, GPI on Gemini, SCExAO on the Subaru telescope, and on the James Webb space telescope launched late 2021. In the near future, the Nancy-Grace Roman space telescope equipped with a state-of-the-art coronagraph should probably give the highest contrast ever reached in astronomical observation.

Cross-References

- [Adaptive Optics](#)
- [CCD](#)
- [Coronagraphy](#)
- [Telescope](#)

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IMF

- [Initial Mass Function](#)

2, 4-Imidazolelidinedione

- [Hydantoin](#)

Imidogen (NH)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[NH](#); [Nitrogen hydride](#)

Definition

This diatomic radical, containing nitrogen and hydrogen, has been detected in both the diffuse

- [interstellar medium](#), where it is seen in

absorption against the light of background stars, and in denser gas toward the center of our ► [Milky Way](#) galaxy. In the latter case the relative abundances of NH_3 , NH_2 , and NH have been interpreted in terms of low-velocity shock activity (Goicoechea et al. [2004](#)).

History

NH was first detected at near ultraviolet wavelengths in 1991 by D. M. Meyer and K. C. Roth. The subsequent observations of the Galactic center were made with the Infrared Space Observatory (ISO). It has been recently observed using the Herschel satellite towards other ► [molecular clouds](#) (Persson et al. [2010](#), [2012](#)).

Cross-References

- [Interstellar Medium](#)
- [Milky Way](#)
- [Molecules in Space](#)

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Impact Basin

Roland J. Wagner
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

An impact basin is a large complex impact crater. The threshold diameter to distinguish between

craters and basins is approximately 150–200 km. In general, basins are characterized by two or more concentric rings, which are ridges or scarps facing toward the basin. One of these rings is the main rim that borders the cavity from which material was excavated and ejected during the impact. Most basins are heavily degraded or have been covered by younger material. All known basins are old impact features created during the first 800 million years of the planet or satellite on which they are found. Examples are Caloris Basin on ► [Mercury](#), the Orientale Basin on the Moon, and the Hellas Basin on ► [Mars](#).

Cross-References

- [Chronostratigraphy](#)
- [Crater, Impact](#)
- [Facula, Faculae](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)

Impact Degassing

Reika Yokochi
Department of Geophysical Sciences, The University of Chicago, Chicago, IL, USA
Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL, USA

Keywords

Planetary accretion · Meteor impacts · Formation of planetary atmospheres · Volatile inventory of planets

Synonyms

[Shock devolatilization](#)

Definition

Impact degassing refers to the release of gas caused by a high-velocity collision of volatile-bearing

solid objects, particularly during collisions between planetary objects. During an event or collision, an intense mechanical shock wave is transmitted, causing changes in specific volumes along the material-specific Hugoniot curve (see ► [Spallation Zone](#)). A rarefaction wave subsequently propagates to reduce the shock pressure, during which the kinetic energy of the collision is released as heat and as high particle velocity of the ejecta. The change in thermodynamic conditions causes phase transitions of the material in the colliding objects, either in the solid state or by melting and vaporization, which releases structurally bonded volatiles as well as interstitially trapped gases.

Overview

The discovery of impact craters on the Moon during the Apollo missions first inspired the studies of collisional shock on geological materials. Theoretical studies started by investigating the thermodynamic stabilities of mineral matrices in colliding geological objects that are free of structural volatiles (Ahrens and O’Keeffe 1972; Luo and Ahrens 2004).

In the context of planetary evolution and the formation of planetary atmospheres that may have fostered emergence of life, the main focus of investigation concerns the release of structurally bound major volatiles from hydrous minerals, carbonate, as well as ice. The shock-loading experimental studies demonstrated that structurally bound water in hydrous minerals (Boslough et al. 1980; Lange et al. 1985) could be lost during hypervelocity impacts, whereas theoretical and experimental studies suggest that minerals containing volatile elements as major constituents (i.e., carbonate, sulfate, and H₂O ice) initiate vaporization at relatively low-impact velocity (Shen et al. 2003; Stewart and Ahrens 2005; Ohno et al. 2008). Tyburczy et al. (1986) experimentally investigated shock-induced volatile loss from the Murchison CM2 chondrite and observed that complete devolatilization occurs at a pressure of about 30 GPa, corresponding to ~27 % of Earth’s present mass. This validates that the conclusions based on individual minerals above generally apply when they are embedded with other

minerals in the primitive meteorite, a potential precursor of planets. It is therefore likely that impact degassing from planetary precursor materials played a significant role in directing the surface evolution of planets and the chemical compositions of planetary atmospheres. Recent shock-loading experiments and theoretical studies involve detailed investigation of chemical changes, for example, on hydration of olivine by shock-released water (Furukawa et al. 2011), on the survival or formation of amino acids that have direct implications for life-forming molecules (Pierazzo and Chyba 1999; Sugita and Schultz 2009), or destruction of complex molecules to form chemically simpler constituents of atmospheres (Fukuzaki et al. 2010).

The moon-forming impact caused large-scale melting of the Earth, resulting in a large-scale degassing from the silicate Earth to the atmosphere. Whether this event resulted in significant loss of atmosphere to space and/or chemical and isotopic fractionation of the terrestrial atmosphere remains controversial.

Cross-References

- [Crater, Impact](#)
- [Earth’s Atmosphere, Origin and Evolution of](#)
- [Oceans, Origin of](#)
- [Water, Delivery to Earth](#)

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Impact Melt Rock

Philippe Claeys
Earth System Science, Vrije Universiteit Brussel,
Brussels, Belgium

Definition

An *impact melt rock* is a type of rock typically found in impact structures. It is an impactite consisting of a mixture of solid and melt fragments all derived from the target rock, floating in a glassy, microcrystalline, or recrystallized matrix. The solid fragments may contain shocked

minerals, most commonly quartz or zircons. An impact melt rock results from the cooling of the melt pool that formed within a crater, because of the high temperature and pressure generated during the impact. The largest craters on Earth such as Sudbury (Ontario, Canada), Chicxulub (Mexico), Popigai (Siberia), or Manicouagan (Québec, Canada) contain a very large volume of impact melt rocks.

Cross-References

- [Chicxulub Crater](#)
- [Impactite](#)
- [Sudbury Impact Structure](#)

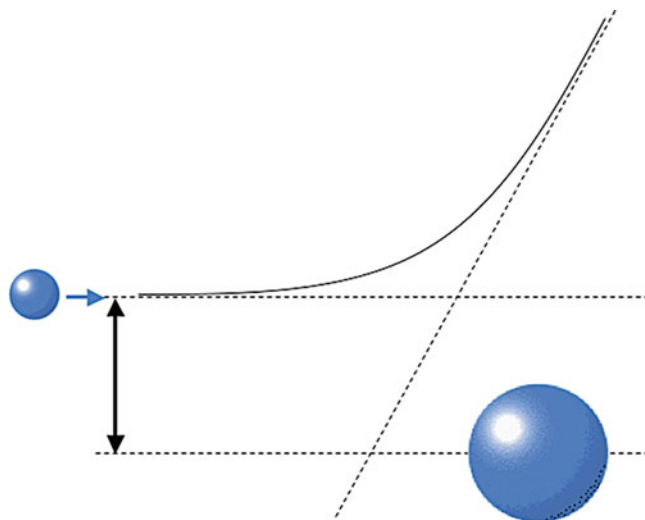
Impact Parameter

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The impact parameter is the projected distance between the axis carrying the initial vector velocity of a projectile and the center of the target that the projectile is approaching (see Fig. 1).

Impact Parameter,
Fig. 1 Definition of the impact parameter (*dark arrow*) of a projectile directed toward a target



Impact, Hit and Run

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

During terrestrial planet formation, the so-called hit-and-run impacts are giant impacts that do not result in a net increase in the mass of at least one of the planetary embryos involved in the collision. Hit-and-run impacts generally imply high relative velocities between bodies and/or oblique impact angles. In such cases, the larger body does not accrete the smaller body, but the larger object could actually be eroded and sometimes severely traumatized by the encounter. A significant amount of debris may be created in hit-and-run impacts.

Cross-References

- [Giant Impact](#)
- [Late-Stage Accretion](#)

Impact, Probability of

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

For purposes of planetary protection, the probability of impact at a target body is the probability, determined by sequential evaluation of possible spacecraft trajectory analyses and failure modes, that a spacecraft might impact a planetary body under nominal and non-nominal conditions. The impact probability for a mission often has a set limit for planetary protection compliance.

Impactite

Philippe Claeys
Analytical-Environmental & Geo-Chemistry,
Vrije Universiteit Brussel, Brussels, Belgium

Definition

Impactite is a term used to describe rocks formed during a meteorite impact on a planetary body. The term covers the lithologies such as breccia, suevite, or impact melt rock found within or at proximity of an impact structure. Monomictic breccias contain fragments of a single rock type; polymictic breccias contain several rock types originating from the target lithologies. Each is composed of chaotic assemblages of solid and shocked fragments, or previously molten fragments, of the target lithologies. Suevite is a breccia containing melt and solid particles surrounded by a fine clastic matrix, first defined in the Ries crater (Germany). Distal impactite, composed of fine ejected material (spherules, shocked minerals), may be widespread in the case of large impacts such as the one that formed the Chicxulub crater, in Yucatan (Mexico), 66 million years ago.

Cross-References

- [Breccia](#)
- [Chicxulub Crater](#)
- [Crater, Impact](#)
- [Impact Melt Rock](#)
- [Monomictic Breccia](#)
- [Polymictic Breccia](#)
- [Suevite](#)

In Vitro Evolution

- [Evolution, In Vitro](#)

Inactivation

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In planetary protection, the term “inactivation” expresses the result of a process that renders microorganisms incapable of reentering a proliferative state. The parameters (time, temperature, concentration, dose, etc.) of such a process which causes inactivation of 90% of the population of a given microorganism define the D-value for each process.

Cross-References

- ▶ [Bioburden Reduction](#)
- ▶ [Disinfection](#)
- ▶ [D-Value](#)
- ▶ [Pasteurization](#)
- ▶ [Sterilization](#)

Inclination (Astronomy)

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The inclination of an object in the solar system is the angle between the orbital plane of the object (planet, comet, or asteroid) and the plane of the ▶ [ecliptic](#).

In binary systems and especially in star/planet systems, it corresponds to the angle i between the orbital plane and the plane of the sky. This angle is especially important in the ▶ [radial velocity](#) technique used for detecting exoplanets, since the derived planetary mass is undetermined by a

factor $1/\sin(i)$: if the orbital plane is close to the plane of the sky, the actual mass can be much larger than the raw value.

Cross-References

- ▶ [Orbit](#)
- ▶ [Radial Velocity](#)

Indeterminacy

- ▶ [Chance and Randomness](#)

Indian Space Research Organization

- ▶ [ISRO, India](#)

Indigenous

- ▶ [Endogenicity](#)

Inelastic Photon Scattering

- ▶ [Raman Scattering](#)

Infrared Astronomical Satellite

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Synonyms

[IRAS](#)

Definition

The Infrared Astronomical Satellite or IRAS was the first observatory to perform an all-sky survey at infrared wavelengths. It was equipped with a telescope of 60 cm diameter and with detectors operating at wavelengths of 12, 25, 60, and 100 μm with angular resolution of 30 arc sec and 2 arc min at 12 and 100 μm , respectively. Launched on January 25, 1983, it was operating up to November 21, 1983. During its primary mission, which was to obtain a complete map of the sky, it discovered 350,000 point-like sources, increasing the number of cataloged astronomical sources by about 70%. IRAS discoveries included a disk of dust grains around the star Vega, six new comets, and very strong infrared emission from interacting galaxies, as well as wisps of warm dust called infrared cirrus which are found in almost every direction of space. IRAS also revealed for the first time the core of our galaxy, the Milky Way. In addition to the infrared sky maps, IRAS was also equipped with a low-resolution spectrometer that was used to observe thousands of objects in the mid-infrared. The outstanding scientific results obtained by IRAS opened a new view of the universe and motivated new infrared space facilities such as ISO, Spitzer, and Herschel.

History

The project was initiated in 1975 as a joint program of the USA, the Netherlands, and the UK. Launched in January 1983, it produced infrared data for a period of 10 months and covered more than 96% of the sky.

Cross-References

- [Herschel Mission](#)
- [Infrared Astronomy](#)
- [ISO](#)
- [Spitzer Space Telescope](#)

References and Further Reading

<http://irsa.ipac.caltech.edu/IRASdocs/iras.html>
<http://www.sron.rug.nl/irasserver/irasserverman.html>

Infrared Astronomy

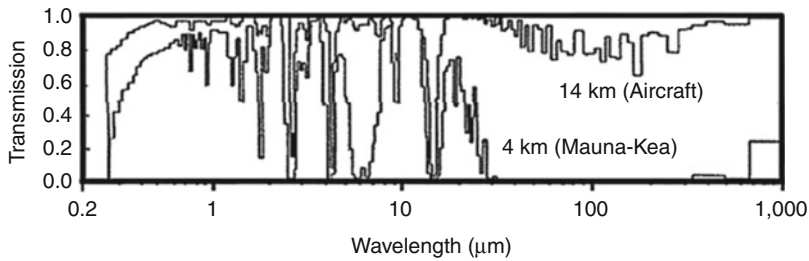
Daniel Rouan
 LESIA, Observatoire Paris-Site de Meudon,
 Meudon, France

Synonyms

[Far infrared \(far IR\)](#); [Near infrared \(near IR\)](#)

Definition

Infrared astronomy is the branch of observational astronomy which studies celestial objects through their infrared radiation, that is, at wavelengths longer than 0.75 μm and shorter than 400 μm . The domain is not strictly defined, and some astronomers consider that it begins at 1 μm where ► [CCDs](#), the most universally used detectors in the visible domain, are no longer sensitive. Infrared astronomy is considered as part of *optical astronomy* because technologies and methods (incoherent detection, classical optics, solid-state digital detectors) are globally the same as in the visible domain. One peculiarity of infrared astronomy is the strong ► [background](#) emission of the environment (atmosphere, telescope) that requires dedicated differential techniques. Another one is the absorption by the atmosphere (see Fig. 1) in a large fraction of the wavelength domain: this explains why balloons, airplanes, and satellites are often used to carry instruments. ► [IRAS](#), ISO, and ► [Spitzer](#) are the space instruments that brought the most spectacular results in the field. Main targets in infrared astronomy are *cold* objects such as cool stars (► [brown dwarves](#), M dwarves), ► [interstellar dust](#), planets of the solar system, and now exoplanets.



Infrared Astronomy, Fig. 1 Transmission of the atmosphere in the infrared range. The Earth's atmosphere absorbs the infrared light in the largest part of the wavelength domain: only in a few windows is the transmission good enough to allow observations from the

ground, particularly with telescopes on the top of high mountains (Mauna Kea is a summit at 4200 m on the island of Hawaii, the best infrared site today). At higher altitudes (aircraft, balloon), the conditions are improving and broader windows are open

The infrared domain is of special importance to study planets, since it's where ► [thermal emission](#) peaks and molecules exhibit many spectral features corresponding to transitions between ro-vibrational levels of energy. ► [Infrared spectroscopy](#) is the major tool to study the planetary atmosphere and surface.

Note that the infrared range is generally subdivided into three domains: near infrared (near iR), $\lambda = 1\text{--}5\ \mu\text{m}$; mid-infrared (mid-IR), $\lambda = 5\text{--}25\ \mu\text{m}$; and far infrared (far IR), $\lambda > 25\ \mu\text{m}$.

Cross-References

- [Blackbody](#)
- [Electromagnetic Spectrum](#)
- [Infrared Astronomical Satellite](#)
- [Infrared Space Observatory](#)
- [Infrared Spectroscopy](#)
- [Spitzer Space Telescope](#)
- [Thermal Emission](#)

Infrared Dark Cloud

Nicolas Peretto
School of Physics & Astronomy, Cardiff
University, Cardiff, UK

Keywords

Mid-infrared extinction · Early phases of star formation · Stellar cluster formation · High-mass star formation

Acronyms

IRDC

Definition

An Infrared dark cloud (IRDC) is a large concentration of ► [interstellar dust](#) and gas that is seen in absorption against a bright infrared background. They often correspond to the densest regions of large ► [molecular clouds](#), and as such, IRDCs are often associated with star formation activity. The infrared extinction towards an IRDC is due to the absorption of the background light by the cold dust embedded within it. IRDCs are best observed in the mid-infrared part of the ► [electromagnetic spectrum](#), typically around 10 micron, where the contrast between the emission of the diffuse ► [interstellar medium](#) (i.e., the background emission) and that of the IRDC dust is maximal. This is a direct consequence of the bright broadband mid-infrared emission of ► [polycyclic aromatic hydrocarbons](#) that pervade the interstellar medium (ISM), along with the cold temperature ($\sim 15\ \text{K}$) of dust embedded within IRDCs. IRDCs are observationally defined entities, they have no physical definition attached to their names. As a result, they can be extremely massive and large (tens of parsec, tens of thousands solar masses) or small and compact (tenths of parsecs, a few solar masses), host the formation of a very rich ► [stellar cluster](#) or of a single stellar system.

History

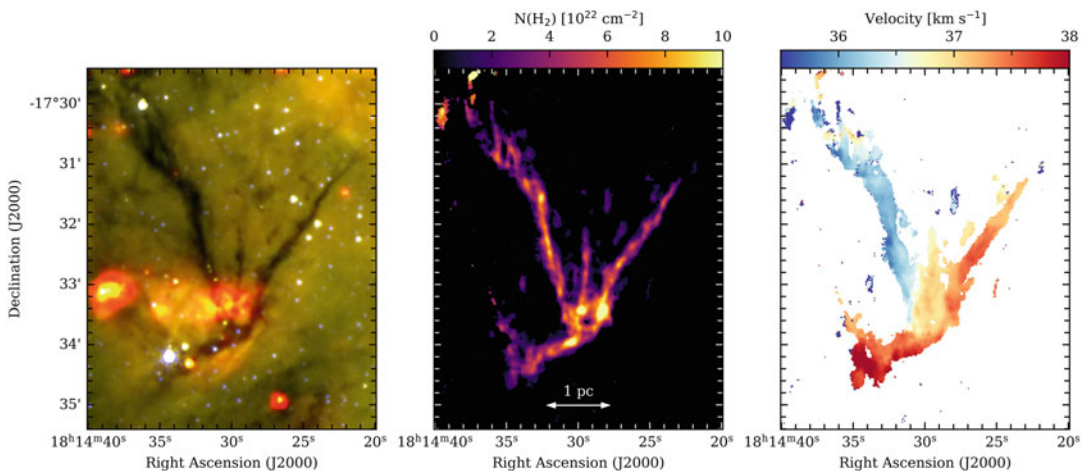
Water vapor efficiently absorbs infrared light. As such, Earth's atmosphere is virtually opaque in the infrared, which makes infrared observations of the diffuse ISM extremely difficult. It is only with the launch of the first space observatories, from the mid-eighties to the mid-nineties, that the first infrared images of the diffuse ISM were taken, and with those the first images of IRDCs. In fact, they were first observed with the ► [Infrared Space Observatory](#) (ISO, Perault et al. 1996), quickly followed by the Midcourse Space Experiment (MSX, Egan et al. 1998). Very early after their discovery, IRDCs attracted a lot of attention due to their possible association with the early phases of massive star formation. The first complete catalogue of galactic plane IRDCs was published in 2006 using the MSX data (Simon et al. 2006a), followed three years later by its ► [Spitzer Space Telescope](#) equivalent (Peretto and Fuller 2009), each containing more than 11,000 entries. IRDCs identified in the 8 micron

Spitzer images were then named Spitzer Dark Clouds (SDCs) (Fig. 1).

Overview

Even though IRDCs can be located anywhere in the sky where the conditions of cold dust and bright infrared background are met, most IRDC literature refers to Galactic plane IRDCs located at a typical heliocentric distance of 5 ± 3 kpc (e.g., Simon et al. 2006b). One advantage of IRDCs compared to other clouds located in the solar circle is that their near/far distance ambiguity is reduced, with IRDCs being most often located at the near heliocentric distance (Ellsworth-Bowers et al. 2013). Reduced distance uncertainties mean more reliable size, mass, and luminosity estimates, which is a very important aspect of IRDC research.

The study of IRDCs is most often associated to that of the early phases of star formation. The cold and dense gas conditions necessary to



Infrared Dark Cloud, Fig. 1 Example of an infrared dark cloud. On the left we have a mid-infrared three colour image of the SDC13 infrared dark cloud (Peretto et al. 2014). Blue and green are the Spitzer 3.6 micron and 8micron emission, respectively, red is the Herschel 70micron emission. The IRDC here is a typical hub, with a set of dark converging filaments seen in absorption. In the middle we see the same SDC13 IRDC, but this time the H_2 column density, derived from ammonia emission, is displayed (Williams et al. 2018). One can see that the

IRDC filaments appear as the densest interstellar structures there is in the field. Local peaks in this image show the fragmentation of the filaments into individual cores that will form stars in the near future. On the right, one can see the centroid velocity map of SDC13 as derived from ammonia emission line. One can see that the IRDC shows important velocity gradients that are interpreted as flows of matter driven by self-gravity (Williams et al. 2018)

produce mid-infrared extinction are those required for the gas to collapse and fragment into individual prestellar cores, that is, the direct progenitors of individual stars or small stellar systems. After the collapse of these cores, protostars start to form and heat up the surrounding dust which then starts to emit in the infrared. IRDCs become therefore less infrared dark as star formation proceeds. As a consequence, studies of IRDCs are often aimed at determining the initial conditions of star formation, before that feedback from newly formed stars perturbs the physical properties of the gas.

One important aspect of IRDC research has focused on determining the initial conditions of ► [high mass star](#) formation, in particular searching for massive prestellar cores. The existence of these objects is predicted by one of the most influential theories of massive star formation that postulates that the formation of massive stars begins within a compact, massive, and initially stable prestellar core (McKee and Tan 2003). The observation of massive prestellar cores would provide a clear-cut test against competing theories (e.g., Vázquez-Semadeni et al. 2019). Massive IRDCs represent the ideal playground for the hunt of massive prestellar cores.

Another aspect of IRDC research that has received significant attention in the past few years is related to hub filamentary systems (Myers 2009). These structures are dense star-forming clouds that exhibit a small network of converging ► [interstellar filaments](#) (Fig. 1). In IRDCs, hubs are easy to spot thanks to the high sensitivity and high angular resolution of infrared extinction mapping. The interest generated by these structures comes from their morphology, suggestive of filament-filament interactions and gravitational collapse, a process that could help the formation of massive stars.

But IRDC research is not limited to the search for massive prestellar cores and characterization of hub filamentary systems. In fact, all aspects of star formation research are being tackled via the study of IRDCs (fragmentation, kinematics, chemistry, magnetic fields, protostellar population, etc...), and their ubiquity across the

► [Milky Way](#) makes statistical analysis of star-forming cloud properties possible.

Basic Methodology

IRDCs are, by definition, first identified as extinction features in ► [continuum](#)-infrared images, typically at around 10 micron (note that they can also be identified at shorter and longer infrared wavelengths). The amount of observed extinction towards the IRDC is a measure of the cloud dust ► [opacity](#) τ which in turn is directly proportional to the mass surface density, or ► [column density](#), of dust and gas. Therefore, by making some assumptions on the emission properties of the IRDC foreground and background dust one can reconstruct the mass surface density structure of any IRDCs, and this independently of the dust temperature (see Peretto and Fuller 2009). Another advantage of extinction mapping is that it typically provides high-angular resolution observations (i.e., $\sim 2''$ with Spitzer at 8 micron).

While infrared extinction is very powerful to recover the structure of infrared dark clouds, it has its own limitations. First, if young stellar objects are present within the IRDC, then these will appear as holes in the reconstructed mass surface density image of the cloud. Second, the foreground and background intensities of a cloud are rather poorly constrained, leading to large uncertainties on the opacities. Finally, infrared extinction can only inform of the mass surface density of the IRDC, and nothing else.

The low dust and gas temperatures in IRDCs, as in any molecular cloud, are such that most of the thermal energy they radiate is at (sub)-millimeter wavelengths (>100 micron). At these wavelengths, thermal dust continuum emission is optically thin up to mass surface densities ~ 100 g/cm² and is therefore an excellent tracer of dust mass for most IRDCs, whose average surface density is typically ~ 0.1 g/cm². In this optically thin regime, IRDC dust masses are proportional to their (sub)-millimeter flux, while gas masses are usually derived by assuming a constant dust-to-gas mass ratio of $R_{dg} = 1\%$ (see Hildebrand 1983).

In IRDCs, molecular line emission mostly corresponds to rotational transitions, the only transitions that can easily be collisionally excited in a ~ 15 K gas. More than 200 ► [interstellar molecules](#) have been identified so far (McGuire et al. 2018), but the combination of abundance and excitation conditions determines which ones are observable in a given region of a molecular cloud. For instance, ► [carbon monoxide](#) is the second most abundant molecule in space and is very easily observed towards molecular clouds. However, in ► [dense clouds](#) such as IRDCs, the low energy transitions of CO tend to be optically thick and are therefore of no use when, for instance, one tries to determine IRDC dynamics. In order to map the kinematics of the gas within IRDCs, optically thinner transitions are used, such as those of ► [diazenylium](#) (N_2H^+) or ► [ammonia](#) (NH_3). The width of the emission line gives access to the velocity dispersion of the gas along the line of sight, the peak velocity gives access to the centroid velocity along the line of sight, the peak intensity can give information on the excitation temperature, and the integrated line intensities provide some information on the column density of the molecule and abundance if the total column density of molecular hydrogen, the most abundant molecule in space, is known.

Finally, for the detection of young stellar objects, infrared dust continuum emission and non-thermal radio emission (cm to m wavelengths) can trace dust heated up by the newly formed stars or gas that has been ionized by them, respectively. The latter mostly happens to young massive stars that are hot enough to produce ionizing ultraviolet photons, resulting in the formation of ► [HII regions](#).

Key Research Findings

Soon after their discovery in the late nineties, a number of studies aimed at characterizing the properties of IRDCs and identifying the role they play in the star formation process. The first studies aimed at determining what was the relation between IRDCs and some of the better known interstellar

structures. In that respect, Teyssier et al. (2002), by observing emission from CO isotopologues towards a sample of IRDCs, showed that they were in fact nothing else than some of the densest regions within Galactic plane molecular clouds. Since then, plethora of dust continuum observations have shown that IRDCs have the correct temperature, mass, and fragmentation properties to be the progenitors of stellar clusters (e.g., Rathborne et al. 2006; Pillai et al. 2006; Peretto and Fuller 2010; Ragan et al. 2011; Battersby et al. 2011; Zhang et al. 2015). IRDCs also often show signs of star formation activity (e.g., Chambers et al. 2009; Peretto and Fuller 2009), highlighting the fact that star formation, even though at an early stage, has already started. In some cases, even evidence of ongoing massive star formation has been found (Rathborne et al. 2005; Pillai et al. 2011, and Wang et al. 2012). In fact, one of the most massive cores ever observed in the Galaxy lies right at the center of an IRDC (Peretto et al. 2013). This discovery shows that the formation of massive cores can occur early on during the evolution of a molecular cloud. But despite intense scrutiny of IRDCs with some of the most powerful millimeter telescopes in the world such as ► [ALMA](#), no significant population of massive starless cores has been found (Svoboda et al. 2019; Sanhueza et al. 2019). All massive cores that exist out there seem to be protostellar in nature.

The question of what physical mechanism drives the fragmentation of IRDCs into cores and how these then evolve is one of the key areas of star formation research. It has been suggested that, at least for filamentary IRDCs, the fragmentation scale is set by the average mass-per-unit-length of the cloud on a large scale, while it is the local density and the thermal Jeans length that determines core separation on small scales (Kainulainen et al. 2013). However, once formed, cores may simultaneously collapse to form protostars and accrete more mass via the collapse of the IRDC itself (Peretto et al. 2020; Rigby et al. 2021). This would naturally explain the absence of massive prestellar cores. The accretion from the IRDC to the cores may occur via filament accretion channels (i.e., hubs) that converge towards the massive ► [protostars](#) at the

center (e.g., Peretto et al. 2014; Williams et al. 2018). When computing the mass distribution of the starless IRDC fragments/cores, one finds that it is much steeper than that of the IRDCs themselves, highlighting in fact the different nature of the process leading to the early fragmentation of IRDCs to that of the formation of IRDCs (Peretto and Fuller 2010). When including protostellar sources, the core mass distribution within IRDCs becomes, at least in the case of one IRDC, flatter than those found in nearby star-forming regions, suggesting that, in the process of star cluster formation, low-mass stars form after high-mass stars (Zhang et al. 2015). This is reminiscent of what Motte et al. (2018) found in the W43-MM1 massive-star forming region, but more studies on the core mass distribution of IRDCs, and how cores are linked to local accretion channels, are necessary in order to determine the importance of such results.

Future Directions

IRDCs, because of their nature and large numbers across the Galactic plane, are great laboratories for the study of the earliest stages of star cluster formation. However, follow-up surveys of IRDCs have so far been limited to small sample sizes of, at best, a few tens of objects. Future large observing programs surveying hundreds of IRDCs, at high angular resolution and across a broad range of spatial scales, will provide enough statistics on the fragmentation and internal IRDC gas kinematics to draw robust conclusions on the physical mechanisms that are at play during the early phases of star formation.

Cross-References

- ▶ [ALMA](#)
- ▶ [Ammonia](#)
- ▶ [Carbon Monoxide](#)
- ▶ [Column Density](#)
- ▶ [Continuum](#)
- ▶ [Dense Cloud](#)
- ▶ [Dense Core](#)

- ▶ [Diazenylium \(\$N_2H^+\$ \)](#)
- ▶ [Dust Cloud, Interstellar](#)
- ▶ [Dust Grain](#)
- ▶ [Electromagnetic Spectrum](#)
- ▶ [Extinction, Interstellar or Atmospheric](#)
- ▶ [Fragmentation of Interstellar Clouds](#)
- ▶ [High-Mass Star](#)
- ▶ [HII Region](#)
- ▶ [Infrared Space Observatory](#)
- ▶ [Initial Mass Function, Origin of](#)
- ▶ [Interstellar Cloud](#)
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- ▶ [Spectroscopy, Rotational](#)
- ▶ [Spitzer Space Telescope](#)
- ▶ [Star Formation, Observations](#)
- ▶ [Star Formation, Theory](#)
- ▶ [Stellar Cluster](#)
- ▶ [Telescope](#)

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Infrared Excess

Steven W. Stahler

Department of Astronomy, University of California, Berkeley, CA, USA

Keywords

Interstellar dust

Definition

Many ► [pre-main sequence](#) stars emit substantial amounts of energy at infrared and longer wavelengths. To the degree that the flux at each wavelength exceeds the corresponding blackbody value (corresponding to the temperature of the stellar photosphere), the star is said to have an infrared excess. At least half of T Tauri stars have infrared excesses. Much of this emission arises from heated dust grains embedded in circumstellar disks. Other T Tauri stars have no infrared excess. Presumably, these stars have no disks, although they are of similar age. All stars must lose their disks by the time they reach the ► [main sequence](#), whose stars do not have an infrared excess.

Overview

Stars radiate over a broad range of wavelengths. A plot of radiation intensity as a function of wavelength, when covering a substantial range in the latter, is known as a spectral energy distribution. In such a plot, each intensity is measured using a relatively broad filter, which admits radiation over a wavelength range of roughly 1000 Å (100 nm).

A main sequence star radiates like a blackbody. That is, its spectral energy distribution resembles, at least approximately, the Planck curve corresponding to the star's surface temperature. The spectral energy distributions of young stars, however, depart sharply from the Planck curve. These objects are often surrounded by considerable amounts of interstellar dust, which absorbs and reddens the radiation in a wavelength-dependent manner. The raw intensities must

therefore be corrected, a procedure known as dereddening.

Even after dereddening, many T Tauri stars exhibit substantial flux above a blackbody at infrared and longer wavelengths. In these so-called classical T Tauri stars, the total excess flux emitted in the infrared can be a substantial fraction of the total stellar luminosity. Other T Tauri stars, the so-called weak-lined class, have no such excess.

T Tauri stars are pre-main sequence objects of roughly solar mass and below. That is, they are contracting slowly and generating energy through that contraction, but not yet capable of fusing hydrogen into helium. Detailed analysis of the infrared excess emission from classical T Tauri stars shows that it arises from radiation by heated dust grains. These grains must be relatively close to the star. Most are embedded in circumstellar disks, which have been imaged directly in some cases. It is surprising that weak-lined T Tauri stars, which have similar ages as the classical ones, apparently lack these disks.

Pre-main sequence objects of larger mass, from about 2 to 10 solar masses, are known as Herbig Ae and Be stars. Many of these also exhibit large infrared excesses. There are also many stars, presumably of lower mass, which are so deeply embedded in dust that all their emission is at infrared and longer wavelengths. Some of these latter sources are believed to be true protostars, objects deriving their luminosity from the infall of cloud material onto the stellar surface.

Cross-References

- [Interstellar Dust](#)
- [Pre-Main-Sequence Star](#)
- [Protostars](#)
- [T Tauri Star](#)

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Infrared Space Observatory

Martin F. Kessler

European Space Astronomy Centre (ESAC),
Madrid, Spain

Keywords

ISO · Infrared astronomy · Organic molecules in space · Space astronomy · Satellite · Water

Synonyms

ISO

Definition

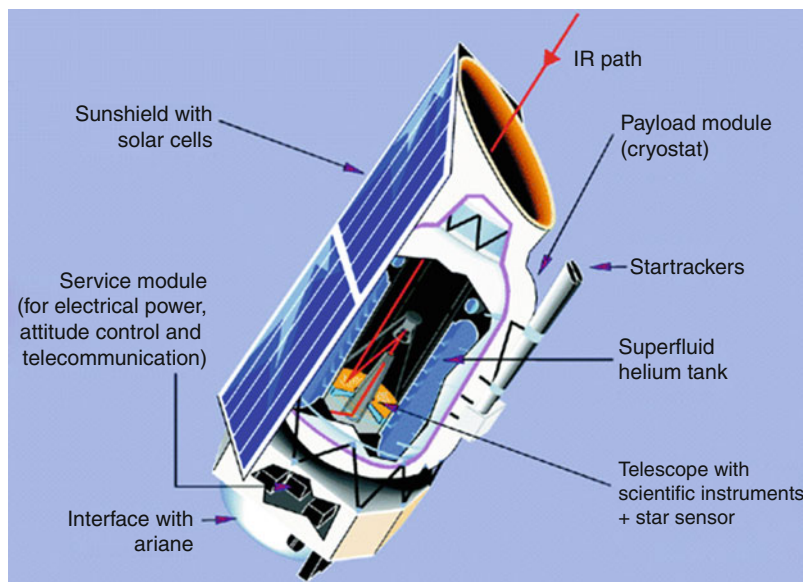
The Infrared Space Observatory (ISO), a project of the European Space Agency (ESA) with the participation of ► [NASA](#) and ISAS (now ► [JAXA](#)), was the first cryogenic spaceborne infrared observatory for astronomy. It operated from 1995 to 1998 and made detailed imaging, photometric and spectroscopic observations at wavelengths from 2 to 200 μm of all kinds of astronomical objects from planets and comets in our own Solar System right out to distant extragalactic sources. Its contributions to astrobiology include the detection in space of water, complex organic molecules, and a rich variety of ices (Fig. 1).

Overview

The Infrared Space Observatory (ISO), selected by ESA in 1983, made a detailed exploration of the infrared universe. Industrial design and development started in 1986 with Aérospatiale (now Thales Cannes) as prime contractor. An Ariane 44P vehicle launched ISO in November 1995, and it operated until May 1998 in an elliptical 24-h orbit with perigee/apogee of 1000/70,000 km. ISO's *Payload Module* was essentially a large cryostat, containing 2300 l of superfluid liquid helium, cooling four scientific

Infrared Space Observatory,

Fig. 1 Schematic of ISO



instruments and a telescope of Ritchey-Chrétien design with a 60 cm diameter primary mirror to temperatures of 2–4 K. The two spectrometers (short-wavelength spectrometer [SWS], long-wavelength spectrometer [LWS]), a camera (ISOCAM), and an imaging photopolarimeter (ISOPHOT) jointly covered wavelengths of 2.5–240 μm with spatial resolutions ranging from 1.5 to 90 arc s, depending on wavelength. The *Service Module* provided the traditional spacecraft services including three-axis attitude stabilization at the arc second level (Kessler et al. 1996).

The mission was a technical, operational, and scientific success with most satellite systems operating far better than specifications and with its scientific results impacting practically all fields of astronomy.

During its 29-month operational lifetime, ISO made over 30,000 individual observations. These data are publically available from the ESA archives (“archives.esac.esa.int” and then click on ISO).

ISO’s scientific legacy is summarized in various overviews and compilations (e.g., First ISO Results 1996; Cox and Kessler 1999; Cesarsky and Salama 2005). The mission made several significant contributions to astrobiology. ISO found water everywhere in the universe – in

comets, ► Mars, the four giant planets and ► Titan, the interstellar medium (toward proto-stars and molecular clouds), evolved stars (both oxygen and carbon rich), and galaxies (e.g., Cernicharo and Crovisier 2005; Encrenaz 2008). ISO’s wide and uninterrupted wavelength coverage, free of telluric contamination, permitted it to make a detailed inventory of interstellar ices (including not only the ubiquitous CO_2 but also $^{13}\text{CO}_2$, CO , H_2O , H_2CO , CH_4 , CH_3OH , CH_3 , OCS , etc.) and gas phase organic molecules (including H_2O , CH_4 , C_2H_2 , CH_3 , HCN , CO_2 , OH , etc.) as well as addressing the rich variety of polycyclic aromatic hydrocarbon features and making an inventory of the reservoirs of the major elements (C, O, N, etc.) (e.g., Ehrenfreund and Charnley 2000; van Dishoeck 2004). In brief, ISO showed conclusively that space is full of the building blocks of life.

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Infrared Spectroscopy

Yoko Kebukawa

Faculty of Engineering, Yokohama National University, Yokohama, Japan

Keywords

Fourier transform infrared microspectroscopy ·
Fourier transform infrared spectroscopy ·
FTIR · Infrared microscopy

Definition

Infrared spectroscopy is spectroscopy using infrared light (0.7–1000 μm ; $\sim 14,000$ – 10 cm^{-1}). Most molecular bonds are characterized by the absorption of specific frequencies of infrared radiation. The 0.7–2.5 μm ($\sim 14,000$ – 4000 cm^{-1}) region is often called the near-infrared, the 2.5–25 μm (4000 – 400 cm^{-1}) region is called the mid-infrared, and the 25–1000 μm (400 – 10 cm^{-1}) region is called the far-infrared.

Overview

Many organic and inorganic materials absorb unique frequencies of infrared light. The absorption is caused by vibrations or rotations of molecules, at frequencies corresponding to the infrared region of the electromagnetic spectrum. Therefore, information about molecular species and structure can be obtained by irradiating samples in the infrared frequency range and subsequently

observing the absorption spectra or by observing the corresponding emission spectra if the intensities exceed that of the background radiation. Vibrational transitions in the infrared for some typical functional groups occur in the regions of ~ 3600 – 2500 cm^{-1} (OH stretching), ~ 3100 – 2800 cm^{-1} (CH stretching), ~ 1800 – 1650 cm^{-1} (C=O stretching), and $\sim 1600\text{ cm}^{-1}$ (aromatic C=C stretching) (Socrates 2001).

In the case of transmission infrared spectroscopy, the spectral intensity is usually reported as a transmittance (T) or absorbance (A). The transmittance is defined as the ratio of infrared energy passing through a sample (I) and irradiated infrared energy (background; I_0):

$$T = I/I_0,$$

which is usually shown in % transmittance (% T).

The absorbance is defined as

$$A = -\log_{10} T = -\log_{10}(I/I_0).$$

The absorbance is linearly correlated with the concentration of the component of interest, a relation known as the Lambert-Beer law:

$$A = \varepsilon dC,$$

where ε is the molar absorptivity, d is the thickness of the sample, and C is the concentration of the component of interest. The infrared absorption intensity (or integral absorption intensity), with appropriate baseline correction, can be therefore used for quantitative analyses.

Today, Fourier transform infrared spectroscopy (FTIR) is more commonly used than traditional monochromatic infrared spectroscopy. The instrumentation of FTIR usually consists of a light source, an interferometer (instead of a monochromator), a detector, and a computer system. In FTIR, the time domain spectrum (interferogram) obtained by infrared light passing thorough an interferometer is converted to the frequency-domain spectrum by a Fourier transform. A microscope is often combined with an FTIR for micro-to-millimeter-sized samples and is useful for spatial characterization. Most recently, a

synchrotron radiation light source has been used instead of a conventional ceramic light source. The greater brightness of a synchrotron source enables a better spatial resolution (close to the expected diffraction limit according to the wavelength) and a higher signal-to-noise ratio than ceramic light sources (Holman and Martin 2006). Nanoscale infrared spectroscopy combined with atomic force microscopy (AFM-IR) has been developed to overcome the limitation of spatial resolution due to the diffraction limit (approximately the same as the wavelength) (Dazzi et al. 2012).

Infrared spectroscopy can be applied to solid, liquid, and gas samples. Reflectance methods, such as diffuse reflectance and attenuated total reflection (ATR), are also used particularly for samples not suitable for transmission IR (e.g., thick samples). Infrared spectroscopy is used in astronomical observations of the solar system and the ► [interstellar medium](#), e.g., for identifying constituents of planetary atmospheres and surfaces, and the constituents of ► [molecular clouds](#) in the Milky Way and external galaxies.

Cross-References

- [Infrared Astronomical Satellite](#)
- [Infrared Astronomy](#)
- [Infrared Space Observatory](#)

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Ingenuity

Michel Viso
Innovaxiom, Paris, CX, France

Definition

Ingenuity is the name of a helicopter which was dropped off on the Martian surface (April 4, 2021) by the rover ► [Perseverance](#) about 2 months after its soft landing. The small helicopter (Balaram et al. 2021), with a height of 0.49 m, a mass of 1.8 kg, has a small solar panel on top of two 1.2-meter-wide, two-blade contra-rotating rotors. The energy from the solar panel is stored in rechargeable Li-ion batteries. Ingenuity is equipped with 2 Commercial Off The Shelf (COTS) cameras. A black and white camera looking downward is a navigation camera mandatory to give, in flight, information to the onboard computer. The color camera is designed to take images to be transmitted to Earth and is not needed to fly. In addition to the radio transmitter to communicate with the rover, Ingenuity is equipped with several COTS sensors like an inclinometer, an inertial measurement unit, an altimeter ...

Ingenuity was designed as a technological demonstrator to prove the powered flight in ultra-thin atmosphere, to demonstrate miniaturized flying systems, and to validate autonomous navigation and operation of the helicopter. The technological demonstration phase has lasted up to May 7, 2021, and cumulated about 395 s of flight in five flights.

Then Ingenuity entered operations demonstration phase to help in the design of the travel of Perseverance while the rover is searching the right spots to study and sample. The rough nominal autonomy of the helicopter is 90s. As of the

beginning of 2022, the longest single flight reached 625 m and the highest height it flew was 12 m above the ground. The planned mission lifetime of Ingenuity was 30 days on ► [Mars](#). On September 2021, Ingenuity was granted with an indefinite mission extension by NASA.

Cross-References

- [Mars](#)
- [Mars 2020](#)
- [Perseverance](#)

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Initial Mass Function

Leticia Carigi
Instituto de Astronomía, Universidad Nacional
Autónoma de México, Ciudad de México,
Mexico

Synonyms

[IMF](#)

Definition

The initial mass function describes the relative number of stars, as a function of their individual initial mass m , that forms during a single star-forming episode. It is generally expressed as the number n of stars per unit volume of space per logarithmic initial-stellar-mass interval $d \log m$, $\text{IMF} = dn/d \log m$.

Overview

The IMF is defined over a large interval of masses, from the most massive stars to the lowest mass stars, created in a single star formation burst. It is known that Nature tends to form much more low-mass stars than high-mass stars. For instance, Chabrier (2003) predicts approximately 4000 stars of $1 M_{\odot}$ and 40 stars of $10 M_{\odot}$ for each star of $100 M_{\odot}$.

The initial mass function is often expressed as a multi-segment power law, $\text{IMF} = \text{constant} \times m^{-\alpha}$, for different mass intervals, where α is the slope of the logarithmic plot. In some ranges, a log-normal law is preferred.

The majority of the empirical IMFs has been inferred from star counts observed in the solar neighborhood. This region has had a long history of star formation bursts, including stars of different ages. Hence, to determine the true IMF, it is necessary to correct the actual count, assuming how the star formation rate has changed over time, stellar ages, the number of binary or multiple stellar systems, the Galactic age, and some other factors.

The first and still most popular IMF is that obtained by Salpeter (1955), with slope $\alpha = 2.35$, over the entire unique mass interval between 0.4 and $10 M_{\odot}$. It is important to mention that the astronomical community has often extrapolated it without careful consideration. When Salpeter's IMF is extrapolated to $m < 0.4 M_{\odot}$, the number of very low-mass stars is one or two orders of magnitude larger than the observed value.

In the literature, there are many different IMFs (see Kroupa et al. 2013 and references therein), generally with several slope values for different mass intervals. The dependence of the slope on density and metallicity is well established for the range of massive stars. The disagreement between them is larger for the very low-mass stars, due to their intrinsically low luminosity, and for very massive stars, due to their low stellar lifetime.

From the theoretical point of view, simulations of compressible turbulence, in particular in super-Alfvénic conditions, reproduce qualitatively and

reasonably quantitatively the determined IMF, while the Jeans-type mechanism, with fragmentation due only to gravity, does not (see Chabrier, ► [“Initial Mass Function, Origin of”](#) and references therein).

It is very important to note that the universality of IMF remains as an unsolved problem; however, some recent observations and simulations lean towards an environment and time-dependent IMF through the evolution of the metallicity and the star formation rate (Jeřábková et al. 2018). Moreover, when the number of stars is low, the IMF is not a continuous function and it should be sampled stochastically.

Since stellar properties mainly depend on their initial masses, the IMF is fundamental to the chemical and spectral evolution of star clusters and galaxies.

Cross-References

- [Initial Mass Function, Origin of](#)
- [Metallicity](#)
- [Solar Neighborhood](#)
- [Stellar Evolution](#)

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Initial Mass Function, Origin of

Gilles Chabrier

Centre de Recherche Astrophysique de Lyon,
Ecole Normale Supérieure de Lyon, Lyon, France

Keywords

Star formation

Overview

It was first recognized by Richard Larson in 1981 that ► [molecular clouds](#) are dominated at large scales by strong turbulent motions. ► [Turbulence](#) thus determines the structure of all density regimes in the interstellar gas and in star-forming molecular clouds (MacLow and Klessen 2004). The sources of this turbulence are multiple and can be due to convergent flows in the interstellar medium, supernova explosions, galactic shear, or even more simply to star formation itself. Given the low density of the medium, the turbulent flow is highly compressible and cascades from large to small scales by shock waves. Typical Mach numbers of this turbulence in star-forming molecular clouds range from about 3–8 under usual Milky Way-like conditions, although more extreme values can be found in starburst environments. Observations show a power law dependence between the typical turbulent velocity dispersion, σ , in molecular clouds and the size of the cloud, L , a relation known as one of the Larson’s relations, $\sigma \propto L^\eta$ (see Hennebelle and Falgarone 2013 for a recent review). The power index of this relation, η , is in fact tightly connected to the index of the turbulence velocity power spectrum, n , with $\eta = (n-3)/2$ (e.g., Hennebelle and Chabrier 2008). Numerical simulations of compressible turbulence show that this index is of the order of $n \sim 3.8$, in three dimensions (Beresnyak et al. 2005; Kritsuk et al. 2007), typically between the Kolmogorov value $n = 5/3$ for incompressible turbulence and the Burgers

value $n = 4$ for shock-dominated turbulence. As discussed below, this index plays a key role in the determination of the slope of the ► [initial mass function](#) (IMF).

Key Research Findings

The statistics of the gas density fluctuations created by turbulence is captured by the so-called probability density function (PDF). A key property of turbulence is that in good approximation, the PDF of the *logarithm* of the density ($\log \rho$) is Gaussian, implying that the PDF is lognormal. Such a distribution is expected from the application of the central limit theorem to a hierarchical density field generated by multiplicative processes, such as shocks (Vázquez-Semadeni 1994). Such a lognormal behavior for density fluctuations has received both observational and numerical support. Observationally, the 3D lognormal shape of the PDF is reflected by the projected (2D) power spectrum column density of molecular clouds, measured from dust extinction maps (Kainulainen et al. 2009; Lombardi et al. 2010; Brunt et al. 2010). On the other hand, various numerical simulations of compressible turbulence do show the emergence of a lognormal form for the PDF, at least for the aforementioned typical Mach values, both in supersonic hydrodynamic (e.g., Padoan and Nordlund 2002; Federrath et al. 2010; Schmidt et al. 2010) and MHD turbulence (Lemaster and Stone 2008; Price et al. 2011). Although departure from such a lognormal form does occur under some circumstances, due to the intermittency of turbulence or the nonisothermality of the gas, it remains a reasonable approximation for the aforementioned typical Mach values.

Interestingly enough, observational determinations of the stellar initial mass function, defined originally as the number of stars per logarithmic mass interval, $dN/d\log M$, in various Galactic environments, in the field, in young clusters, and in star-forming regions, confirm that the IMF exhibits a power law tail for masses above about a solar mass, the well-known Salpeter IMF (Salpeter 1955), but

rolls over below about 0.8 solar masses. The IMF is globally well described by a combination of this power law tail and a lognormal form, extending well into the brown dwarf regime (Chabrier 2003, 2005). Most interestingly, the observations of gravitationally bound prestellar cores in various star-forming regions, as revealed in particular by the Herschel satellite (André et al. 2010), called the core mass function (CMF), precursor of the stellar IMF, displays as well a Salpeter power law tail turning down to a lognormal shape at low masses, closely resembling the Chabrier IMF. All these numerical experiments and observations thus strongly suggest that star formation and turbulence are closely linked and that the IMF is imprinted by turbulence in the cloud at the very early stages of the star formation process.

Theory of the Stellar Initial Mass Function

Several attempts have been made to develop a theory linking turbulence and the origin of the IMF. The first attempt to demonstrate the link between the lognormal form of the turbulence PDF and the distribution of Jeans unstable prestellar cores was made by Padoan and Nordlund (2002). Although indeed illustrating the relationship between these two quantities, this theory, however, is based on several ad hoc assumptions and cannot properly reproduce the Salpeter slope of the IMF in the pure hydrodynamic case (without magnetic field), in contrast to what is obtained in numerical simulations. Later on, Hennebelle and Chabrier (2008, 2009), using the analogy between cosmological and turbulence Gaussian density fluctuations, have extended the formalism of Press and Schechter (1974), originally developed to determine the mass function of collapsing dark halos in the primordial universe, to the star formation process. In that case, however, the random field of density fluctuations is no longer uniform, as for the primordial universe, but lognormal, as mentioned above. Combining this distribution of initial density fluctuations with the

virial condition for gravitational collapse, which states that only fluctuations within which gravity dominates over all other sources of support are gravitationally unstable, this theory reproduces all of the key features of the observed CMF and, by extrapolation, of the stellar IMF, including the mass distribution of brown dwarfs, for appropriate density and Mach number conditions. In this theory, the impact of turbulence is twofold. First of all, turbulence-induced shocks lead to a field of overdensities, and fluctuations of the underlying velocity field follow a Kolmogorov-like scale dependence. Fluctuations dense enough to become gravitationally unstable provide the seeds for the future collapsing prestellar cores, including pre-brown dwarf cores at very small scales. The more powerful the turbulence, i.e., the higher the large-scale typical Mach number, the larger the number of small-scale overdensities, thus, of low-mass cores. On the other hand, turbulence constantly sweeps away gas reservoirs which, otherwise, would become Jeans unstable and collapse. As a consequence, mass reservoirs can grow much larger than in the absence of turbulent motions, until eventually they exceed a mass defined as the turbulent, as opposed to purely thermal, Jeans mass. In other words, overdense regions with lower masses than the turbulent Jeans mass will be dispersed back into the flow under the action of turbulence within a turbulent crossing time, before they become dominated by gravity. Only in regions exceeding the turbulent Jeans mass will gravity take over, yielding the collapse of the corresponding mass reservoirs, providing the initial seeds for the massive gravitationally bound prestellar cores.

In this theory, this often called “turbulent support” should thus not be confused with a static support, equivalent to a pressure, but should rather be seen as a random process selecting *at the very early stages of the star formation process* the pieces of gas that will be dominated by gravity and will thus collapse, from the ones that will be dispersed. Eventually, turbulence will of course quickly dissipate, and by the time they are observed, the bound cores will exhibit only thermal inner motions, but turbulence will have been the initial triggering mechanism. This key role of turbulent motions,

characterized by the velocity power spectrum index mentioned previously, is mandatory to obtain the proper Salpeter slope at high masses for the IMF, the slope being directly related to this index (Hennebelle and Chabrier 2008; Chabrier and Hennebelle 2010). This concept of turbulent Jeans mass for collapse has received some support from numerical simulations aimed at exploring this issue (Schmidt et al. 2010). Later on, also using analytical tools originally developed for cosmology, Hopkins (2012) generalized the concept of Hennebelle and Chabrier to larger, galactic scales, which yields the mass function of giant molecular clouds in galactic disks. As in the Hennebelle-Chabrier theory, the stellar IMF in the Hopkins formalism is entirely determined by one single parameter, namely, the turbulent velocity power spectrum index.

Future Directions

The striking resemblance between the prestellar core mass function and the final stellar IMF, added to the growing evidence for this latter being the combination of a Salpeter power law at large masses and a lognormal form below about one solar mass, clearly points to two fundamental results for the origin of the IMF. First of all, this latter seems to be imprinted in the cloud at the very early stages of star formation and be determined by the very conditions in the cloud, density, temperature, and large-scale Mach number. Second, observations and numerical simulations show that compressible turbulence, with or without the presence of a magnetic field, leads to a roughly lognormal distribution of overdensities mirroring the shape of the IMF. As discussed above, this concept of turbulence-induced fragmentation for the origin of the IMF can now rely on a sound theoretical support, which shows that the very shape of the IMF is entirely determined by the density and velocity power spectra of compressible turbulence, which are universal properties. Quantitatively speaking, however, the IMF, notably its extension in the low-mass domain, depends on the essential properties of the cloud, density, temperature, and large-scale Mach number. Under standard Milky

Way-like molecular cloud conditions, these properties obey Larson's relations and display rather similar values, leading to a rather universal IMF. It is not excluded and is indeed predicted by the above theories, however, that under quite different conditions, for instance, in extreme environments, the IMF might differ *quantitatively* from the one inferred in the galactic neighborhood, in particular for the peak position and the extension in the low-mass regime. If the theory is correct, however, the IMF should qualitatively remain the same, with a high-mass power law tail rolling down to a lognormal form below about the characteristic thermal Jeans mass of the medium.

Future observations, both in the galactic neighborhood and in extragalactic or widely different environments, should allow us to test further these theories and verify the robustness of this general paradigm for the origin of the stellar initial mass function.

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Initial Mass Function](#)
- [Star Formation, Observations](#)
- [Star Formation, Theory](#)

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Insoluble Organic Matter

Hiroshi Naraoka

Department of Earth and Planetary Sciences,
Kyushu University, Fukuoka, Japan

Keywords

Alteration · Extraterrestrial · Insoluble · Organic matter · Unusual isotopic composition

Synonyms

IOM; Kerogen-like matter

Definition

Insoluble organic matter (IOM) is a major component of organic matter found in primitive extraterrestrial materials such as carbonaceous meteorites. Most of this is organic carbon with lesser amounts of hydrogen, nitrogen, oxygen, and sulfur forming aromatic hydrocarbon cores (two to four aromatic rings) and short-chain aliphatic hydrocarbons with various functional groups including nitrile, carboxyl, and ether. Unusual isotopic signatures such as extreme δ and ^{15}N -enrichment are observed.

Overview

Insoluble organic matter (IOM) is a major constituent of organic matter in extraterrestrial materials. Even though various organic compounds including amino acids, carboxylic acids, and polycyclic aromatic hydrocarbons (PAHs) have been identified in meteorites, particularly in carbonaceous chondrites, these solvent-extractable organic compounds are only 10–30% of the total organic carbon. Most meteoritic organic matter is insoluble in water, acids, or organic solvents. This insoluble organic matter is used to be called kerogen-like material (cf. kerogen is a solvent-insoluble organic matter in terrestrial rocks) or macromolecular organic matter. Now, it is generally called IOM.

For the ► [Murchison meteorite](#), which is relatively enriched in soluble organic compounds, the IOM consists of more than 90% of the meteoritic organic carbon with minor amounts of hydrogen, nitrogen, oxygen, and sulfur. Although the chemical structure of IOM has not been defined accurately yet, it has aromatic hydrocarbon cores (two to four aromatic rings) with short-chain aliphatic hydrocarbons. IOM from various meteorites has a wide variation in

chemical composition. The H/C ratio of chondritic IOM varies from <0.1 to 0.7 , the more metamorphosed meteorite having a lower H/C ratio. Therefore, the H/C ratio is a sensitive indicator for thermal processing during the meteorites' history. ^{13}C -NMR and ► [XANES](#) studies have also revealed various chemical bonding and functional groups, including aromatic and aliphatic structures with carbonyl, carboxyl, and aldehyde as well as amide and nitrile groups. As the Murchison IOM generates abundant PAHs and acetic acid (ca. four times higher compared to solvent-extractable acetic acid) during hydrous pyrolysis, the IOM may be an important precursor for organic compounds in meteorites.

The most primitive IOM also possesses unusual isotopic signatures such as extreme δ and ^{15}N -enrichment, which have not been observed in solar system processes. Such isotopic behavior suggests that meteoritic organic matter may have originated from interstellar processes. However, the unusual isotope signals are diminished or lost during the thermal and aqueous alteration on meteorite parent bodies.

Cross-References

- [Carbonaceous Chondrite](#)
- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Murchison](#)
- [XANES](#)

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Institut for Rumforskning og -teknologi

► [DTU Space, Denmark](#)

Instituto de Astrobiología de Colombia

► [IAC, Colombia](#)

Intellect

► [Intelligence](#)
 ► [Intelligence, Evolution of](#)

Intelligence

Lori Marino

Emory Centre for Ethics, Emory University,
 Atlanta, GA, USA

Keywords

Cognition · Complexity · Brain · f_i ·
 Encephalization · Neuroanatomy

Synonyms

[Cleverness](#); [Cognition](#); [Intellect](#)

Definition

Intelligence is a term referring to a range of abilities that have to do with how an individual (or collective entity) acquires, processes, stores, analyzes, and acts upon information and situations. It includes capacities such as memory, learning, problem solving, abstract thinking, creativity, and behavioral flexibility. Intelligence is, by nature, a fuzzy concept. That is, there are no strict boundaries on it and there is no scientific consensus on its definition. Intelligence is often referred to as cognitive complexity.

Overview

In the domain of ► [SETI](#), intelligence has been operationalized as the presence of a technology detectable from Earth. In the broader framework of astrobiology, however, there is no need to limit the study of intelligence to a strict technical criterion. The study of intelligence in the astrobiological paradigm involves applying our knowledge and understanding of the myriad intelligences on earth to develop scientific hypotheses about extraterrestrial intelligence. Intelligence is a reflection of the kinds of cognitive adaptations each species has had to make in its evolutionary history and is, thus, multidimensional, interacting

with many other adaptive features, such as sensory-perceptual and motor abilities.

Intelligence across species on this planet is measured in a variety of ways. These include experimental studies of learning, memory, and other aspects of cognition in animals. It also involves determining what cognitive capabilities are evinced in animals in a natural setting. There are trade-offs with the validity of both approaches. Several neuroanatomical measures are used as proxies for intelligence across species, including relative brain size (also known as encephalization quotient), the volume of specific structures in the brain, and nerve cell density and connectivity. Some combination of all of the above features within the categories of brain size and organization forms the neurological basis of the phenomenon we know as intelligence. Correlations among various measures of brain size, cognitive capacity, problem solving, and behavioral ecology, e.g., social complexity, dietary complexity, have been found in many groups of animals across phyla. These patterns of association point to possible scenarios about the causal relations between intelligence and the physical and social environment. The challenge is to determine how all of these features relate to each other to form the range of intelligence that exists both within and across species on earth.

Basic cognitive processes forming the fundamental groundwork for intelligence in animals are found in unicellular organisms as mechanisms of learning and memory are shared across all species, including humans. There are fundamental capacities which even simple nervous systems allow which are ubiquitous among all motile life forms on earth. And there is a deep continuity in the domain of intelligence across species. Likewise, in metazoans, intelligence is often correlated with other psychological capacities such as self-awareness, emotional complexity, and personality structure. Even “high-level” cognitive abilities once thought to be exclusively possessed by humans, such as for planning, basic mathematics, self-recognition, and a technological culture, are not unique to our species.

Cross-References

- ▶ [Astrobiology](#)
- ▶ [Bioastronomy](#)
- ▶ [Biological Evolution](#)
- ▶ [Complex Organisms](#)
- ▶ [Complexity](#)
- ▶ [Drake Equation](#)
- ▶ [Ecological Niche](#)
- ▶ [Exobiology](#)
- ▶ [Intelligence, Evolution of](#)
- ▶ [Search for Extraterrestrial Intelligence](#)
- ▶ [SETI](#)
- ▶ [Species](#)

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Intelligence, Evolution of

Lori Marino

Emory Centre for Ethics, Emory University,
Atlanta, GA, USA

Keywords

Cognition · Complexity · Brain · Central nervous system · Encephalization · f_i

Synonyms

[Cleverness](#); [Cognition](#); [Intellect](#)

Definition

Intelligence, those features of an organism that mediate the way in which that organism represents, processes, and acts upon information, is a biological trait subject to the same evolutionary principles that shape all other biological features of organisms on this planet. The evolution of intelligence refers to the pattern, distribution, and mechanisms of neurobiological, cognitive, and behavioral characteristics within and across species over time. The question of the evolution of intelligence is often framed as one of cognitive (psychological) complexity.

Basic Methodology

The main task in studying the evolution of intelligence is to find ways to reconstruct the past and place the cognitive characteristics of modern species in the proper temporal and phylogenetic context. This begins with a well-supported phylogenetic tree, i.e., a branching diagram of species showing their inferred evolutionary relationships based on physical and genetic traits. Connected taxa on the tree are implied to have descended from a common ancestor. Nodes represent species or some other taxonomic unit and branch lengths, often, are used to represent time. Phylogenetic comparative methods are then employed, using the tree, to test for patterns of evolutionary change from which we can draw inferences about the evolutionary process.

The kinds of data used to develop a phylogenetic tree range from phenotypic, behavioral, and anatomical traits to genotypic characteristics. Comparative phylogenetic analysis provides a way to, for instance, infer the ancestral state of a given trait, e.g., toolmaking or mirror self-recognition, or whether there is evidence for convergent evolution in some component of intelligence. The actual data compared against a phylogenetic framework derive from a variety of approaches.

Research on intelligence in living animals is typically conducted using two approaches: laboratory-based experimental studies and

observations in a naturalistic ethological setting. There are trade-offs with the validity of both approaches, and this is why both must be combined to understand intelligence in a comparative evolutionary framework. The strength of laboratory-based experimental tests of cognition is that they can be well controlled for extraneous variables, providing a way to test specific hypotheses about the existence of certain capacities in a species. The weakness in this approach is in the questionable generalizability to a natural setting. The challenge for laboratory-based approaches when studying animal intelligence is to devise tasks which are species appropriate, i.e., tap into the natural proclivities and sensitivities of the species. Yet, despite the artificial setting of a laboratory, many members of other species score high marks on human-devised tests of intelligence and even exceed human performance in specific domains. For instance, chimpanzees far exceed human performance on numerical short-term memory tests under equivalent laboratory conditions, i.e., using a touch-sensitive computer screen (Inoue and Matsuzawa 2007).

The other approach, known as cognitive ethology, assesses abilities of animals in their natural habitat and therefore frames intelligence more directly as a set of cognitive adaptations to a specific ecological niche over evolutionary time. Studies in this domain do not always feature the tight controls of a laboratory study but can provide a more appropriate setting for the display of abilities that might be restricted and thus unobserved, under artificial conditions. For instance, our knowledge of cultural transmission in chimpanzees, orcas, sperm whales, and many other species could only come from field studies over long periods of observation. The cognitive ethological approach provides a window into the adaptive significance of behaviors and abilities in other species, providing insights into how and why the many facets of intelligence evolved across species on this planet.

Another method used to obtain data about the evolution of traits related to intelligence is through the fossil record. This approach, called paleoneurology, is the study of brain evolution by analysis of fossil skulls and endocasts.

A brain endocast is the imprintation of the inner features of a cranium that captures the details created from pressure exerted on the skull by the brain itself. Endocasts can be formed naturally by sedimentation which enters the skull through the cranial foramina and hardens over time or artificially by creating a mold from silicon or latex that reproduces the inner structure of the cranium. While complete natural endocasts are rare and artificial ones dependent upon a clean interior cranial space, the state-of-the-art method for seeing inside the cranium is computed tomography (CT), which can be used if the skull is filled with or encased in hardened matrix. CT is employed to reconstruct the shape of the brain *in vivo*, estimate cranial volume (or brain size), and conduct other morphometric analyses. These data are then used to infer evolutionary changes in the brain thought to reflect changes in cognitive abilities. These data are analyzed against existing trees and also provide more data for improved trees. Moreover, and importantly, these endocranial characteristics are compared with those of modern species to infer evolutionary routes of traits associated with intelligence. Of course fossil data is only obtainable from specimens that are preserved in the record as actual fossils or, in some cases, trace fossils. Trace fossils can be used to infer behavior. However, the limitation on the paleontological method is clearly the relative paucity of preserved data from very early in the Earth's history. CT is most applicable to the study of vertebrate brain evolution for these reasons.

Another particularly productive approach to research on the evolution of intelligence and the brain involves combining the knowledge bases and methodologies of developmental biology with evolutionary biology, an approach called ► [evo-devo](#). The evo-devo approach is to examine the way mechanisms of development have been influenced by, and reveal, evolutionary forces and vice versa. Developmental patterns are shaped by phylogenetic relationships, and evolution is influenced by genetic modifications during early development. This approach has revealed much about the genetic mechanisms behind such characteristics as brain segmentation and brain-to-body scaling.

Finally, it is important to note that none of the above approaches to studying the evolution of intelligence are entirely mutually exclusive. Data from studies of cognitive abilities in living animals, fossil evidence of changes in brain size and shape, and genetic mechanisms underlying the development of the brain and the rest of the nervous system are brought together to create an ever-growing picture of the evolution of intelligence at the multiple levels required to understand such a complex aspect of organisms.

Key Research Findings

The evolution of intelligence on Earth is characterized by evolutionarily highly conserved processes and, thus, a great deal of continuity across phyla. The actual nature of the first organisms and the exact circumstances of the origin of intelligence will be forever unknown. But research on extant organisms using techniques to reconstruct phylogenetic relationships can aid in identifying the major milestones in the evolution of intelligence from brain-like functions in unicellular organisms to the development and centralization of the nervous system in metazoans. These evolutionary processes reveal a shared set of fundamental cognitive characteristics across all species and lead to the deep insight that all brains and intelligence on Earth, including those of humans, are a variation on a universal theme laid down 600 million years ago with the appearance of the first animals.

Intelligence in Early Unicellular Life

The need to process and act upon information is intimately tied to the varied distribution of elements in the environment that impact survival. An immobile organism or one living in a highly predictable, stable environment would not have much need for a nervous system. But motile organisms must have a way to detect and analyze the range of information in their environment and make adaptive behavioral responses to it. Motile bacteria, for example, are attracted or repelled by various stimuli and need to be able to act upon detection of these inputs. They exhibit taxes,

guided movements to a stimulus, which include ► **chemotaxis**, phototaxis, energy taxis, and magnetotaxis. Therefore, the first stage in the evolution of intelligence arose very early in the Earth's history with the emergence of motile single-celled organisms. They sense their environment, briefly store the information, integrate it in different channels of input, and then act upon it – producing basic adaptive behavior. These brain-like processes work at a molecular level but they reveal a common ancestry with all modern brains.

The mechanism by which unicellular organisms detect their environment is known as “membrane excitability” and involves sensitivity to electrochemical gradients typically accomplished through the flow of ions into and out of the cell. This basic mechanism was built upon and adapted to become the basis of information flow in neurons, cells specialized for information processing, in metazoans. Evidence for continuity derives from the fact that the membranes of modern neurons operate by the same electrochemical principles (voltage-gated ion movement across a membrane) as in single-celled organisms (Allman 1999).

One example of a bacterium with brain-like capacities is *Escherichia coli*, which senses its environment through a dozen different types of protein receptors embedded in its cell wall that allow chemicals outside the cell to communicate with mechanisms inside. Each receptor specializes in a specific kind of information or input, e.g., toxins, sugars, amino acids, etc. The input is integrated, and the result is the “decision” to behave in a certain way, i.e., use of its flagellar motors to swim toward or away from the environmental stimulus. Another unicellular organism, *Halobacterium salinarum*, derives energy from light in the orange spectrum. It possesses a light-sensitive pigment similar to rhodopsin, the photo-receptive pigment in vertebrate eyes. Detection of orange light causes the *Halobacterium* to swim toward the source (Allman 1999). These simple responses were elaborated upon to allow for more complex behavior in metazoans.

The fact that all mobile unicellular organisms possess the fundamental characteristics of

nervous systems suggests that the two critical factors for the early emergence of intelligence on any planet are environmental variability and motility. With environmental variation, a way to sense and act upon that environment to optimize one's survival will inevitably evolve. Thus, environmental variation is key to the emergence of nervous system functions and the potential for complex intelligence.

The Evolution of Intelligence in Metazoans

When metazoans (multicellular animals) appeared, approximately 600 million years ago, cells became specialized for different functions. The next major milestone in the evolution of intelligence was the specialization of some cells with excitable membranes as neurons. The neuron is the basic unit of information processing in all nervous systems on Earth and has remained, fundamentally, unchanged since early metazoan evolution, with only some smaller modifications added later, e.g., myelination of fibers to increase transmission fidelity and efficiency. A neuron is an electrochemically polarized cell which controls the flow of information through the organism. It has a characteristic architecture consisting of a body with branching processes, called dendrites, containing chemical receptors. When the dendritic input reaches an electrochemical summation threshold, a long axon transmits an electrical pulse to terminal branches which then release chemicals (neurotransmitters) that are picked up by the dendrites of another neuron and so forth. Importantly, information flows from the dendrites to the cell body and is converted into all-or-none signals, action potentials, which are relayed along the axon to the terminal branches. (These characteristics of directionality and “digitization” of neural impulses set the stage for an unprecedented level of organization and neural computational potential in the bilaterians).

The early radially symmetrical metazoans, e.g., cnidarians, ctenophores, hydrozoa, etc., were the first animals to possess a nervous system of any kind. Theirs is a decentralized nerve net (a loose arrangement of sensory neurons connected to motor neurons by interneurons).

While these animals lack a level of organization found in the nervous systems of bilaterians, the shared basic characteristics of these early nervous systems and more modern brains are striking. Voltage-gated sodium channels are present in jellyfish neurons and all modern brains. The neurotransmitters coursing through the brains of all modern species, including those with nerve nets, were derived from simple amino acids with precursors in single-celled organisms. In many of these radially symmetrical animals, there are the very beginnings of the next step in the evolution of nervous systems, centralization, in the form of nerve rings and clusters of neurons called ganglia which allow these animals to exhibit complex behaviors requiring coordination of parts of the body. Despite possessing no brain, many animals with nerve nets evince simple learning capacities, such as habituation, and can navigate complex environments.

Intelligence in Bilaterally Symmetrical Invertebrates and Vertebrates

The third major milestone in the evolution of intelligence coincided with the appearance of bilaterians (laterally symmetrical animals) 550–600 million years ago. Early bilaterians were wormlike creatures with a nerve cord running down the body and an enlarged ganglion at the front or head region. The process of enlarging the ganglionic cluster at the head region along with the sensory organs is called encephalization, and this process led to the first central nervous systems or brains. An anterior bilobed (left- and right-sided) brain connected to a nerve cord became the bauplan of the nervous system for all organisms with a central nervous system. The earliest true brains were segmented and differentiated into regions and structures. The first vertebrates, who appeared about 500 million years ago, evinced the characteristic four-part segmentation plan which all modern vertebrate brains adhere to: a telencephalon (part of the forebrain, including the neocortex), diencephalon (also forebrain), mesencephalon (midbrain), and rhombencephalon (hindbrain). And all vertebrates possess the same brain structures within those segments. In addition to the

basic layout, the function of structures within these segments is highly conserved across all vertebrates.

From an evo-devo perspective, the connection between vertebrate and invertebrate brains is evinced in the embryonic development of nervous systems across species from different phyla (Striedter 2005). The genetic mechanisms underlying nervous system formation also reveal a strong degree of conservation. For instance, homeotic genes that segment insect bodies are co-opted to segment parts of the vertebrate central nervous system. Other genes controlling the formation of part of the brain in fruit flies are replicated and regulate the newest part of the mammal brain, the neocortex. Therefore, even the human brain is organized by genes with antecedents going back half a billion years (Allman 1999).

Neurobiologist Eric Kandel and his colleagues have shown that the basic neural mechanisms of learning are the same from mollusks to mammals (Kandel 2009). But the range of shared cognitive capacities is not limited to very basic processes. Members of the phylum Mollusca (octopus, squid, cuttlefish, and nautilus) exhibit complex cognitive and behavioral abilities on a par with vertebrates, including social learning and tool use. Insects and arthropods, too, exhibit a vertebrate level of intelligence in many domains. For instance, in addition to their complex collective or swarm intelligence, individual bees understand counting, abstract concepts, and categorizations. These findings of cognitive complexity in invertebrates reveal a striking insight about the evolution of intelligence on Earth. The basic capacities of the human mind are demonstrable in the minds of beings who we commonly viewed as very different from us. These capacities in invertebrates – learning concepts, counting, and even tool use – point to the continuity of mind among humans and all other animals at a deep evolutionary level.

Within the realm of vertebrate intelligence, which arose about 500 million years ago, there is a striking degree of shared cognitive complexity across many species. Differences in even the most complex “high-level” capacities can be best

understood as varying along a continuum of complexity, as there are no cognitive abilities that are completely unique to any species, including humans. Even the most sophisticated components of intelligence, i.e., symbolic thinking and communication, self-awareness, and culture, are distributed across vertebrate species because all intelligences on Earth derived from preexisting capacities and the need to solve similar problems for survival. The centralized nervous system found in all animals and, in particular, the vertebrate brain and spinal cord are variations on the same basic theme.

Interest in the evolution of intelligence has been framed as a “rewinding of the tape of life” to address hypotheses about the causes and drivers of changes in brain and intelligence. Historically, studies of brain allometry (how brain size scales with body size) have focused on variations in adult brains and how they might be related to brain size and morphometry, sensory and motor specializations, and behavioral and ecological niches. Though evolutionary hypotheses cannot ever be tested directly by going back in time, correlational analyses can provide some insight into the drivers of evolutionary patterns. The conventional approach is to interpret correlations as proxies for “as-yet-unknown” causal relationships. Such studies in recent years have benefited from enhanced technological methods of measuring brain size (e.g., computed tomography), the collection of large behavioral databases, and application of powerful statistical tests to such data. Collectively, this body of scientific work has brought to light some broad consistent patterns of association among brain size, cognition, and ecology across animal groups that can be summarized as follows: Various measures of brain size (e.g., encephalization quotient, brain–neocortex ratio, etc.) are positively correlated with (1) feeding innovation rate, learning, and tool use in birds and primates; (2) behavioral repertoire size in mammals; (3) social complexity in birds, primates, carnivores, and some insectivores; and (4) dietary complexity in primates. These associations between neural mass and complexity, individual cognitive ability, and social complexity point to

the possibility that there may be general or even universal principles that shape intelligence on this planet – and perhaps, by extension, on others.

Brain Size and Organization

Brains are modified in various ways to reflect the adaptive specializations of each species. Encephalization, the process of elaborating on the size of the brain, is one dimension by which species differ. One measure of brain size or encephalization is the encephalization quotient (EQ). EQ is a statistical measure of average brain size relative to average body size for a species taking into account the fact that brain and body size are not independent. EQ is calculated by regressing average brain size onto body size for a wide range of species. Therefore, EQ is a normalized metric allowing one to compare directly the encephalization level of a cat and an elephant. A species with an average brain size expected for its body size has an EQ of 1 and lies on the regression line throughout the full range of body sizes. Modern humans have an EQ of 7.0, i.e., our brains are seven times larger than one would expect for an animal of our body size. Many cetaceans (dolphins and whales) possess EQs in the 4.0–5.0 range, and our nearest relatives, the great apes, have brains 2.5–3.0 times larger than expected. Species with EQ values of less than one have smaller brains than expected on the basis of body size. Encephalization should always be interpreted within the context of phylogeny. For instance, despite the fact that crow brains are smaller in absolute size than many mammal brains, the crow brain is much larger as an avian brain than, say, a camel brain, which is as a mammal brain. And crows, with EQs >2.0, are considered among the most intelligent of birds, whereas camels, with EQs closer to 1.0, are quite average as mammals on a cognitive level.

There are a number of scaling factors which come into play when brain size is modified that impact brain organization. These include preservation of neural conduction time and connectivity, which are addressed by increasing axon (fiber) diameter through myelination

(adding an insulating covering to the axon) and increased multiplication of local connectivity through modularization. The result is that, across species, larger brains containing more white matter (myelinated fibers) than gray matter (cell bodies) are less dense (due to increases in glial cells to support the larger neurons) and more modularized (maximizing local conductivity). These changes are observed in all brains and represent a universal set of principles for how brains change in size and organization over evolutionary time.

Evo-devo studies have revealed mechanisms underlying the conservative nature of the way in which bodies, including brains, have developed and evolved across taxa. The same genes are used repeatedly to create species-specific differences in body plan, including the brain and the rest of the nervous system. Current evidence shows that there is a very limited set of potential ways genes can alter development to create variety in nervous systems across species. And this point becomes the basis for the fact that all brains are a variation on the same theme. Diversity in the number of brain segments, basic segmental structure, and neural circuit organization are rare as are changes in the molecules which make up neurotransmitters and neuromodulators. On the other hand, changes in relative brain size or the volume of specific brain structures (allometric changes), in the morphology of single neuron types, and in the distribution of neurotransmitter substances occur commonly. The evolution of intelligence is, therefore, a history of modifications in some aspects of brain development more than others. The predominant way genes shape brains is through the timing and duration of sequences of neurogenesis and cell cycle rates. This results in correlations between brain size (and related measures) and life-history parameters, such as gestation length and length of the juvenile period. These life-history parameters, in turn, are related to aspects of intelligence, for instance, how much of an individual's life is spent learning before adulthood. Therefore, there are basic patterns of commonality across species with regard to neurogenetic, developmental, and evolutionary components of intelligence.

Common Biases

Darwin laid the groundwork for our modern understanding of evolution as a dynamic process shaped, mainly but not entirely, by the mechanism of natural selection, and his work is the basis of current methods of comparative phylogenetic analyses. Life on Earth, and thus intelligence, is characterized by a nonlinear branching pattern of taxonomic relationships over time (the phylogenetic tree). No modern species are ancestral to any other modern species. Likewise, no modern species is more advanced than another modern species. However, our current understanding of intelligence is fraught with preconceptions which continue to bias thinking to this day.

The most pervasive and insipient model of life on Earth and, thus, the distribution and nature of intelligence on Earth is known as the *scala naturae* or great chain of being. According to this model, nature is arranged on a linear scale of progression with inorganic substances and objects, e.g., rocks, on the lowest rung, then plants, then up to "lower" animals (invertebrates), then vertebrates, then to "higher" mammals such as primates, and, finally, humans, who occupy a separate, superior position above all other animals. Even Darwin's phylogenetic tree is often referred to as the phyletic scale, preserving the linear concepts of the *scala naturae*. Although few adhere to the *scala naturae* model explicitly, it still implicitly dominates our way of thinking about our own species and the rest of nature.

The incorrect assertion that humans are (1) qualitatively different from and (2) superior to other animals has led to a number of biases and false assumptions about the evolution of intelligence on Earth, e.g., anthropocentrism, typically embodied by the anthropic principle, which imbues much of the thinking about extraterrestrial intelligence. The historical result has been an unending and misdirected argument about contingency versus convergence between those who view intelligence in the narrowest sense, that is, as human intelligence, and those who take a broader view.

Scala naturae thinking is also closely related to teleological assumptions about intelligence. Teleology is the appeal to a goal-directed, purposeful

progression toward an end point as a means of explaining phenomena. Teleological thinking suggests that all life on Earth has been a progressive move toward the eventual emergence of human intelligence. It is entirely understandable that one would propose this after examining average relative brain size (a biological proxy for intelligence) across species over the last 200 million years. The result is a graph with a positive slope which seems to make the case for a progressive increase in brain size and intelligence over time. But this is an illusion in the fossil record. When understood properly, this graph represents the fact that brains simply need time to get large and, thus, larger brains are found in more recent species. When proper phylogenetic analyses are conducted, there is no directional trend. There is no evidence for any progressive linear trends in biological evolution which lead to humans. There is no “lower,” no “higher,” no “advanced,” and no “primitive” among extant species. To summarize, teleological and anthropocentric notions about the evolution of intelligence are not supported by any scientific evidence and should be avoided.

Future Directions

Moving forward, studies of intelligence and how it evolves should become increasingly ecologically valid as we begin to fold in several lines of data to seek insights into how and why intelligence evolves. Computational abilities currently provide a way to take a big data approach to analyzing behavior, ecology, genetics, etc. and looking for patterns of correlation which may support certain hypotheses about the evolution of intelligence on Earth. So much of the data relevant to the question of the evolution of intelligence has not yet been mined, brought together, and analyzed in the framework of extraterrestrial intelligence, so there is tremendous potential to be realized. Finally, progress can only be made if we shed preexisting assumptions and biases about intelligence which are inconsistent with the scientific evidence and adopt, instead, a more inclusive non-anthropocentric approach to the study of the evolution of intelligence on Earth.

Cross-References

- ▶ [Astrobiology](#)
- ▶ [Bioastronomy](#)
- ▶ [Biological Evolution](#)
- ▶ [Cell Membrane](#)
- ▶ [Complexity](#)
- ▶ [Complex Organisms](#)
- ▶ [Drake Equation](#)
- ▶ [Ecological Niche](#)
- ▶ [Evo-Devo](#)
- ▶ [Evolution, Biological](#)
- ▶ [Exobiology](#)
- ▶ [Fermi Paradox](#)
- ▶ [Intelligence](#)
- ▶ [Natural Selection](#)
- ▶ [Search for Extraterrestrial Intelligence](#)
- ▶ [SETI](#)
- ▶ [SETI, History of](#)

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Interference Zone

► [Spallation Zone](#)

Interferometry

Pierre Kervella
LESIA, Observatoire de Paris-PSL, Meudon,
France

Keywords

High angular resolution · Interferences ·
Interferometer · Optical interferometry · Radio
interferometry

Synonyms

[Hypertelescope](#); [Multiple aperture astronomy](#)

Acronyms

ALMA	Atacama Large Millimeter Array
CHARA	Center for High Angular Resolution Astronomy
KI	Keck Interferometer
mas	Milliarcsecond (or millisecond of arc)
VLA	Very Large Array
VLBI	Very Long Baseline Interferometry (radio domain)
VLTI	Very Large Telescope Interferometer

Definition

Astronomical interferometry is an observing technique that makes use of several separate sub-apertures instead of a single, large-aperture light collector for the observation of celestial objects. The separation between two individual sub-apertures is called the baseline and defines, together with the observing wavelength, the resolving power of the instrument. The longer the baseline and the shorter the wavelength, the higher the resolving power. Astronomical

interferometry is currently operational in the radio, infrared, and visible ► [wavelength](#) ranges. The presently available facilities give access to angular resolutions of the order of 1–10 millisecond of arc (milliarcsecond, abbreviated as *mas*), i.e., ten to hundred times smaller than that provided by the ► [Hubble Space Telescope](#) or 8–10 m class ground-based telescopes equipped with adaptive optics.

History

Interferometry's application to astronomy was first implemented in the visible in the late nineteenth and early twentieth centuries (Lawson 1997). The first measurement of the angular size of a star (Betelgeuse) was obtained in 1921 by Albert A. Michelson and Francis Pease using interferometry in the visible. Its development as a mainstream observing technique effectively started in the 1950s in the radio domain, at wavelengths for which the constraints on the quality of the reflector surfaces and optical path length equalization are less stringent than in the optical. Several giant radio interferometers were built in the 1970s and 1980s. In the 1960s, intensity interferometry in the visible was developed by Robert Hanbury Brown and Richard Q. Twiss in Australia. It was soon followed in the 1970s by the first multi-telescope observations in the visible, obtained by Labeyrie (*Interféromètre à 2 Télescopes*, I2T, followed by the *Grand Interféromètre à 2 Télescopes*, GI2T).

Several optical interferometers with collecting telescopes of a few decimeters to a meter were built in the 1980s and 1990s, including the Mark III (visible), the Palomar Testbed Interferometer (PTI, near infrared), the Navy Prototype Optical Interferometer (NPOI, visible), the Infrared Optical Telescope Array (IOTA, near infrared), the Infrared Spatial Interferometer (ISI, mid-infrared), and the CHARA array (visible and near infrared). As a remark, optical interferometry is not formally restricted to the visible domain, but includes the application of interferometric techniques from the blue to the mid-infrared wavelengths, for which the light is manipulated using optical mirrors or lenses.

Overview

Due to the diffraction laws of optics, the larger the telescope and the shorter the observing wavelength, the better the angular resolution (i.e., the smallest details on the sky that the telescope can distinguish). However, the cost of building a telescope increases rapidly with its size. Astronomical interferometry offers a relatively cost-effective way to achieve high angular resolution by using a cluster of comparatively small telescopes rather than a single, very expensive monolithic telescope. The light-collecting surface of a multi-aperture interferometer is naturally much smaller than that of a single aperture with the same diameter, thus limiting its sensitivity. In the optical-infrared domain, the Very Large Telescope Interferometer (VLTI) has recently achieved the first direct interferometric detections and resolved spectroscopy of giant [extrasolar planets](#). Future instruments installed in space have the potential to collect direct images and spectra of Earth-like

planets, as the absence of atmospheric turbulence permits very-high-contrast interferometric nulling observations (See “[► Nulling Interferometry](#)”).

The largest single-site radio interferometer is the Very Large Array (VLA, see Fig. 1), near Socorro, New Mexico, USA. Intercontinental interferometric observations were obtained with antennas spread over baselines of thousands of kilometers (Very Long Baseline Interferometry). Such extremely long-baseline observations are made possible in the radio domain by the fact that the amplitude of the electric field of the light can be recorded and recombined a posteriori, provided that accurate time signals are recorded with the data. This technique is generally not applicable in the optical. The international Atacama Large Millimeter Array (ALMA, see Fig. 2) is the largest radio interferometer at millimeter wavelengths, as well as one of the largest ground-based astronomical observatories ever built. Its 66 antennas, 7–12 m in diameter, can be positioned on baselines of 150 m–16 km,



Interferometry, Fig. 1 View of part of the antennas of the Very Large Array radio interferometer aligned on one of its three arms (New Mexico, USA)



Interferometry, Fig. 2 Antennas of the Atacama Large Millimeter Array (ALMA) interferometer, located at the Chajnantor plateau in northern Chile

Interferometry,

Fig. 3 The two 10-m Keck telescopes (Mauna Kea, Hawaii) were used together as an interferometer with a nulling capability for the observation of exozodiacal disks and exoplanets until 2012



allowing radio imaging observations down to an angular resolution of a few milliarcseconds.

In 2001, two large optical interferometers with collecting apertures of 8–10 m were inaugurated: the Keck Interferometer (KI, two 10-m telescopes, see Fig. 3) and the Very Large Telescope Interferometer (VLTI, four 8-m telescopes, see Fig. 4). These arrays include a variety of focal instruments that combine the light collected by the sub-pupils at different wavelengths in the near- and mid-infrared domains. The Keck Interferometer ceased operations in early 2012. The VLTI continues its development with a second generation of beam

combiners, GRAVITY and MATISSE that saw first light in 2015 and 2018, respectively.

Basic Methodology

The principles behind interferometry are founded on the wave properties of light. The superposition of light waves collected by the different sub-apertures results in an interference pattern whose properties are related to the structure of the observed object through the Zernike-Van Cittert theorem. The light waves that have the



Interferometry, Fig. 4 The Very Large Telescope Interferometer (Cerro Paranal, Chile) combines the light from four 8-m telescopes (in the background), or four 1.8-m telescopes (white spherical domes in the forefront)

same phase produce constructive interferences, while the waves that are out of phase produce destructive interferences. The accurate measurement of the interference pattern (i.e., the visibility and phase of the fringes) then gives access to the spatial structure of the observed object at very high angular resolution. In the optical, the sub-apertures are telescope mirrors, and the light is transported to the recombination point using a series of mirrors or optical fibers. One particular difficulty of interferometry is that the optical path length between the observed source and the recombination point must be equal for the light beams going through the different sub-apertures. The acceptable uncertainty on the path length is of the order of the wavelength. This constraint is particularly stringent for interferometers with long baselines operating in the visible, as path lengths of up to several hundred meters must be controlled with an accuracy of less than a micron.

Interferometric measurements can also be produced with a monolithic telescope by using the aperture masking technique. The principle of this technique is to insert a mask in the light beam collected by the telescope, punched with a number of holes arranged in a nonredundant pattern. This pattern is defined so that each baseline (the vector separation between two sub-apertures) is uniquely

defined on the mask. The focal image of the masked telescope is the same as that of a multi-aperture interferometer (i.e., is made of the superposition of fringe patterns). Compared to full-aperture imaging, aperture masking allows a more efficient recovery of the highest spatial frequencies (the finest details) observable by the telescope. This is achieved at the cost of a loss in sensitivity, since part of the telescope aperture is covered by the mask, and an increased complexity of the data analysis. The extremely large telescopes currently under development all employ segmented primary mirrors and are therefore similar in principle to multi-aperture Fizeau interferometers.

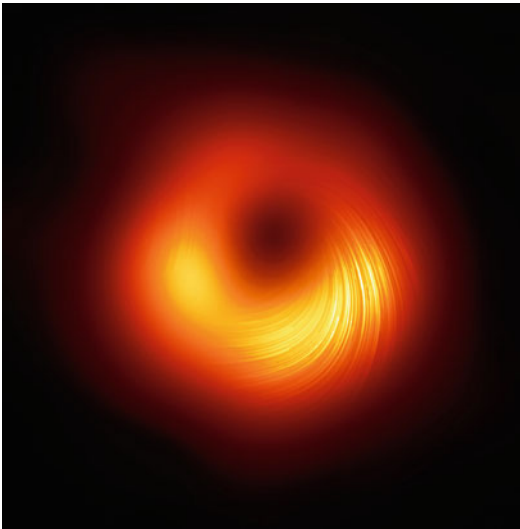
A variant of classical interferometry is called intensity interferometry. This technique uses two light detectors, typically either radio antennas or optical telescopes. Both detectors are pointed at the same astronomical source, and intensity measurements acquired at very high frequency are transmitted to a central correlator facility. The intensity interferometer measures interferometric visibilities like all other astronomical interferometers. These measurements can be used to measure, for instance, the angular diameter and limb darkening of stars. However, with intensity interferometers, aperture synthesis images are more

difficult to produce as the phase information of the fringes is not preserved. Novel approaches have been proposed to circumvent this difficulty and obtain interferometric images at visible wavelengths from intensity interferometry (e.g., Gori et al. 2021).

Key Research Findings

Radio interferometry was used successfully to image the vicinity of black holes and quasars, the surfaces of nearby stars, and to obtain high-precision astrometric measurements. Most remarkably, the combination of a number of millimeter wavelength telescopes (including ALMA) in the Event Horizon Telescope provided in 2019 an interferometric image of the accretion disk of the black hole at the core of the M87 galaxy. The analysis of the polarization properties of the collected light enabled the measurement of magnetic field in the disk (Fig. 5).

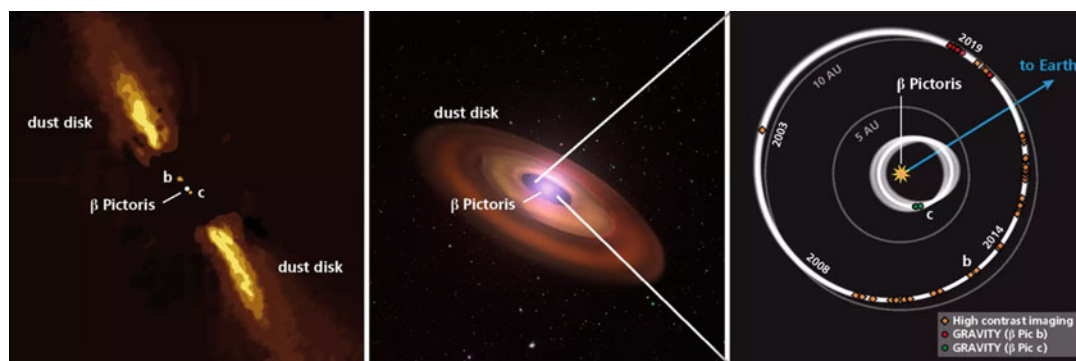
The position of quasars measured by radio interferometry is the basis of the definition of the International Celestial Reference Frame.



Interferometry, Fig. 5 Image of the disk surrounding the supermassive black hole of the M87 galaxy, obtained by the Event Horizon Telescope in 2019. The orientation of polarization is represented with the curved lines, tracing the magnetic field in the disk. (Credit: EHT Collaboration)

Historically, optical interferometry produced important results essentially in the stellar physics field. The first optical interferometric images of the surfaces and close environment of stars of various classes were obtained in the early 2010s, as well as high-resolution observations of a sample of active galactic nuclei in the near- and mid-infrared. The imaging capabilities of optical interferometers are progressing rapidly. However, they are traditionally used to constrain model parameters (e.g., stellar angular diameters, limb darkening coefficients, circumstellar environment of young and evolved stars, and binary orbits) rather than reconstruct *ab initio* interferometric images, due to their relatively small number of apertures compared to radio interferometers.

The dual field GRAVITY beam combiner at ESO's VLTI interferometer (GRAVITY Collaboration 2017) can measure differential astrometry of two targets located within 2–5 arcseconds (with the 8 m or 1.8 m telescopes, respectively) to an extreme accuracy of a few tens of microarcseconds. With this instrument, it is also possible to observe very faint targets close to brighter ones by integrating the fringe signal in one of the two channels of the interferometer, while using the other channel to compensate for the atmospheric turbulence using the bright object as reference. GRAVITY has been designed and successfully used to observe the immediate vicinity of the central supermassive black hole of our galaxy (Sgr A*) and measure the orbits of the neighboring stars. GRAVITY has also contributed to the exoplanet field by directly detecting, for the first time by interferometry, the giant exoplanet HR 8799e (GRAVITY Collaboration 2019) and the two giant exoplanets b and c orbiting in the Beta Pictoris system. These astrometric observations tightly constrain the orbital parameters and masses of the planets, and also provides their spectra with an unprecedented accuracy (Fig. 6). An upgrade of the GRAVITY instrument (the GRAVITY+ project) is expected between 2022 and 2024 to considerably improve the sensitivity and sky coverage of the instrument, enabling very high angular resolution observations of faint targets such as active galactic nuclei at high redshift or low mass exoplanets.



Interferometry, Fig. 6 The system of Beta Pictoris, whose planets b and c have been monitored using the VLTI/ GRAVITY interferometric instrument. (Credit: Axel Quetz/MPIA Graphics Department)

Future Directions

There exist several projects to install optical interferometers in space, where the environment is very stable and no atmospheric turbulence perturbation of the wave fronts is present. Apart from gravitational wave detectors (that use laser interferometry for metrology), the most advanced project for space interferometry is the Space Interferometry Mission (SIM) and its spin-off SIM-Lite, that were designed to obtain micro-arcsecond astrometric measurements in the narrow-angle regime. However, as of 2021, the development of interferometric astrometry in space is stopped. Such an extremely high accuracy permits the detection of the astrometric wobble induced on a star's position by the presence of orbiting planets, down to terrestrial masses. Other space projects include interferometric coronagraphs optimized for the observation of extrasolar planets, as well as ultraviolet and X-ray interferometers for stellar physics. The only operating interferometer presently in space is the Fine Guidance Sensor (FGS) of the Hubble Space Telescope. This three-aperture instrument is primarily employed to guide the telescope during scientific exposures, but has also produced important scientific results, such as the measurement of trigonometric parallaxes of nearby Cepheid variable stars.

New generations of interferometric instruments are specifically developed for high-contrast observation of the surroundings of nearby stars. The principle of these instruments is to recombine

the light from the target star in a destructive way: the in-phase light from the central star collected by one sub-aperture is cancelled by its superposition with 180° phase-delayed light from another sub-aperture. This technique, called nulling interferometry (the instrument being called a nuller) or alternatively dark fringe interferometry, can be understood as the interferometric version of the coronagraph. It is particularly promising for the observation of extrasolar planets and exozodiacal disks, as it provides simultaneously high-contrast and high-resolution observing capabilities (Defrère et al. 2022). An interferometric nuller was successfully operated on the Keck Interferometer (the KIN instrument) up to 2012, and projects exist for the development of an interferometric nuller in space.

Cross-References

- [Exoplanet, Detection, and Characterization](#)
- [Exozodiacal Light](#)
- [Nulling Interferometry](#)
- [Parallax](#)
- [Radio Astronomy](#)
- [VLBI](#)
- [VLT](#)

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Interior Degassing

Iris van Zelst and Caroline Brachmann
Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Keywords

Atmosphere · Crust · Volcanism · Mantle ·
Volatile elements · Water · Carbon · Nitrogen ·
Sulfur · Oxygen · Hydrogen · Carbon dioxide ·
Gas speciation

Synonyms

Interior outgassing

Definition

Interior degassing is the process of ► **volatile** elements, such as carbon, hydrogen, and oxygen, being released from the solid planetary body

(i.e., the ► **crust** and ► **mantle**), into the atmosphere. This occurs through volcanism and volatile escape through the lithosphere as a result of intrusive magmatism and is influenced by large-scale, global processes such as mantle convection and ► **plate tectonics**. An important aspect of interior degassing is the chemical speciation of the volatile elements where, e.g., hydrogen can be outgassed as water (H₂O) or dihydrogen (H₂). Hence, it plays a major role in (the evolution of) the composition of the atmosphere.

Overview

During planetary accretion, volatile elements such as ► **carbon** (C), ► **hydrogen** (H), ► **oxygen** (O), ► **nitrogen** (N), and ► **sulfur** (S; together forming the C-H-O-N-S elements) are entrapped in the solid planetary body. During the lifetime of a planet these volatiles are released to form the atmosphere of the planet in a process known as “interior degassing or outgassing”. The most common outgassed species in the C-H-O-N-S system are ► **water** (H₂O), ► **carbon dioxide** (CO₂), dihydrogen (H₂), ► **carbon monoxide** (CO), ► **methane** (CH₄), sulfur dioxide (SO₂), ► **hydrogen sulfide** (H₂S), disulfur (S₂), ► **ammonia** (NH₃), and ► **nitrogen** (N₂). Besides that, minor amounts of chlorine, fluorine, and ► **dioxygen** compounds may occur.

In order to outgas volatiles from the solid interior of a planet, rocks first need to be sufficiently heated and/or depressurized such that they melt. Volatile elements are then initially dissolved in the melt. The amount of outgassing of the different gases does not solely depend on the abundance of the volatile elements they are composed of, but also the prevailing conditions of the ► **magma** and the atmosphere such as pressure, temperature, and ► **redox state** (i.e., the availability of oxygen to form chemical compounds). The solubility of volatiles is mainly dependent on pressure (Parfitt and Wilson 2008). Hence, when magma rises and the pressure decreases, volatiles that were initially dissolved in the melt form gas bubbles. Different species have different solubilities, with, e.g., 0.5 wt% water degassing more efficiently at lower

pressures up to 35 bar. In contrast, 0.5 wt% carbon dioxide is efficiently outgassed up to 220 bar (Parfitt and Wilson 2008).

Temperature and redox state of the magma influence the speciation of the gases with H₂O, CO₂, SO₂, and N₂ occurring in a more oxidized system, and H₂, CO, H₂S, S₂, and NH₃ outgassing from reduced magmas (Oppenheimer et al. 2011; Li and Keppler 2014). Methane outgasses at very low temperatures (<600 °C) (Ortenzi et al. 2020).

When a magma ocean is present in the early stages of planetary formation, the large amounts of near-surface melt result in the outgassing of the first (usually large) atmosphere of a planet (Nikolaou et al. 2019; Lichtenberg et al. 2021).

At later stages of a planet's evolution, like the conditions of present-day Earth, the melting of rocks is limited to smaller, isolated pockets within the planet's solid mantle, at shallow depths. Then, there are two main processes by which the gases in the melt can reach the atmosphere in order to outgas the interior. Firstly, gases are released to the atmosphere during volcanic eruptions in a process called “volcanic degassing.” As a second mechanism, intrusive magmatism, where the magma does not reach the surface of the planet, can also result in degassing. In this case, the gases in the melt travel to the surface through cracks and pores in the overlying porous rocks.

On Earth, the outgassing of the interior is balanced by the active recycling of volatiles into the mantle and crust through ► [subduction](#) processes in a geodynamic cycle. On other planets that feature predominantly stagnant-lid regimes like ► [Mercury](#) or ► [Mars](#), this recycling is largely absent, leading to the gradual depletion of the interior of volatile elements (Foley and Driscoll 2016; Noack et al. 2017; Tosi et al. 2017).

The concentrations of C-H-O-N-S elements in the atmosphere and the specific chemical species in which they occur affect the surface temperature and pressure of a planet. In addition, the elements of the C-H-O-N-S system are important building blocks for the molecules of life (Seager et al. 2016). As interior degassing plays a large role in providing these volatiles to the atmosphere, it is an important process that needs to be taken into account when assessing planetary habitability.

Cross-References

- [Accretion](#)
- [Ammonia](#)
- [Carbon](#)
- [Carbon Dioxide](#)
- [Carbon Monoxide](#)
- [Crust](#)
- [Degassing](#)
- [Dinitrogen](#)
- [Dioxygen](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Habitability of the Solar System](#)
- [Hydrogen](#)
- [Hydrogen Sulfide](#)
- [Magma](#)
- [Magma Oceans](#)
- [Mantle](#)
- [Mantle Redox State](#)
- [Mantle Volatiles](#)
- [Mars](#)
- [Mercury](#)
- [Methane](#)
- [Nitrogen](#)
- [Oxygen \(Molecule\)](#)
- [Plate Tectonics](#)
- [Stagnant Lid Convection](#)
- [Subduction](#)
- [Sulfur](#)
- [Volatile](#)
- [Water](#)

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Interior Outgassing

► Interior Degassing

Interior Structure of Low-Mass Exoplanets

Philipp Baumeister and Nicola Tosi
Institute of Planetary Research, German
Aerospace Center Berlin, Berlin, Germany

Keywords

Exoplanet · Interior · Atmosphere ·
Equation of state · Terrestrial planet · Gas
giant · Mini-Neptune · Super-Earth

Definition

Extrasolar planets with relatively low masses (below $\sim 20\text{--}30 M_{\oplus}$) show a wide range of bulk

densities. This hints at a great compositional diversity, with planet classes that do not exist in the Solar System such as $\Rightarrow$ *Super-Earths* and $\Rightarrow$ *Mini-Neptunes* (Jontof-Hutter 2019; Spiegel et al. 2014). Models of the $\Rightarrow$ *interior structure* describe the hydrostatic and thermodynamic state of these planets. They provide radial distributions of density, pressure, temperature, and composition consistent with given mass and radius measurements. Due to the lack of observable planetary properties, interior structure models are often underconstrained and thus subject to large inherent degeneracies. Finding ways to break these degeneracies is a major goal in exoplanetary science.

Overview

In the $\Rightarrow$ *Solar System*, a wealth of information about the interiors of the planets is available from direct observations, space probes, and in situ measurements, which helps building a rather comprehensive picture of the internal structures of these bodies. Yet, all these observations are largely unavailable for exoplanets. Furthermore, so-called $\Rightarrow$ *Mini-Neptunes* and $\Rightarrow$ *Super-Earths* form two planetary classes with no equivalent in the Solar System. This poses a unique challenge in that many fundamental properties are difficult to constrain, and a definitive internal composition cannot be determined.

Owing to the wide diversity of observed exoplanets, a variety of computational models exists, from those designed to treat $\Rightarrow$ *gas giants*, where interior and atmosphere are closely interlinked, to those suited to describe $\Rightarrow$ *terrestrial planets* mainly consisting of iron and $\Rightarrow$ *silicate minerals* (rocks) (Perryman 2018).

Models aimed at characterizing the interior of low-mass exoplanets generally assume that the planet consists of layers with distinct physical and chemical properties (e.g., Sotin et al. 2007; Fortney et al. 2007; Valencia et al. 2007; Seager et al. 2007; Wagner et al. 2011; Zeng and Sasselov 2013). Metal and silicate rocks, ices, and gas are the three main compounds to form the bulk planet interior. In terrestrial (rocky) planets, the interior is dominated by rocky silicate $\Rightarrow$ *mantles* and

metal-rich $\rightarrow$ *cores*. Planets with large radii (above $\sim 1.6R_{\oplus}$, Rogers 2015) are instead likely to contain significant amounts of volatiles in the form of $\rightarrow$ *hydrogen-helium atmospheres* and heavier volatile species (“ices” such as H_2O and CH_4). The larger planets of this class are likely similar to Neptune and Uranus in terms of their interior structure ($\rightarrow$ *Mini-Neptunes*, see Nettelmann et al. 2011), whereas smaller planets could also be $\rightarrow$ *ocean planets* with rocky cores, but substantial amounts of water (Zeng et al. 2019).

More general models typically make no distinction between planet classes and treat the interior as composed of iron, rock, ice, and gas, permitting a wide range of possible internal structures to be addressed (e.g., Rogers and Seager 2010a; b; Dorn et al. 2017a).

The interior structure of a planet is governed by two main equations describing the mass distribution within a sphere and the condition of $\rightarrow$ *hydrostatic equilibrium*:

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2}$$

where m , P , and ρ are the mass, pressure, and density dependent on the radius r , and G is the gravitational constant. The link between density, pressure, temperature (T), and other state variables is given by a suitable $\rightarrow$ *equation of state* $\rho(r) = f(P(r), T(r))$.

Equations of state are commonly derived experimentally, and for more extreme conditions theoretical models and numerical ab initio calculations are employed (e.g., Baraffe et al. 2014a; b). For the treatment of the distribution of pressure and temperature within the atmosphere, dedicated models often substitute for the role of equations of state (e.g., Guillot 2010; Lopez and Fortney 2014).

It is often assumed that the temperature distribution within different interior layers follows an adiabatic gradient:

$$\frac{dT(r)}{dr} = \frac{\alpha(P, T)g(r)}{c_P(P, T)}T(r),$$

where α , g , and c_P are the thermal expansion coefficient, the gravitational acceleration, and the heat capacity, respectively. Processes such as radiogenic heating or viscous dissipation can lead to deviations from an adiabatic temperature profile (Bunge et al. 2001). While the temperature dependence typically only plays a secondary role in the silicate part of planetary interiors in terms of density, it plays a crucial role in the treatment of $\rightarrow$ *water-rich* and atmospheric layers (e.g., Thomas and Madhusudhan 2016).

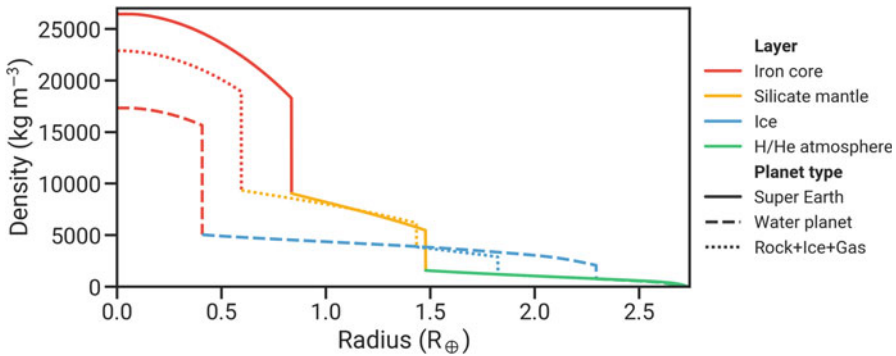
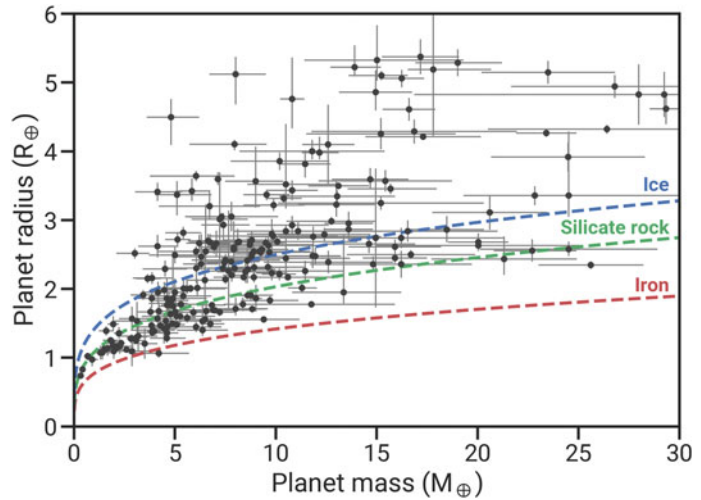
$\rightarrow$ *Transit* and $\rightarrow$ *radial velocity* observations of exoplanets allow the determination of the planetary mass and radius. Mass-radius diagrams (Fig. 1) give a first indication of what a planet’s interior may look like by comparing it to theoretical curves describing spherical bodies of homogeneous composition (Swift et al. 2011). A planet larger than one made of pure rock must contain some amount of lighter species such as water, or have an extended atmosphere. However, with only mass and radius, it is not possible to infer a unique interior structure. Instead, due to the problem being underconstrained, there exists a wide range of degenerate solutions with different radial mass distributions that fit given mass and radius equally well (Fig. 2). This is only exacerbated by mass and radius measurement uncertainties. Moreover, without extensive follow-up studies, for most exoplanets mass and radius will remain the only available measurements.

A number of approaches have been developed to treat and quantify the degeneracy of exoplanetary interiors, such as Bayesian inference models using Markov Chain Monte Carlo sampling (Rogers and Seager 2010a, b; Dorn et al. 2017a), or machine learning models (Baumeister et al. 2020).

Efforts are being made to find observable parameters which can break these degeneracies. Spectroscopic measurements of exoplanetary atmospheres ($\rightarrow$ *Atmospheric Retrieval for Exoplanets*) can give indications toward the existence of an atmosphere and its composition (e.g., Miller-Ricci et al. 2008). The stellar abundance of refractory elements such as Mg, Fe, and Si may help to constrain the mineralogy of an

Interior Structure of Low-Mass Exoplanets,

Fig. 1 Mass-radius diagram of exoplanets below $30 M_{\oplus}$. The dashed lines show the theoretical mass-radius relation for planets with homogeneous composition (pure iron, silicate rock, or water ice). (Exoplanet data is taken from exoplanet.eu (November 2021))



Interior Structure of Low-Mass Exoplanets,
Fig. 2 Three examples of qualitatively different interior structures which all fit the well-studied exoplanet GJ 1214 b ($8.17 \pm 0.43 M_{\oplus}, 2.742^{+0.050}_{-0.053} R_{\oplus}$ Cloutier et al. 2021). The mass and radius of GJ 1214 b could be explained in

terms of a Super-Earth (solid line) with an iron-rocky core and an extensive gas envelope, or a volatile-rich $\rightarrow$ ocean planet (dashed line), or some mixture of the two (dotted line). (See also Rogers and Seager (2007) and Nettelmann et al. (2011))

observed planet (e.g., Dorn et al. 2017b; Brugger et al. 2017; Hinkel and Unterborn 2018).

Cross-References

- 55 Cancri
- Abundances of Elements
- Atmosphere, Primitive Envelope
- Atmosphere, Structure
- Atmospheric Modeling, Gray Gas Model
- Atmospheric Modeling, Radiative-Convective Equilibrium
- Atmospheric Retrieval for Exoplanets
- Bulk Silicate Earth
- Condensation Sequence
- CoRoT 7b
- Differentiation, Planetary
- Exoplanet, Detection, and Characterization
- Habitable Planet, Characterization
- Hot Neptunes
- Mini-Neptunes
- Modelling Terrestrial Planetary Atmospheres
- Ocean Planet
- Planet Characterization: High-Resolution Spectroscopy

- Planet Formation
- Planetary Evolution
- Radiative Transfer (Atmospheres)
- Rheology, Planetary Interior
- TRAPPIST-1 system
- Water in the Solar System

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Interior Structure, Planetary

Tilman Spohn

International Space Science Institute, Bern,
Switzerland

Keywords

Core · Crust · Density · Mantle · Pressure ·
Temperature

Definition

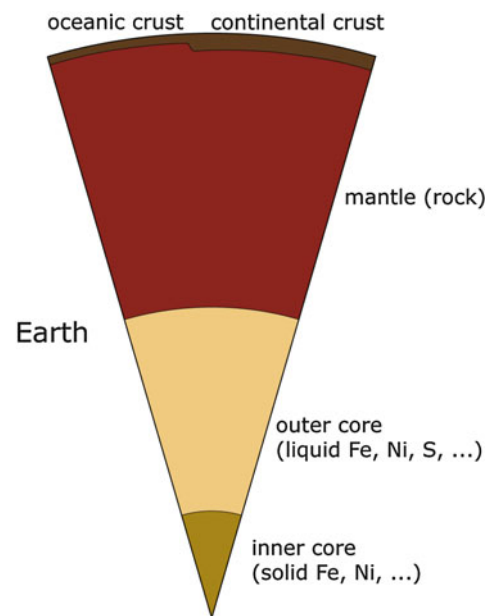
Models of the interior structure of a ► [planet](#) or ► [satellite](#) give the variations of thermodynamic state variables as functions of radius (starting at the center) or depth (starting at the surface). The thermodynamic state variables are pressure, temperature, density (or specific volume), and the concentration of chemical species. In many cases chemical layering is described in more specific terms as ► [crust](#), ► [mantle](#), and core or in shells described by characteristic elements, ► [minerals](#), and phases. In other circumstances shells are characterized by their rheological or transport properties such as the ► [lithosphere](#).

Overview

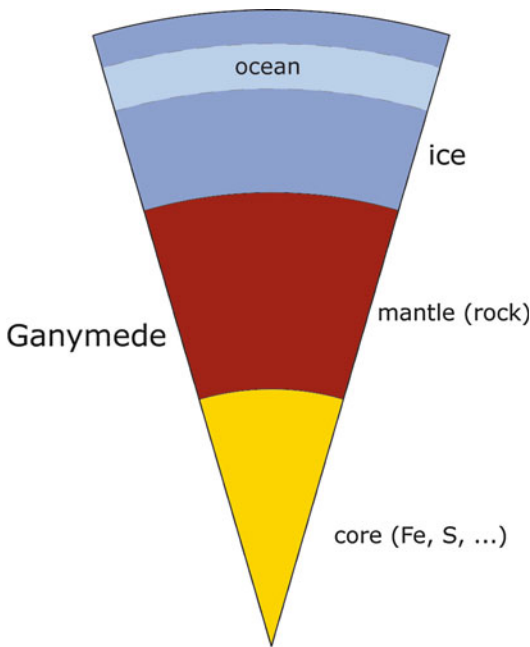
Knowledge of the interior structures of planets and satellites is a major prerequisite for understanding the evolution of planets and for models of how planets work. From a thermodynamic point of view, planets can be regarded as heat engines that convert thermal and gravitational

energy into mechanical work and ► [magnetic field](#) energy and evolve by differentiating, cooling, and contracting. The process of converting thermal or chemical energy into magnetic field energy is the ► [dynamo](#) process. The process that converts energy into mechanical work in ► [terrestrial planets](#) and satellites is associated with mantle convection and is discussed in the section on ► [heat transfer \(planetary\)](#). Mantle convection is the most important heat transfer mechanism in terrestrial planets and satellites. Convection is also the likely dominant heat transfer mechanism in the interiors of the ► [giant planets](#).

Most planets and satellites are thought to be differentiated with the density increasing toward the center (for a recent review on the interior structure of terrestrial planets, see, e.g., Sohl and Schubert 2015 and Sohl et al. 2009). In a terrestrial planet (compare Fig. 1), an Earth-like or rocky satellite such as the ► [Moon](#) or the Jovian satellite ► [Io](#), or a differentiated icy satellite such as ► [Europa](#) and ► [Ganymede](#) (compare Fig. 2), the central region is an iron-rich core. The core is the region where a planetary magnetic field may



Interior Structure, Planetary, Fig. 1 Interior structure of the Earth as a generic model for the interior structure of a terrestrial planet



Interior Structure, Planetary, Fig. 2 Interior structure of Ganymede as a generic model for a differentiated icy satellite

be generated by a dynamo. The core may be layered like in the Earth with a solid inner core and a liquid outer core. Growth of the inner core may release gravitational energy that may power the dynamo.

The core is overlain by the rocky [mantle](#), which, in turn, is overlain by the rocky, mostly basaltic [crust](#). The crust is the product of partial melting and [differentiation](#) of the mantle and is thought to have grown in thickness over time. The mantle and the crust may be chemically layered with discontinuities in density and other material properties. There may, in addition, be discontinuities caused by solid-state phase change boundaries. It is further possible that regions of the mantle are partially molten causing an asthenosphere.

The core radius of the [Earth](#) is very well known from the inversion of geophysical data to be 3485 km on average. The thickness of the crust is up to a few kilometers in oceanic regions and a few tens of kilometers in continental areas. [Venus's](#) interior structure is much less well known with a core radius of probably $0.5 R_P$,

where R_P is the planetary radius, and a basaltic crust of between 20 and 50 km average thickness.

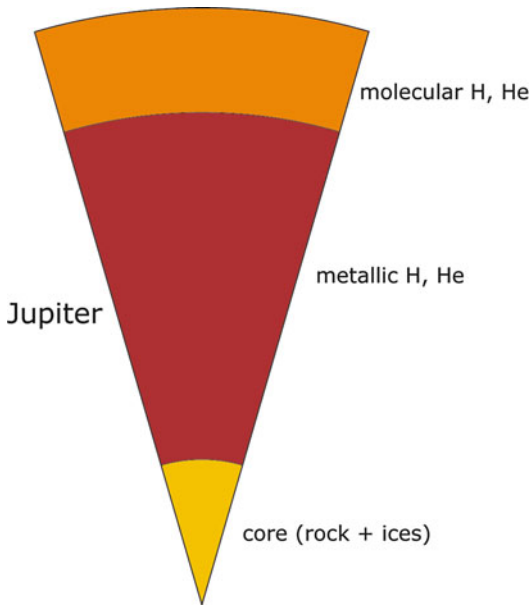
► [Mars's](#) core is also about $0.5 R_P$ in radius and its average crust thickness is between 30 and 80 km.

► [Mercury's](#) core radius is about $0.8 R_P$ and the crust thickness is estimated to be 20–50 km. Sohl et al. 2009 give a compilation of interior models of terrestrial planets, satellites, and icy satellites.

The above generic model also applies to the Moon whose iron-rich core should be small, comprising only 0.3 planetary radii R_P (see Weber et al. 2011) and Io with a core radius of about $0.5 R_P$. The average lunar crust thickness is 30–43 km and varies between 67 km underneath the farside and close to zero underneath the South Pole–Aitken basin (Wieczorek 2015). Other large differentiated satellites such as Ganymede and Europa may have ice shells above their [rock](#) mantles and iron-rich cores (see, e.g., Hussmann et al. 2007 and Sohl et al. 2009). The ice shell on Ganymede may be about 700–900 km thick, while on Europa a thickness of about 150 km is likely. The iron core radius for Ganymede varies between $0.2 R_P$ and $0.3 R_P$ depending on model details, while for Europa the core radius varies between $0.3 R_P$ and $0.6 R_P$. The Jovian satellite [Callisto](#) and the Saturnian satellite [Titan](#) are believed to be incompletely differentiated, with hundreds of kilometers thick ice shells overlying undifferentiated ice/rock/iron cores.

The giant planets [Jupiter](#) and [Saturn](#) have a molecular gaseous atmosphere underlain by a molecular layer of mostly hydrogen and helium (see Fig. 3 and, e.g., Guillot and Gautier 2015 for a review). At a pressure of 0.5 TPa, hydrogen becomes metallic, the transition pressure depending to some extent on temperature. In Jupiter this transition occurs at about $0.75 R_P$; in Saturn the transition occurs at $0.45 R_P$. At the center of these planets, there is a core with a mass of up to ten Earth masses and $0.2 R_P$ radius composed of heavier elements like iron, silicon, and magnesium but also of [water](#), [ammonia](#), and [methane](#). The latter are sometimes termed the planetary ices regardless of whether they are in a solid, liquid, or gaseous state.

The interiors of [Uranus](#) and [Neptune](#) are also thought of as layered, although the transitions



Interior Structure, Planetary, Fig. 3 Interior structure of Jupiter as a generic model for the interior structure of a giant planet

between the layers should be more gradual (see, e.g., Guillot and Gautier 2015). In these models, the outer layer extending down from 0.8 to 0.9 R_P consists of mostly molecular H and He but also of water, ammonia, and methane. The shell below is composed of ice plus little H and He, and there is a rock/iron plus ice core component of a few Earth masses.

Knowledge about the interior structure is derived by using the gravity and magnetic fields of a planet or satellite, its shape, and the propagation of elastic waves through the interior of the body. The latter is the basis of seismology, which is the best method provided one can have seismometers operating on the surface of a planet that is sufficiently seismically active. A similar method uses global oscillations of a giant planet and requires that the oscillations can be observed with telescopes or from satellites. In addition, an equation of state is needed to relate density to pressure and temperature. The parameters in the equation of state need to be determined through laboratory experiments. For the Earth gravity, magnetic and seismic data have been inverted to provide detailed models of the interior structure

that even include lateral variations of density and elastic properties.

The shape of a gravitational equipotential surface about a planet will reflect the distribution of mass in its interior (see, e.g., Wieczorek 2015 for a review). An equipotential surface can be traced by Doppler tracking of an orbiting spacecraft. For a rotating, rotationally symmetric model planet in ► [hydrostatic equilibrium](#), the shape of an equipotential surface will be a flattened spheroid of rotation (one of which will coincide with the physical surface, if in perfect equilibrium). The gravitational potential $V(r, \theta)$ can be expanded in a series of Legendre polynomials with

$$V(r, \theta) = G \frac{m}{r} \left(1 - \sum_{n=2}^{\infty} \left[\left(\frac{R_p}{r} \right)^n J_n P_n(\cos \theta) \right] \right) + \sum_{n=2}^{\infty} \sum_{m=1}^{\infty} \left(\frac{R_p}{r} \right)^n (C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) \times P_{nm}(\cos \theta),$$

where r is the distance to the observer from the center of the planet, θ is the planetocentric polar angle (measured from the pole such that $\theta = 90^\circ$ at the equator), λ is the longitude, G is the universal gravitational constant, m is the planet's mass, and R_p is the average radius. The J_n , C_{nm} , and S_{nm} are coefficients and $P_n(\cos \theta)$ and $P_{nm}(\cos \theta)$ are Legendre polynomials and associated Legendre polynomials, respectively (for an introduction to spherical harmonic functions for geophysical applications, see Stacey and Davis 2008). The coefficients J_n , C_{nm} , and S_{nm} measure the mass distribution in the planet. In particular,

$$mR^2 P_2 J_2 = C - A,$$

where C is the moment of inertia of the planet about the rotation axis and A is the average moment of inertia about an axis in the equatorial plane. The flattening f of the planet depends on J_2 and the rotation rate via

$$f = \frac{3}{2} J_2 + \frac{1}{2} \psi$$

with

$$\psi \equiv \frac{\omega^2 R_P^2}{Gm}.$$

For a constant density body $C/mR_P^2 = 0.4$, $J_2 = \frac{1}{2}\psi$ and $f = \frac{5}{4}\psi$. The latter is the maximum value of the flattening for a given value of ψ . With an increasing concentration of mass toward the center, C/mR_P^2 will become smaller than 0.4, and the flattening will decrease as well.

While the low-order terms are used to constrain the deep interior structure – degree 2 for the terrestrial and degrees 2–6 for the giant planets that are closer to hydrostatic equilibrium – high-order terms can be used to constrain density variations closer to the surface such as thickness variations of the planetary crust. It must be noted that any interpretation of the gravity field is fraught with nonuniqueness problems. The reason is that for the same gravitational force or potential at the location of an observer, mass can be traded against distance. Therefore, interior models based on the gravity field need additional constraints. For Mars the chemistry of the ► [SNC meteorites](#) together with the assumption of an overall chondritic composition of the planet has been used to constrain the core radius. The variation of the thickness of the Martian crust has been derived from the ► [Mars Global Surveyor](#) gravity data and the assumption of a constant crust density.

The magnetic field recorded at a planet or satellite provides additional constraints on the properties of the interior. A near-dipole-shaped magnetic field usually indicates a dynamo and that electrical currents are flowing deep in the interior. The closer the field geometry resembles a dipole, the deeper the source region of the field usually is to be expected. The Earth's magnetic field is understood as being produced in its outer core. The Earth's outer core must therefore be electrically conductive and fluid to allow for dynamo action. That the Earth's outer core is liquid is proven beyond any doubt by the absence of seismic shear waves propagating through that layer. Through analogy it is concluded that there must be at least a liquid outer

core shell in Mercury, the only other terrestrial planet that presently produces a magnetic field. The remnant magnetization of the Martian crust (see, e.g., Connerney et al. 2004) suggests that this planet once produced a magnetic field and that – again – at least an outer core layer was liquid. More evolved modeling of the planet suggests that the entire core is fluid, even today.

The magnetic fields of Jupiter and Saturn are thought to be generated in the metallic hydrogen shells, again allowing for electric currents to flow and dynamo action. The fields of Uranus and Neptune are thought to be produced in ionic oceans relatively close to their surfaces. This is consistent with the observation that their magnetic fields are rich in higher-order terms.

Periodically varying magnetic signals have been recorded at Europa, Ganymede, and Callisto by the ► [Galileo spacecraft](#). The orbits of all three satellites lie within the giant ► [magnetosphere](#) of Jupiter, and the signals at Europa and Callisto have been found to vary with their orbital period. Ganymede has a static dipole magnetic field superimposed with a weak time variable field. Hence, it has been concluded that there must be an electrically conducting layer in the interiors where a magnetic field can be induced as the satellites move through the global magnetic field of their primary. Since the satellites have ice shells and salty water is a good electric conductor, the magnetic signals have been taken as evidence of oceans in these satellites. Moreover, the static field of Ganymede suggests that it too has a partly fluid iron core.

Little is known about the interior structures of the many small satellites and ► [Kuiper belt](#) objects in the outer ► [solar system](#). Gravity data taken from ► [Cassini](#) flybys at the Saturnian satellites have been interpreted to suggest that ► [Rhea](#) may be differentiated. Interpretation of these data does rely on the assumption of equilibrium, which becomes even more questionable for small satellites.

The about 500 exoplanets detected to date suggest that there may be planets that differ from the ones found in our solar system. Even if the three chemical components of our planets,

gas (H, He), ice (H₂O, NH₃, CH₄), and rock/iron were universally representative, the relative proportions may differ. Thus there may be Super-Ganymedes or Sub-Jupiters (e.g., Stevenson 2004). ► [Transit](#) observations and ► [radial velocity](#) observations allow the masses and radii of these planets to be measured. With these and mass-radius relations, the interior structure of these planets can be estimated. Of course, these models do have even more severe uniqueness problems than models of the interior structure of the planets in our solar system. Major difficulties lie with the unknown equations of state of degenerate matter at extremely high pressures and temperatures and the unknown volumes of potential ultra high pressure phases of solids. The difficulties may be more severe for Super-Earths than for large gaseous planets, since Jupiter is close to the maximum radius of an H-He sphere anyway.

- [Mars Global Surveyor](#)
- [Mercury](#)
- [Methane](#)
- [Mineral](#)
- [Moon, The](#)
- [Neptune](#)
- [Planet](#)
- [Radial Velocity](#)
- [Rhea](#)
- [Rock](#)
- [Rotation Planet](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [SNC Meteorites](#)
- [System Solar Formation, Chronology of](#)
- [Terrestrial Planet](#)
- [Titan](#)
- [Transit](#)
- [Uranus](#)
- [Venus](#)
- [Water](#)

Cross-References

- [Ammonia](#)
- [Callisto](#)
- [Cassini](#)
- [Core, Planetary](#)
- [Crust](#)
- [Differentiation](#)
- [Dynamo, Planetary](#)
- [Earth](#)
- [Europa](#)
- [Exoplanets, Discovery](#)
- [Galileo Galilei](#)
- [Ganymede](#)
- [Giant Planets](#)
- [Heat Transfer, Planetary](#)
- [Hydrogen](#)
- [Hydrostatic Equilibrium](#)
- [Io](#)
- [Jupiter](#)
- [Kuiper Belt](#)
- [Magnetic Field](#)
- [Magnetosphere](#)
- [Mantle](#)
- [Mars](#)

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International Astrobiology Society

► [ISSOL](#)

International Astronautical Federation

► [IAF](#)

International Astronomical Union

► [IAU](#)

International Organization for Standardization

► [ISO \(Normative Organization\)](#)

International Society for the Study of the Origin of Life

► [ISSOL](#)

International Space Science Institute

► [ISSI](#)

International Space Station

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[ISS](#); [MKS](#) (Russian acronym)

Definition

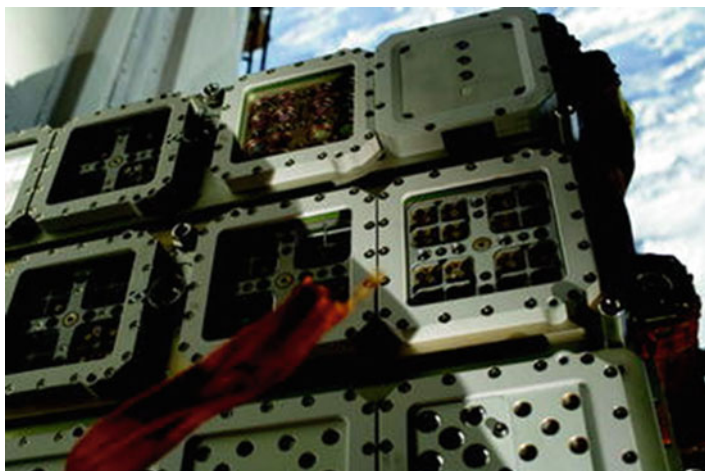
The International Space Station (ISS) is orbiting the Earth at an altitude between 335 and 460 km in an orbital plane inclined by 51.8°. The assembly of this internationally developed research facility began in 1998 with the Russian module Zarya, to be almost completed in 2011. The ISS is the result of the merging of former projects in an international effort including Russia, the United States of America, Europe, Japan, and Canada. The inter-governmental agreement is planning operations until at least 2020 and now extended to 2028. The orbital complex has been permanently occupied since November 2, 2000, and since May 2009 the ISS has the capability to host simultaneously up to six astronauts or cosmonauts. The astrobiology interest of the ISS includes functioning as the permanent base for long-lasting experiments. Scientists have the opportunity to expose directly to space radiations, for several months or more, samples in facilities attached to external payload supports as Bartolomeo on Columbus (European module), the external wall of Zarya (Figs. 1 and 2) (Russian core module), on the exposure facility of Kibo (Japanese Module).

The ISS was completed within around 10 years. It is composed of various pieces: trusses, arms, docking modules, solar panels, experimental modules, and so on. The main modules are: Zarya (Russia 1998), Zvezda (Russia, 2000), Destiny (USA, 2001), Harmony (2003, USA), Columbus (2008, ESA), Kibo -Japanese Experient Module- (2008, Japan), Tranquility (2010, USA), Leonardo (USA, 2011), Bigelow Expandable Activity Module (private-2016, USA), and Nauka (2021 Russia).

The servicing with cargo spacecrafts rely in 2022 on Dragon 2 (Space X), Cygnus (Northrop Grumman Innovation Systems); two commercial companies, and on the Russian Progress spacecraft. The former European ATV and Japanese HTV are no longer in use.

After the retirement of the NASA Shuttle in early 2011, for a while, the expeditions to the ISS were relying only upon the Russian Soyuz spacecraft. Since November 15th, 2020, Dragon

International Space Station, Fig. 1 The European instrument Expose R placed outside the Zarya module. (Photo ESA)



International Space Station, Fig. 2 The International Space Station with the docked European ATV in June 2008. (Photo NASA)



crewed capsules (Space X) are also able to carry 4 astronaut to the ISS. These spacecrafts are launched from the Kennedy Space Center in Florida (USA). Soyuz continues to launch crew from the Russian spaceport, Baikonur in Kazakhstan.

Cross-References

► [Expose](#)

International Union of Pure and Applied Chemistry

► [IUPAC](#)

Interplanetary Dust Particle

William M. Irvine
University of Massachusetts, Amherst, MA,
USA

Keywords

Dust, interplanetary · Zodiacal light ·
Gegenschein · Comet · Isotopic anomalies

Synonyms

[Brownlee particle](#); [IDP](#)

Definition

In addition to the Sun; the planets plus their satellites; smaller bodies including asteroids, comets, and meteoroids; and ► [Kuiper belt](#) objects, the roughly defined plane of the solar system contains gas and dust, referred to as the interplanetary medium. The dust grains are, naturally, called interplanetary dust particles, although that nomenclature (and particularly the abbreviation IDPs) is often used to designate particles of presumed interplanetary origin collected on the Earth, primarily in the stratosphere but also from Antarctic and Greenland ice. In the interplanetary medium, sunlight scattered by the dust is responsible for the phenomena of the zodiacal light (the “false morning” of poets, including Omar Khayyam) and the gegenschein (a very faint glow in the antisolar direction). In addition, interplanetary dust particles produce meteors (“shooting stars”) when they strike the Earth’s atmosphere and are incinerated as a result of friction.

Overview

Because these small particles tend over time to be either expelled from the solar system by radiation pressure or to fall into the Sun as a result of ► [Poynting-Robertson drag](#), there must be sources to replenish them. These sources are thought to be collisions among asteroids and Kuiper belt objects, and the release of particles trapped in cometary ices as the comets approach the Sun and the ices sublimate. These sources are confirmed by the ► [Infrared Astronomical Satellite](#) (IRAS) observations of dust bands in the asteroid belt and by meteor showers that are dynamically related to the orbits of comets.

The laboratory study of IDPs began in 1978 when D. Brownlee, using an ex-CIA high-altitude U2 spy plane, collected particles in the stratosphere whose extraterrestrial origin was confirmed by the presence of cosmic ray tracks and isotopic anomalies, particularly deuterium enhancements. Interplanetary particles with

diameters approximately in the range 1–100 μm are slowed sufficiently by friction to survive atmospheric entry; in fact, the Earth is estimated to accrete some 4×10^7 kg of such material annually, and this influx was certainly much greater early in the history of the solar system. The IDPs are composed predominantly of silicates, but there is also up to about 10% by mass of carbon, together with other minerals such as sulfides and magnetite. Evidence for solid carbonaceous compounds (such as ► [HCN polymers](#)) that progressively evaporate with decreasing solar distance in the interplanetary medium, at least in the 1.5–0.3 AU range, confirm that IDPs might have significantly contributed to the enrichment of the telluric planets in organics during the LHB (► [Late Heavy Bombardment](#)) epoch. The so-called anhydrous cluster IDPs appear to be the least processed of these particles reaching the Earth, and they are usually thought to have a cometary origin. Their highly porous structure increases their deceleration and heat transfer in planetary atmospheres, and thus favors the survival of carbonaceous compounds reaching the Earth. These presumably cometary IDPs seem to contain preserved interstellar material, including ► [GEMs](#) and organic material with significant isotopic anomalies relative to terrestrial values, for example, in D/H and $^{15}\text{N}/^{14}\text{N}$. IDPs have also been collected in space by the ► [Stardust](#) mission to comet 81P/Wild 2 and by experiments on the International Space Station. The analysis of the organic matter in IDPs is a very active subject of current research.

Cross-References

- [GEMs](#)
- [Infrared Astronomical Satellite](#)
- [International Space Station](#)
- [Kuiper Belt](#)
- [Late Heavy Bombardment](#)
- [Micrometeorites](#)
- [Poynting-Robertson Drag](#)
- [Stardust Mission](#)

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Interplanetary Transfer of Life

► [Panspermia](#)

Interstellar Chemical Processes

Stefanie N. Milam
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Keywords

Anion · Gas-phase chemistry · Grain chemistry · Ion-neutral reaction · Neutral-neutral reaction · Photochemistry · Shocks · Surface chemistry

Synonyms

[Interstellar chemistry](#)

Definition

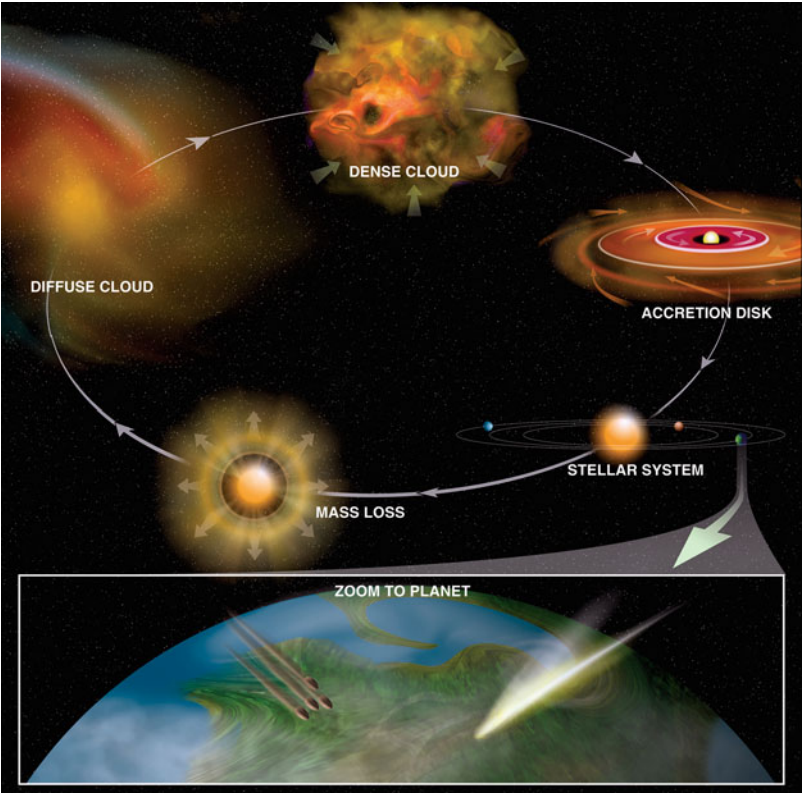
Interstellar chemical processes manipulate matter by either creating or destroying molecular material. These processes, acting on gas and dust, include heating, irradiation, shocks, and ► [cosmic ray](#) bombardment, as well as chemical reactions such as ► [ion-neutral](#) and ► [neutral-neutral](#) reactions and surface chemistry.

Overview

All interstellar material is cycled during various phases of stellar life (Fig. 1): from the diffuse medium, to the formation of a star and planetary system, to stellar death. The molecular complexity that arises during each phase can be attributed to the physical and chemical processes that dominate the various environments. In general, the chemistry found throughout the ► [interstellar medium](#) (ISM) involves low densities and extreme temperatures with respect to Earth and varies due to the range of physical conditions found in specific environments. These environments can be divided into distinct regions, based primarily on temperature and density (see Table 1).

In the diffuse interstellar medium (ISM), where densities ($1\text{--}100\text{ cm}^{-3}$) and temperatures ($\sim 100\text{ K}$) are low, the chemistry is dictated by the large flux of ultraviolet radiation coming from nearby stars. The growth of molecular complexity in these regions is minimal due to the limited stability of larger organic species in the presence of an ultraviolet (UV) field. Nonetheless, ► [polycyclic](#) aromatic hydrocarbons (PAHs) do thrive in these harsh conditions and are ubiquitous throughout the ISM (see review by Peeters). On the other hand, ► [dense clouds](#), the cold, dense molecular regions of the ISM, tend to have a much richer chemistry. In these clouds, external UV radiation is insignificant in the inner regions, and cosmic rays are the dominant radiation source creating ions and electrons, as well as providing a source of heating. Within these dark clouds, not only does gas-phase chemistry play a key role, but grains and surface chemistry are also important. The molecular inventory of each region helps

Interstellar Chemical Processes, Fig. 1 Cosmic cycle of interstellar material. (Image credit: Bill Saxton, NRAO/AUI/NSF)



Interstellar Chemical Processes, Table 1 ISM components

Region	Common name	Temperature (K)	Density (cm ⁻³)
Hot ionized medium (HIM)	Coronal gas	10 ⁶	0.003
Warm ionized medium (WIM)	Diffuse ionized gas	10 ⁴	>0.1
Warm neutral medium (WNM)	Intercloud H I	10 ³ –10 ⁴	0.1
Atomic cold neutral medium (CNM)	► Diffuse clouds	100	10–100
Molecular cold neutral medium (CNM)	Molecular clouds, dense clouds, dark clouds	0–50	10 ³ –10 ⁵
Hot molecular cores	Protostellar cores	100–300	>10 ⁶

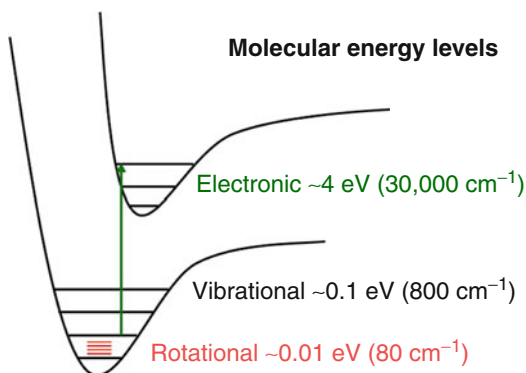
Adapted from Wooden et al. (2004). See ► [Interstellar Medium](#)

delineate the chemical processes that occur throughout the ISM and how they influence the cycle of material from stellar birth to death.

Basic Methodology

The methods by which interstellar processes are studied typically involve high-resolution spectral

line observations and maps of molecular emission that trace different regions and/or processes that may be occurring (e.g., Evans 1999). Molecules have rotational and vibrational motions coupled to electronic states, all of which are quantized. Molecular transitions are characterized by their energy as either electronic (~ 4 eV; 10^4 K), vibrational (~ 0.1 eV; 1000 K), or rotational (~ 0.01 eV; ≤ 100 K) (see Fig. 2). The visible and ultraviolet



Interstellar Chemical Processes, Fig. 2 Molecular energy levels (in electron volts and wavenumbers)

wavelengths are typically associated with electronic transitions, the infrared traces mostly vibrations, and millimeter/submillimeter wavelengths are dominated by rotational transitions. The large range of temperatures and densities throughout the ISM has led to the detection of numerous species at multiple wavelengths (see ► [Molecules in Space](#); or the CDMS web site at <http://www.astro.uni-koeln.de/cdms/molecules>). All of the ~150 identified interstellar species are just minor constituents of the molecular material, which is dominated by H₂ in dense regions. As can be noted from Table 1, most of the molecular material and the atomic cold neutral medium are traced by low-temperature, rotational transitions at millimeter/submillimeter wavelengths. Spectra obtained for simple, closed-shell (no unpaired electrons), neutral (no charge), diatomic species are simple, having one feature, or line, per rotational transition. This clean spectrum rapidly becomes quite complex when asymmetry, charge, and/or unpaired electrons are present. A detailed review of ► [spectroscopy](#) and analysis at these wavelengths can be found in Townes and Schawlow (1955). The following will be a brief overview of the various interstellar processes that occur in various regions of the ISM and are used to examine the chemistry and physical conditions.

Gas-Phase Chemistry

Matter expelled from stellar atmospheres, particularly older stars, is in the form of molecules and dust. Most species tend to not survive the harsh

conditions of the ISM and are photodissociated or fragmented into smaller molecules. Some species will remain in molecular form and become part of the natal material for new stars in diffuse and ► [molecular clouds](#). In molecular clouds, significant chemistry will occur due to the higher densities and protection from external destructive UV photons. Numerous chemical models have been developed to simulate the chemistry that occurs throughout stellar evolution (see Millar 2006 and references therein). Most of these models employ large chemical networks involving over 5000 reactions and hundreds of atoms and molecules. Most of these reactions are found in either the UMIST Database for Astrochemistry 06 database (Woodall et al. 2007; <http://www.udfa.net/>) or the Ohio State site (Herbst and Wakelam 2008; <http://www.physics.ohio-state.edu/~eric/research.html>).

The ISM is very diffuse with respect to terrestrial densities. Even the “dense” protostellar cores are rarified compared to the Earth’s atmosphere. In these low-density environments, typically only two-body collisions can occur. Temperatures vary from tens to thousands of Kelvin. UV and EUV radiation from nearby stars also plays a key role in the chemistry that occurs throughout the Galaxy.

Photochemistry

Regions within the ISM that have a strong UV field from nearby hot massive (OB) stars or the general interstellar radiation field are known as ► [photodissociation](#) regions (PDRs). The chemistry of PDRs is dominated by the formation and destruction of H₂ (Hollenbach and Tielens 1999). Electron recombination reactions combined with charge transfer help maintain the ionization balance (see Table 2). ► [Photoionization](#) and photodissociation drive additional chemistry. The extent of chemistry that may occur in these objects depends on the gas density and pressure, intensity of the incident radiation field, dust scattering, and elemental abundances (Sternberg and Dalgarno 1995).

PDRs have distinguishable molecular regions, dependent on the ► [optical depth](#) of the source from the radiation field. The most exposed region contains atomic hydrogen, helium, oxygen, and ionized carbon and generally a higher temperature

Interstellar Chemical Processes, Table 2 Reaction categories

Reaction	Example
Ion-neutral	$\text{H}_3^+ + \text{O} \rightarrow \text{H}_2\text{O}^+ + \text{H}$
Neutral-neutral	$\text{OH} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{H}$
Photoionization	$\text{H}_2\text{O} + h\nu \rightarrow \text{H}_2\text{O}^+ + e^-$
Photodissociation	$\text{H}_2\text{O} + h\nu \rightarrow \text{OH} + \text{H}$
Photodetachment	$\text{C}_6\text{H}^- + h\nu \rightarrow \text{C}_6\text{H} + e^-$
Radiative association	$\text{H}_2 + \text{S}^+ \rightarrow \text{H}_2\text{S}^+ + h\nu$
Dissociative recombination	$\text{H}_3\text{O}^+ + e^- \rightarrow \text{H}_2\text{O} + \text{H}$
Associative detachment	$\text{C}_6\text{H}^- + \text{H} \rightarrow \text{C}_6\text{H}_2 + e^-$

Adapted from Bergin (2009). Rates for reactions can be found on the UMIST database (<http://www.udfa.net/>) by Woodall et al. (2007). $h\nu$ represents a photon

(~100–1000 K). The next region is defined by the formation of molecular hydrogen (H_2), but carbon is still in its ionized form. In more shielded regions, carbon is converted into the molecular form of CO, and temperatures are lowered (~10–100 K) due to rotational emission from this molecule.

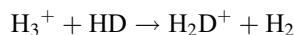
Photochemistry also plays a key role on ► [interstellar grains and ices](#). This is briefly discussed below.

Ion-Neutral Chemistry

Interstellar chemistry is highly influenced by the low temperatures, which require exothermic reactions, and the low densities that restrict these reactions to mostly two bodies. Reactions that involve ions, either positively or negatively charged species, typically meet the exothermic requirement and tend to dominate interstellar gas-phase chemistry (e.g., Herbst and Klemperer 1973). The formation of positive ions in the ISM is highly dependent on ► [cosmic ray](#) (CR) bombardment. Ionization of H_2 , via this process, to produce H_3^+ drives most ion-neutral chemistry in dense regions, leading to a variety of complex ions (Bergin 2009). These newly formed ions then typically undergo dissociative recombination (see Table 2) to form less protonated neutral fragments. Radiative association with H_2 does occur, though these reactions tend to be much slower (Herbst and van Dishoeck 2009).

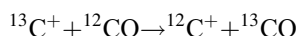
At low temperatures, ► [ion-neutral reactions](#) may also influence interstellar isotope enrichments,

known as fractionation, due to small differences in the zero-point vibration energies. This is most commonly observed via the deuterium exchange reaction with H_3^+ , where HD is favored over H_2 :



H_2D^+ will then fractionate other species by deuterium transfer reactions.

Other isotope exchange reactions, mostly ion neutral, are also quite significant in the ISM and can enhance abundance ratios to extreme values. These mechanisms are typically of the form



The reverse reaction barely proceeds at low temperatures, thereby enhancing one isotopologue, ^{13}CO in this case, in cold regions (e.g., Langer et al. 1984).

Neutral-Neutral Chemistry

The interaction between two uncharged species, or ► [neutral-neutral reactions](#), also plays a role in interstellar chemistry. These reactions are typically endothermic with high activation barriers for the interaction between two nonradicals (species bearing no unpaired electrons). These reactions are insignificant in cold, diffuse interstellar chemistry. However, the presence of a radical or an atom can significantly lower the barrier, and such reactions then become important to the formation and destruction of molecules (Smith et al. 2004). Reactions involving radicals still have a limited number of experimental studies, though a few have been tested at low temperatures and have proven the current theories (Smith et al. 2006; Sabbah et al. 2007; review by Smith).

Anions

The recent discovery of ► [anions](#), negatively charged species, in the ISM and in circumstellar envelopes has expanded the gas-phase molecular processes typically considered in these environments. The formation of these negative ions is by radiative association of an electron to a neutral parent species, which is fairly efficient for precursors with large electron affinities (Herbst and

Osamura 2008), or through dissociative recombination of a neutral and electron. Anions are considered to be readily destroyed by three mechanisms: associative detachment, ion-neutral reactions, and photodetachment (Table 2 and Herbst and van Dishoeck 2009).

Recently, models of interstellar chemistry have incorporated anion chemistry and have found consistency with observed abundances in the ISM (Millar et al. 2007). These studies have verified the enhanced abundances of larger (long-chain) anions compared to their shorter counterparts. This is due to the radiative association rate increase with the number of atoms (Roueff and Herbst 2009). However, these processes have only limited experimental data.

Shocks

The interstellar plasma is highly compressible, and wave motions can easily exceed characteristic signal speeds leading to the formation of either hydrodynamic or magnetohydrodynamic (MHD) shocks, depending on the magnetic field strength. The former have been classified as J-type (jump), or J-shocks, in which physical flow variables (e.g., density and temperature) undergo a discontinuous jump at the shock front. The latter case gives rise, in weakly ionized plasma, to C-shocks where the neutral and (ion-electron) plasma components behave as individual fluids and in which the flow variables are continuous (see ► [Shock, Interstellar](#)).

The principal chemical effects in shocked gas arise from the elevated gas temperatures. Temperatures in the range ~ 1000 – 4000 K can drive endothermic reactions and exothermic processes possessing activation-energy barriers. In multi-fluid MHD C-shocks, the relative streaming motion between the ion-electron plasma and the neutral fluid imparts additional energy into endoergic ion-molecule reactions.

Shock chemistry thus opens up molecular formation and destruction pathways that are not accessible in cold pre-shock gas leading, for example, to high abundances of sulfur-bearing molecules. Particularly important are reactions with H_2 , as in the reaction sequence that converts oxygen atoms into hydroxyl and then into water

molecules in shock waves around newly formed stars. Apart from allowing new high-temperature pathways for two-body molecular chemistry in the post-shock gas, strong shocks produce a UV radiation field that can initiate photochemistry both upstream and downstream of the shock front.

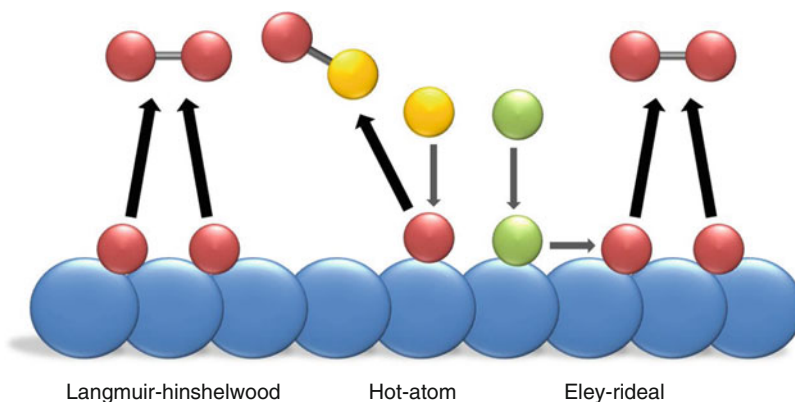
An important chemical process involving interstellar shock waves is dust processing. Refractory dust particles coated by molecular ices can be efficiently sputtered by high-energy collisions with gaseous atoms and molecules. This leads to the removal of the icy mantles and consequently high abundances of the constituent molecules in the gas (e.g., methanol). At higher shock speeds, the refractory core itself is sputtered, and this is the origin of the pronounced ► [SiO](#) emission observed in the outflows and winds from young protostars.

Surface Chemistry

Dust and grains formed in the outflows of evolved stars are dispersed throughout the ISM. At low temperatures, atoms and small molecules will collide with and/or adhere to the surface of these grains, forming an ice layer. The formation of some molecules on the surfaces of grains, particularly hydrogenated species that are subsequently ejected into the gas phase, is a significant process for interstellar chemistry (van Dishoeck and Blake 1998). There are three major theories explaining surface reactions in interstellar grains: ► [Langmuir-Hinshelwood](#), hot atom, and ► [Eley-Rideal](#) (Fig. 3). Small molecules or atoms will accrete onto a binding site of a molecular surface with some amount of efficiency. They can then react with an atom or a molecule already on the grain, and the product can desorb by either thermal evaporation (sublimation) or various other nonthermal processes (Herbst and van Dishoeck 2009).

Such gas-grain processes dominate the formation of molecular hydrogen (H_2), which is not efficiently formed by two-body collisions in the gas. However, due to our limited knowledge of the composition and structure of interstellar grains, the exact formation mechanism of H_2 is not understood, regardless of numerous theoretical and experimental studies (e.g., Cazaux and Tielens

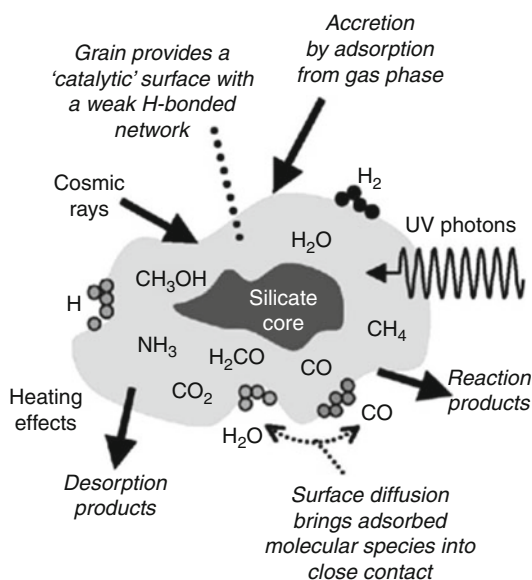
Interstellar Chemical Processes, Fig. 3 Grain-surface reactions mechanisms



2002, 2004, 2010; Habart et al. 2004; Pirronello et al. 1997, 1999, among others). Surface processes are also considered to be the dominant method for hydrogenation of C, O, N, and S forming CH_4 , H_2O , NH_3 , and H_2S , respectively (Wooden et al. 2004). CO also follows the same process once accreted onto a surface to produce CH_3OH (Charnley et al. 1997).

Radiation Effects

Icy grain mantles are observed throughout the ISM and are subjected to ultraviolet radiation, cosmic rays, and temperature variations that will alter the surface composition (e.g., Bernstein et al. 1995; Moore and Hudson 1998). Such effects as amorphization, formation of residues, ► **sputtering**, and surface chemistry are produced (Hudson and Moore 2001). Most observed interstellar ices are composed of H_2O , CH_3OH , NH_3 , CO, and CO_2 though they likely bear other minor constituents not detectable at trace concentrations beneath the strong infrared bands of the simple species (e.g., Gibb et al. 2000). These simple ice mixtures may then be exposed to external radiation (UV photons or cosmic rays), which will either sputter simple species from the mantle or stimulate molecular reactions to occur, and products will desorb (Fig. 4; see ► **Photodesorption**). Photolysis of interstellar ices will produce radicals and ions that react on the surface as well as during heating events. Numerous experiments have been conducted to gain further understanding of these reactions upon exposure to UV photons and H^+ irradiation (radiolysis). Particular focus has been



Interstellar Chemical Processes, Fig. 4 Illustration of the makeup of an icy dust grain in the ISM and the typical energetic processes to which it is exposed. (From Fraser et al. 2002)

toward the hydrogenation reactions of CO ices, typically mixed with H_2O , in forming CH_3OH in observed quantities (e.g., d'Hendecourt et al. 1986; Watanabe et al. 2003; Hudson and Moore 1999). However, these experimental yields are not fully consistent with observed abundances in the ISM.

Ice-grain photolysis chemistry has received much attention for its astrobiological implications. Multiple studies have been conducted on the formation of prebiotic species including

amino acids, nucleobases, amphiphiles, etc. (e.g., Bernstein et al. 2002; Nuevo et al. 2009; Dworkin et al. 2001). These studies suggest that prebiotic compounds are readily produced by energetic processing of interstellar ices and may therefore be ubiquitous throughout the ISM.

Cross-References

- Abundances
- Chemical Reaction Network
- Dense Cloud
- Dense Core
- Diffuse Cloud
- Dust Cloud, Interstellar
- Electron Dissociative Recombination
- Electron Radiative Recombination
- Eley-Rideal Mechanism
- Gas-Grain Chemistry
- Interstellar Medium
- Isotopic Fractionation (Interstellar Medium)
- Langmuir-Hinshelwood Mechanism
- Molecular Cloud
- Molecular Depletion
- Molecules in Space
- Photochemistry
- Photodesorption
- Photodissociation
- Photodissociation Region
- Photoionization
- Polycyclic Aromatic Hydrocarbon
- Radio Astronomy
- Shock, Interstellar
- Spectroscopy

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Interstellar Chemistry

- [Interstellar Chemical Processes](#)

Interstellar Cloud

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

The gas and dust in the ► [interstellar medium](#) are distributed in a somewhat clumpy manner, with denser regions referred to as interstellar clouds. The least dense of these are called ► [diffuse clouds](#) or HI (atomic hydrogen) clouds, while denser regions are, naturally, called ► [dense clouds](#) or ► [molecular clouds](#).

Cross-References

- [Dense Cloud](#)
- [Diffuse Cloud](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

Interstellar Dust

Douglas Whittet

Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY, USA

Keywords

Absorption · Astrochemistry · Chemical reactions · Infrared radiation · Interstellar medium · Polarization · Scattering · Solid particles · Substrate

Synonyms

[Cosmic dust](#); [Interstellar grains](#); [Interstellar particles](#)

Definition

Interstellar dust consists of small solid particles with sizes in the nanometer to micrometer range, accounting for approximately 1% of the total mass of the ► [interstellar medium](#). The particles are generally thought to be composed of a mixture of silicates and solid carbon (amorphous or graphitic carbon, aliphatic or aromatic hydrocarbons, and possibly kerogen-like organic material). They are responsible for the extinction and polarization of starlight and for ► [scattering](#) that produces ► [reflection nebulae](#) around dust-embedded stars; they also act as efficient radiators in the infrared, providing an important cooling mechanism for interstellar clouds and protostellar envelopes. The surfaces of dust grains provide a substrate for important chemical surface reactions.

History

The earliest evidence for the presence of dust in the interstellar medium was provided in the late nineteenth and early twentieth centuries by photographic images of dark nebulae, such as those reported by E. E. Barnard in his *Atlas of the Milky Way*, and by studies of the distribution and colors of stars by Wilhelm Struve, Jacobus Kapteyn, Robert Trumpler, and others (see Whittet 2022 for a review). It was found that the apparent number of stars per unit volume of space shows an anomalous decline with distance from the Sun unless it is assumed that starlight is dimmed by extinction in proportion to the distance traveled. The dust was also shown to redden starlight. Much subsequent work in the mid-twentieth century on the optical properties of the dust was motivated by the desire to correct data for its presence rather than by an intrinsic interest in the phenomenon. In more recent times, dust has been recognized as a vital and active ingredient of the interstellar medium and as a primary carrier of the elements needed to make planets and life in solar systems.

Overview

Studies of interstellar dust are aimed at understanding its role in physical and chemical processes that are of great importance in astrophysics, astrochemistry, and astrobiology. Dust is a vital ingredient of the molecular universe: It provides the raw materials for the origins of planets and compounds essential to the origins of planetary life. Techniques used to investigate its properties include telescopic observations across the electromagnetic spectrum, mathematical modeling, and laboratory studies of primitive solar-system materials and interstellar analogs.

Basic Methodology

The study of interstellar dust involves astronomical observation over a wide range of wavelength, interpreted with the aid of mathematical modeling and laboratory data (e.g., Mathis 1996; Draine 2003; Witt et al. 2004; Whittet 2022). The primary observational phenomena arising from dust are extinction, polarization, and infrared emission. Extinction is the combination of two physical phenomena: absorption (whereby photons are removed from a transmitted beam and their energy is converted to internal kinetic energy of the particle) and scattering (whereby photons are deflected from the transmitted beam). Scattering is primarily responsible for the reddening of starlight by selective removal of blue light from the transmitted beam, and scattered light is observed directly as bluish reflection nebulae in the vicinity of dust-embedded stars and as a weak background (the diffuse galactic light). The absorptive component of extinction may produce discrete spectral features, including a broad, strong absorption “bump” centered at 217 nm in the ultraviolet, and various features associated with vibrational modes of solids in the infrared. For grains in thermal equilibrium, the balance of energy absorbed at shorter wavelengths is reemitted in the mid-to-far infrared. The spectral energy distribution of this emission provides basic information on the temperature and optical properties of the

dust grains. The intensity of the emission also provides a means of estimating the total mass of an interstellar cloud or prestellar core. The smallest (nano-sized) interstellar particles undergo substantial transient heating on absorption of individual energetic photons, causing them to exhibit both line and continuum emission in the near-to-mid infrared. The interaction of dust with radiation also results in polarization. This is observed in starlight, in scattered radiation produced by reflection nebulae, and in infrared radiation emitted by the dust. Polarization phenomena are generally attributed to nonspherical (flattened or elongated) particles that are partially aligned by the presence of ► [magnetic fields](#). Other methods used to study interstellar dust include gas-phase abundance measurements for chemical elements that may be adsorbed onto dust (Whittet 2010, 2022) and laboratory investigations of presolar grains in primitive meteorites (Nittler and Ciesla 2016).

Key Research Findings

The efficiency of the interaction between radiation and a solid particle is optimized when the dimensions of the particle are of the same order as the wavelength of the radiation. Because of this, spectral variations in interstellar extinction and polarization are highly sensitive to particle size. The observations show that particles with dimensions in the nanometer to micrometer range are present in the interstellar medium. Small particles greatly outnumber larger ones (the number of particles in a given size interval varies approximately with size to the power -3.5), but the larger particles nevertheless contain the bulk of the total mass. Dust has been shown to contain virtually all of the interstellar endowment of the abundant planet-building chemical elements Mg, Si, and Fe, together with substantial fractions of the key life elements C and O. In low-density (“diffuse”) regions of interstellar space, the dust is composed primarily of amorphous, anhydrous silicates such as olivine and pyroxene, and of carbon in various forms (amorphous or partially graphitized carbon,

aliphatic or aromatic hydrocarbons, and possibly kerogen-like organic refractory matter). The smallest particles include a variety of ► [polycyclic aromatic hydrocarbons](#) responsible for a characteristic family of spectral emission lines in the infrared (Tielens 2008). The grains exchange material with the interstellar gas: Gas-phase atoms and molecules become attached to the surfaces of the grains and may react there to form new molecules, including ices, which are widely observed in lines of sight that intercept relatively dense molecular clouds. Reactions on the surfaces of dust grains provide the only viable route to formation of H_2 , the most abundant interstellar molecule. The grains are destroyed on timescales of a few 100 million years by energetic shock waves that permeate interstellar space as the result of supernova explosions.

The composition and evolution of interstellar dust in molecular clouds is of particular importance to astrobiology because the dust acts as both a carrier of key chemical elements needed to form planets and life and a crucible for chemical evolution of those elements (Whittet 2017, 2022). Catalytic surface reactions on dust are effective sources of molecules such as H_2O , NH_3 , CH_4 , CH_3OH , $HCOOH$, and H_2CO that are produced much less efficiently by gas-phase reactions. These relatively simple molecules are subsequently processed into more complex prebiotic compounds in regions of star formation. It is not yet clear to what extent such molecules survive the formation of new solar systems such as our own, to become incorporated into planetesimals and delivered to planetary surfaces. However, analyses of the isotopic compositions of meteorites and interplanetary dust particles (including cometary samples returned by the Stardust Mission) indicate that they contain material of exotic (presolar) origin. The high deuterium content of some organic compounds in meteorites is consistent with an origin at cryogenic temperatures in interstellar clouds.

Interstellar dust plays a key role in the physical process of star formation for sunlike stars. Stars are born in dense cores within molecular clouds at initial temperatures of order 10 K. As a

► [protostar](#) begins to collapse, the release of gravitational potential energy causes it to become warmer, and the resulting thermodynamic pressure would halt the contraction in the absence of a mechanism to dissipate heat. Dust grains provide such a mechanism: They are warmed by collisions with the gas and dissipate heat by radiating at far-infrared wavelengths, allowing the collapse to continue.

The radiation field that permeates a region of active star formation is regulated by the presence of dust. The dust attenuates energetic radiation, providing shielded environments in which complex molecules can survive. Warm regions (hot cores and corinos) in which sublimated ice products interact with molecules already present in the gas promote the formation of complex organic molecules (Herbst and van Dishoeck 2009). Modern observational facilities such as the Atacama Large Millimeter/submillimeter Array enable the distribution of these molecules to be studied in protoplanetary disks around young sunlike stars. This interaction of dust and radiation can also lead to the production of significant levels of circular polarization in regions containing luminous protostars, typically as the result of scattering by aligned grains. It has been proposed that ► [photochemistry](#) driven by circularly polarized radiation of a given handedness may lead to chiral selectivity and might explain the observed excess of L-enantiomers in amino acids extracted from carbonaceous meteorites in our solar system (see Whittet 2017 for a review).

Future Directions

Important questions concerning the nature and evolution of interstellar dust and its relevance to astrobiology remain to be answered. Two key projects are summarized here.

The life cycle of dust. Refractory dust grains composed of silicates or carbon are formed by condensation in the ejecta of dying stars such as red giants, red supergiants, and ► [supernovae](#). The grains may undergo growth in the interstellar medium by coagulation or mantle deposition, and

they may be cycled in and out of star-forming regions or destroyed by shocks. The quantitative details of these processes are not yet well understood. Estimates suggest that dust is destroyed more rapidly than it is replenished by stellar ejecta, implying that the bulk of the solid material is formed in the interstellar medium itself (Jones and Nuth 2011). This is facile for ► [interstellar ices](#), which readily condense (and survive) within the confines of molecular clouds, but an interstellar origin is problematical for the refractory dust that persists in harsher environments. The uptake of elemental oxygen into the dust material is also poorly understood, suggesting the existence of a previously unrecognized reservoir such as O-rich carbonaceous solids or ice particles much larger than those typically assumed in grain models (Whittet 2010, 2022). New observations are needed to test the hypothesis that organic refractory matter, formed by energetic processing of the ices in regions of active star formation, is a significant constituent of dust in the general interstellar medium. Future observations of greater sensitivity will be needed, facilitated by the availability of the James Webb Space Telescope, together with new laboratory work on the spectra of analogue materials.

The interstellar endowment of protoplanetary disks. Models for the origin of primitive bodies such as ► [comets](#) and icy planetesimals in our solar system span the range from simple assemblages of interstellar dust and ices to material that has been almost completely reprocessed and recondensed in the solar nebula. Whether interstellar matter has any direct influence on the inventory of life-relevant molecules delivered to planetary surfaces thus remains an open question. Progress toward an answer to this question is likely to result from integration of research activities in several areas: These include astronomical observations of ► [protoplanetary disks](#) around sunlike stars and of comets in our solar system, mathematical modeling of processes in protoplanetary disks, and laboratory analyses of available samples of primitive solar system material, including ► [carbonaceous chondrites](#), interplanetary dust particles, and stardust samples.

Cross-References

- Absorption Spectroscopy
- Alignment of Dust Grains
- Carbonaceous Chondrite
- Coagulation, Interstellar Dust Grains
- Comet
- Dust Cloud, Interstellar
- Extinction, Interstellar or Atmospheric
- Interplanetary Dust Particle
- Interstellar Chemical Processes
- Interstellar Ices
- Interstellar Medium
- Kerogen
- Magnetic Field
- Molecular Cloud
- Molecules in Space
- Photochemistry
- Polarized Light and Homochirality
- Polycyclic Aromatic Hydrocarbon
- Protoplanetary Disk
- Protostars
- Protostellar Envelope
- Reddening, Interstellar
- Reflection Nebula
- Refractory Organic Polymer
- Scattering
- Shock, Interstellar
- Silicate Minerals
- Star Formation, Observations
- Stardust Mission
- Supernova

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Interstellar Dust Spectroscopy

Karine Demyk

Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, 9 Av. du Colonel Roche, 31028 Toulouse Cedex 4, France

Definition

Spectroscopy is an essential tool to investigate the composition and structure of cosmic matter. To interpret astronomical observations, laboratory astrophysics experiments are built and dedicated to the measurement of the spectroscopic properties of interstellar dust analogs such as silicate and carbonaceous dust and ices. Interstellar dust spectroscopy includes electronic, vibrational, and rotational spectroscopy from the X-ray to the millimeter domain.

Overview

Spectroscopic observations of astrophysical environments have revealed number of spectral features attributed to cosmic dust. These features provide information on the composition and structure of the dust components: silicates, carbonaceous dust, and ices (Demyk 2011). In astrophysical environments, interstellar dust interacts with radiation through absorption and scattering. The interpretation and modeling of

astronomical and planetary observations, which allow to probe the chemical and physical conditions and evolution of the medium, rely on the knowledge of the optical properties of analogs of cosmic dust and of their absorption and scattering cross sections on the broadest spectral range (Andersen et al. 2013).

Measuring these properties is a broad and active field of research motivated by the development of observatories more and more performant in terms of sensitivity, angular and spectral resolution on wider and wider spectral domain (among which ISO, Spitzer, instruments on the VLT and Keck telescopes and in the future JWST, METIS on the ELT, Athena. . .). State-of-the-art experiments have been developed to measure the spectroscopic properties of interstellar dust analogs in conditions as close as possible to the astrophysical and planetary conditions in terms of temperature, pressure, and in terms of sample size, structure, and morphology (Henning and Mutschke 2010; Jäger et al. 2009). To cover the broadest spectral range some of them may be coupled to large infrastructures such as synchrotron sources (for example in the X-ray or in the far-infrared domains). These devices are in most cases also used to study the processing of interstellar dust (for instance submitted to irradiations of high energy photons and particles, to study gas-grain interaction).

Absorption spectroscopic measurements of interstellar dust analogs, such as minerals (silicates and oxides), carbonaceous dust, and ices are generally performed in transmission or in reflection. The study of ices requires experimental devices combining the production of ice thin films with spectroscopic capabilities. Spectroscopic measurements of silicate, oxide, and carbon-based dust analogs are usually performed on bulk, film or powder samples depending on the method of synthesis. Powder samples, which are more representative of interstellar nanograins, are usually dispersed in a solid transparent matrix (KBr, CsI, polyethylene). A lot of experimental work has been devoted to the characterization of the influence of the grain shape, grain size, and of the matrix on the measured spectra, especially on the band shape and position. The very small grains

(VSGs) and the carriers of the aromatic infrared band (AIB), although not very well constrained, are thought to be carbonaceous nanograins or aggregates with sizes ranging from 1 to a few nanometers. In space, their temperature fluctuates on a large range from 10 to more than 2000 K depending on the species. Large polycyclic aromatic hydrocarbons (PAHs) have been proposed to account for the emission in the AIB. Analogs of this dust component are difficult to produce and to study in the gas phase on such a wide range of temperature. Their spectroscopic characterization combines solid-state and gas-phase measurements to theoretical calculations for the species that cannot be studied experimentally (Joblin et al. 1995).

Laboratory spectra of interstellar dust analogs may be directly compared to astrophysical or planetary observations. They are also used to calculate extinction cross sections and optical constants (Gerakines and Hudson 2020; Mutschke 2013). The latter, related to the dielectric function, describe the response of a material submitted to an electromagnetic field. Optical constants make it possible to model the size and shape distribution of cosmic dust which are difficult to reproduce in the lab but which must be taken into account for a good modelling of astrophysical and planetary environments. Spectra, extinction cross sections, and optical constants of interstellar dust analogues are delivered to the scientific community through databases (Mattiola et al. 2020; Mallocci et al. 2007; Schmitt et al. 2018).

Cross-References

- [Interstellar Dust](#)
- [Laboratory Dust Analogs](#)
- [Spectroscopy](#)

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Interstellar Filaments

Philippe André

Laboratoire d'Astrophysique (AIM), CEA Paris-Saclay, Gif-sur-Yvette, France

Definition

An interstellar filament may be defined as any elongated structure in the cold ► [interstellar medium](#) which has an aspect ratio larger than ~5–10 and is significantly overdense with respect to its surroundings.

History

The presence of parsec-scale filamentary structures in nearby interstellar clouds and their potential importance for star formation have been pointed out by many authors for more than three decades. For example, Schneider and Elmegreen (1979) discussed the properties of 23 elongated dark nebulae, visible on optical plates and showing evidence of marked condensations or internal globules along their lengths, which they named “globular filaments.”

Overview

Recent studies of the nearest star-forming clouds of the galaxy at submillimeter wavelengths with the *Herschel* Space Observatory have provided us with unprecedented images of the initial conditions and early phases of the star formation process. The *Herschel* images reveal an intricate network of filamentary structures in every interstellar cloud. These filaments all exhibit remarkably similar widths – about a tenth of a parsec – but only the densest ones contain prestellar cores, the seeds of future stars. The *Herschel* results favor a scenario in which interstellar filaments and prestellar cores represent two key steps in the star formation process: first turbulence stirs up the gas, giving rise to a universal weblike structure in the interstellar medium, and then gravity takes over and controls the further fragmentation of filaments into prestellar cores and ultimately ► [protostars](#). This scenario provides new insight into the inefficiency of star formation, the origin of stellar masses, and the global rate of star formation in galaxies. Despite an apparent complexity, global star formation may be governed by relatively simple universal laws from filament to galactic scales.

Basic Methodology

Two main approaches have been used to trace the filamentary structure of the cold interstellar medium: (1) mapping the optically thin far-infrared and submillimeter continuum emission from the cold (~10–30 K) dust contained in the

clouds and (2) mapping the absorption of the local background infrared emission (from warmer cloud dust or remote stars) by the same cold dust component in the clouds. Mapping the molecular gas component is generally less effective in this respect as most molecules tend to freeze out onto dust grains in the dense, cold inner parts of molecular clouds.

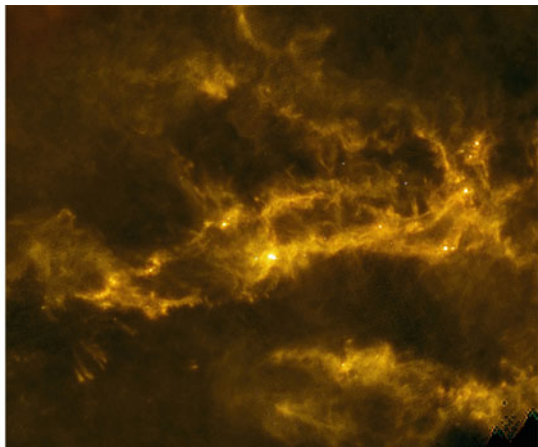
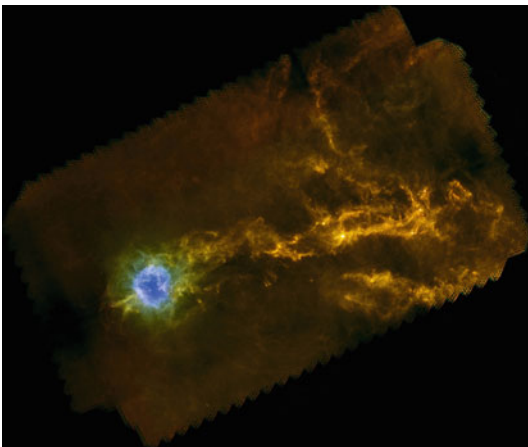
Two key advantages of *Herschel* dust continuum imaging observations for studies of interstellar cloud structure have been (1) an unprecedented mapping speed at wavelengths ranging from $\lambda = 160\ \mu\text{m}$ to $\lambda = 500\ \mu\text{m}$ where cold interstellar clouds emit the bulk of their thermal radiation and (2) a very good angular resolution $18''$ (half-power beam width) at $\lambda = 250\ \mu\text{m}$, corresponding to $\sim 0.03\ \text{pc}$ at a distance $d = 350\ \text{pc}$, which is sufficient to resolve the typical Jeans length and thus individual prestellar dense cores in nearby molecular clouds.

Key Research Findings

Omnipresence and Universality of Filamentary Structures in the Cold ISM

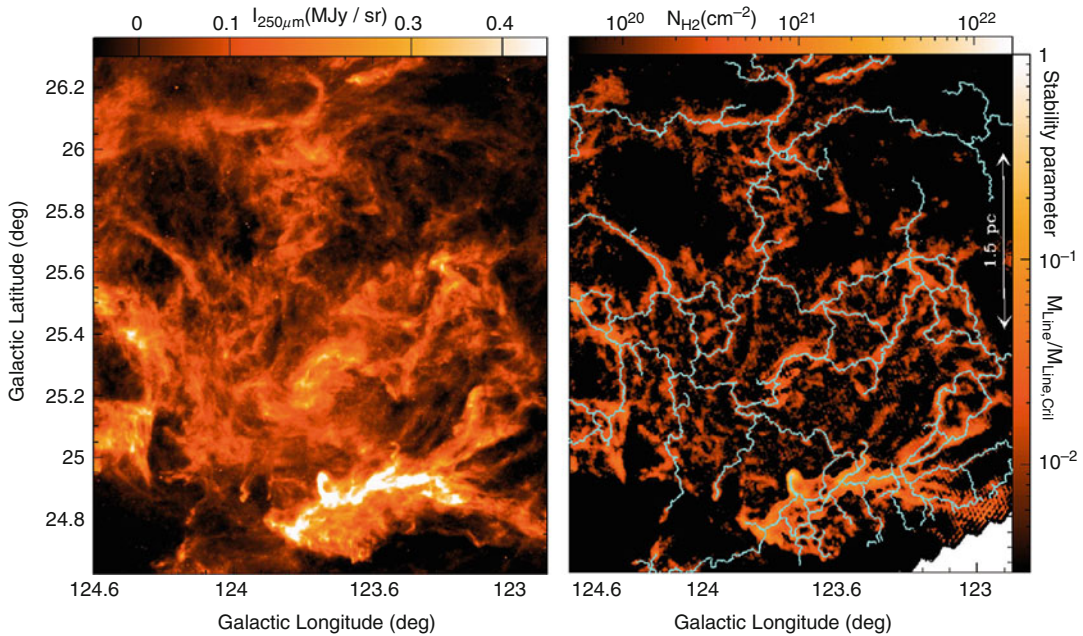
The high quality and dynamic range of the *Herschel* images are such that they provide key information on both dense cores on small ($< 0.1\ \text{pc}$)

scales *and* the structure of the parent background cloud on large ($> 1\ \text{pc}$) scales. In particular, one of the most spectacular early findings made with *Herschel* is the ubiquitous presence of long ($> \text{pc}$ scale) filamentary structures in the cold interstellar medium (ISM) (cf. Fig. 1) and the apparently tight connection between the filaments and the formation process of dense cores (e.g., André et al. 2010; Men'shchikov et al. 2010; Molinari et al. 2010). Remarkably, filaments are omnipresent even in diffuse, non-star-forming complexes such as the Polaris translucent cloud (cf. Fig. 2 – Miville-Deschênes et al. 2010; Ward-Thompson et al. 2010). Moreover, in any given cloud complex, the *Herschel* images reveal a whole network of filaments (see Fig. 1), making it possible to characterize their properties in a statistical manner. Detailed analysis of the radial column density profiles derived from *Herschel* data shows that interstellar filaments are characterized by a very narrow distribution of central widths with a typical FWHM value of $\sim 0.1\ \text{pc}$ (Arzoumanian et al. 2011, 2019). A plausible interpretation of this common width of filaments is that it corresponds to the sonic scale below which interstellar turbulence becomes subsonic in diffuse, nonstar-forming gas (cf. Padoan et al. 2001; Federrath 2016).



Interstellar Filaments, Fig. 1 *Left:* The star-forming cloud IC 5146 as imaged by the *Herschel* Space Observatory. The color coding is such that *red* = SPIRE $500\ \mu\text{m}$ and $350\ \mu\text{m}$, *green* = SPIRE $250\ \mu\text{m}$ and PACS $160\ \mu\text{m}$, *blue* = PACS $70\ \mu\text{m}$. *Right:* Blow-up *Herschel* image of

part of the field shown on the *left*, emphasizing the filamentary structure of the IC 5146 cloud. (From Arzoumanian et al. 2011. © ESA/*Herschel*/SPIRE PACS “*Herschel* Gould Belt survey” Key Program)



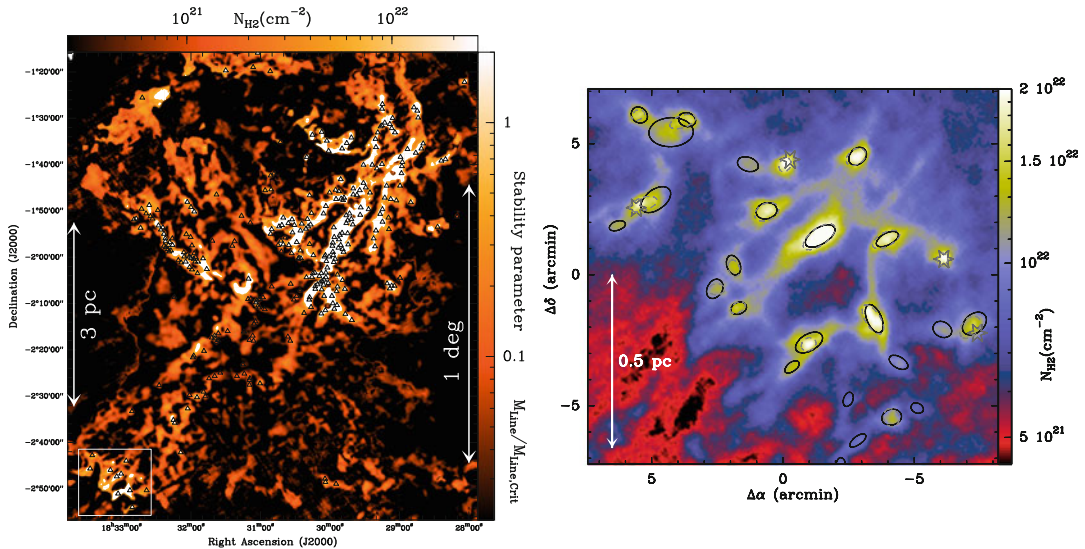
Interstellar Filaments, Fig. 2 Left: *Herschel*/SPIRE 250 μm dust continuum map of a portion of the Polaris flare translucent cloud (e.g., Miville-Deschênes et al. 2010; Ward-Thompson et al. 2010). Right: Skeleton of the

filament network traced with the DisPerSE algorithm in the *Herschel* image of the Polaris cloud shown on the left (© ESA *Herschel* SPIRE “Gould Belt survey” & “Evolution of interstellar dust” Key Programs)

The Key Role of Interstellar Filaments in the Star Formation Process

The observed correspondence between the filaments and the spatial distribution of compact cores is also remarkable (see Fig. 3), suggesting that *dense cores form primarily along filaments*. More precisely, the prestellar cores identified with *Herschel* are preferentially found within the *densest filaments* with masses per unit length exceeding $16 M_{\odot}/\text{pc}$ and column densities exceeding $\sim 7 \times 10^{21} \text{ cm}^{-2}$ (Könyves et al. 2015 and Fig. 3). In the Aquila region, for instance, the distribution of background cloud column densities of the prestellar cores shows a steep rise above $N_{\text{H}_2, \text{back}} \sim 5 \times 10^{21} \text{ cm}^{-2}$ and is such that $\sim 90\%$ of the candidate-bound H_2 cores are found above a background column density $N_{\text{H}_2, \text{back}} \sim 7 \times 10^{21} \text{ cm}^{-2}$, corresponding to a background visual extinction $A_{V, \text{back}} \sim 8$ (André et al. 2014). The *Herschel* observations of the Aquila Rift complex therefore strongly supports the existence of a column density or visual extinction threshold for the formation of prestellar cores at $A_{V, \text{back}} \sim 5\text{--}10$, which

had been suggested by earlier ground-based studies of, for example, Taurus and Ophiuchus (cf. Onishi et al. 1998; Johnstone et al. 2004). In the Polaris flare, the *Herschel* results are also consistent with such an extinction threshold, since the observed background column densities are all below $A_{V, \text{back}} \sim 8$, and there are no examples of bound prestellar cores in this cloud. Moreover, the *Herschel* results provide an *explanation* of this threshold in terms of the filamentary structure of molecular clouds. Given the characteristic width $\sim 0.1 \text{ pc}$ measured for the filaments (Arzoumanian et al. 2011), the threshold at $A_{V, \text{back}} \sim 8$ or $\Sigma_{\text{back}} \sim 130 M_{\odot} \text{ pc}^{-2}$ corresponds to within a factor of <2 to the critical mass per unit length $M_{\text{line, crit}} = 2 c_s^2 / G \sim 16 M_{\odot}/\text{pc}$ required for the hydrostatic equilibrium of isothermal filaments (cf. Ostriker 1964; Inutsuka and Miyama 1997), where $c_s \sim 0.2 \text{ km/s}$ is the isothermal sound speed for a typical gas temperature $T \sim 10 \text{ K}$. Thus, the core formation threshold approximately corresponds to the *threshold above which interstellar filaments are*



Interstellar Filaments, Fig. 3 *Left:* Column density map of the Aquila star-forming region derived from *Herschel* data (André et al. 2010). The contrast of the filaments has been enhanced by image processing. The filaments which have “supercritical” masses per unit length ($M_{\text{line}} \geq M_{\text{line,crit}}$; see text) and are thus likely gravitationally unstable are

gravitationally unstable. Prestellar cores are mostly observed above this threshold because they form out of a filamentary background and only filaments with transcritical or supercritical masses per unit length ($M_{\text{line}} \geq M_{\text{line,crit}}$) are able to fragment efficiently into self-gravitating cores (cf. André et al. 2010 and Fig. 3).

Toward a Universal Scenario for Star Formation?

The results obtained with *Herschel* in nearby clouds and summarized above provide key insight into the first phases of the star formation process. They emphasize the role of filaments and support a scenario according to which the formation of prestellar cores occurs in two main steps. First, the dissipation of kinetic energy in large-scale magnetohydrodynamic (MHD) turbulent flows generates a whole network of 0.1 pc-wide filaments in the ISM; second, the densest filaments fragment into prestellar cores by gravitational instability above or close to the critical mass per unit length $M_{\text{line,crit}} \approx 16 M_{\odot} \text{ pc}^{-1}$.

The realization that prestellar core formation occurs primarily along gravitationally unstable

highlighted in *white*. Note how the prestellar dense cores identified with *Herschel* (small blue triangles) tend to be concentrated in such “supercritical” filaments. *Right:* Close-up column density map of the area marked by a *yellow box* on the *left*, showing several examples of prestellar cores (See Könyves et al. 2015)

filaments of roughly constant width $W_{\text{fil}} \sim 0.1 \text{ pc}$ may also have implications for our understanding of star formation on global galactic and extragalactic scales. Remarkably, the critical mass per unit length of a filament, $M_{\text{line,crit}} = 2 c_s^2 / G$, depends only on gas temperature (i.e., $T \sim 10 \text{ K}$ for the bulk of molecular clouds, away from the immediate vicinity of massive stars) and is modified by only a factor of order unity for filaments with realistic levels of magnetization (Fiege and Pudritz 2000). This may set a quasi-universal threshold for star formation in the cold ISM of galaxies at $M_{\text{line,crit}} \sim 16 M_{\odot} \text{ pc}^{-1}$ in terms of filament mass per unit length, or $M_{\text{line,crit}} / W_{\text{fil}} \sim 160 M_{\odot} \text{ pc}^{-2}$ in terms of gas surface density, or $M_{\text{line,crit}} / W_{\text{fil}}^2 \sim 1600 M_{\odot} \text{ pc}^{-3}$ in terms of gas density (i.e., a number density $n_{\text{H}_2} \sim 2 \times 10^4 \text{ cm}^{-3}$). Indeed, *Spitzer*-infrared studies of the star formation rate as a function of gas surface density in molecular cloud complexes (e.g., Heiderman et al. 2010; Lada et al. 2010) show that the star formation rate tends to be linearly proportional to the mass of dense gas above a surface density threshold of $\Sigma_{\text{th}} \sim 120\text{--}130 M_{\odot} \text{ pc}^{-2}$ and drops to negligible values below Σ_{th} .

Moreover, essentially, the same relation between the global star formation rate and the total mass of dense gas above the threshold is found in nearby galactic clouds (Lada et al. 2010) and external galaxies (Gao and Solomon 2004). This suggests that there may be a quasi-universal “star formation law” converting the dense molecular gas of self-gravitating filaments into stars above the threshold (Lada et al. 2012; André et al. 2014).

Future Directions

The *Herschel* results on interstellar filaments are very encouraging as they tentatively point to a unified picture of star formation in both galactic molecular clouds and external galaxies. Much more work is needed, however, to understand the detailed fragmentation physics of dense molecular filaments, in particular the origin of their common inner width, and to determine whether the same 0.1 pc width also holds beyond the nearby clouds of Gould’s Belt.

The study of interstellar filaments is becoming a very active research field. Interesting new results on the fragmentation properties of star-forming molecular filaments have been obtained recently with submillimeter interferometers such as ALMA and NOEMA (e.g., Beuther et al. 2015; Kainulainen et al. 2017; Hacar et al. 2018; Shimajiri et al. 2019) and call for modifications to standard linear fragmentation models of quasi-equilibrium cylindrical filaments (cf. Inutsuka and Miyama 1992; Clarke et al. 2017).

Confirming and refining the filament scenario sketched in the previous section will also require extensive follow-up spectroscopic observations to constrain the dynamics of the filaments imaged with *Herschel*, as well as detailed comparisons with numerical simulations of molecular cloud formation and evolution. Recent observations suggest the presence of significant velocity gradients both along and across filaments (e.g., Williams et al. 2018; Dhabal et al. 2018), with a tendency for the transverse velocity gradients to dominate. More systematic studies will be required, however, to draw general conclusions.

Last, but not least, ALMA and NOEMA will be instrumental in testing whether the filament

paradigm is truly universal and applies to both the whole Milky Way beyond Gould’s Belt and the cold ISM of other galaxies.

Cross-References

- [ALMA](#)
- [Dense Core](#)
- [Fragmentation of Interstellar Clouds](#)
- [Gravitational Collapse, Planetary](#)
- [Herschel Mission](#)
- [Molecular Cloud](#)
- [Pillars](#)
- [Turbulence, Interstellar](#)

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Interstellar Grain

► Dust Grain

Interstellar Grains

► Interstellar Dust

Interstellar Ice Spectroscopy Experiments

Jennifer Noble
 PIIM, CNRS/Aix-Marseille Universite,
 Marseille, France
 School of Physical Sciences, University of Kent,
 Canterbury, UK

Synonyms

[Astrophysical ice spectroscopy](#); [Laboratory ice spectroscopy](#)

Definition

Interstellar ice spectroscopy experiments are performed in the laboratory under conditions reproducing, as closely as possible, those in astrophysical environments. The primary aim is the interpretation of observational ice spectra. The majority of observational data on ices are measured in the mid-infrared range (mid-IR, approximately 2.5–25 μm), where molecules absorb light via their vibrational modes. In the laboratory, IR spectrometers are used to record spectra of solid samples of relevant species (e.g., water, carbon dioxide, etc.). The positions, profiles, and intensities of vibrational bands are compared to observational spectra to identify and quantify the molecular composition of astrophysical ices.

Overview

In astrophysical environments that are sufficiently cold and dense, molecules accumulate in icy layers covering dust grains. Such ices are probed via mid-IR absorption spectroscopy, usually from satellite-based telescopes in order to avoid telluric absorption (Boogert et al. 2015). The major aim of interstellar ice spectroscopy experiments is to provide laboratory spectra of ices prepared under temperature and pressure conditions approaching those in space so that they can be used as a reference for the analysis of observational spectra.

A sample of molecules is prepared in the gas phase, then deposited onto a cold substrate (~ 10 – 20 K) inside an (ultra-)high vacuum chamber. The mid-IR absorption spectrum of the solid sample is measured in transmission using an IR spectrometer. The number of molecules deposited on the substrate is determined based upon the deposition rate (pressure) and time, allowing the spectrum to be converted into optical constants – i.e., the complex refractive index – via a Kramers-Kronig analysis (Hudgins et al. 1993). Finally, a spectrum on an optical depth scale is generated by application of corrections for scattering of light due to dust grains (Bohren and Huffman 1998) and of instrument-specific parameters such as spectral resolution. The resulting mid-IR spectrum can be compared to the observed ice

spectrum in order to identify the presence of specific molecules and to quantify their abundance along the observed line of sight (Boogert et al. 2015).

Many factors need to be taken into account when using laboratory spectra as references to benchmark observations, including physical parameters such as the deposition temperature, which influences the long range order of the deposited ice, the relative concentration of different ice components, which can modify the position, profile, and intensity of the vibrational modes of other molecules, and the structure of the ice – i.e., whether the molecules are deposited as a mixture or in layers – which also influences the optical properties of the solid.

A secondary aim of interstellar ice spectroscopy experiments is to understand the physical and chemical evolution of an ice by monitoring changes induced by different processes. An increase of the sample temperature can induce post-deposition diffusion of species on/in the ice, which may allow chemical reactivity to occur between molecules present in the ice, as well as modifying the ice structure. The introduction of energy into the ice in the form of irradiation by photons or bombardment with particles (ions, electrons, atoms, and molecules) may also modify the phase and/or composition of the ice. Using IR spectroscopy as a probe of the changes induced in the ice sample allows laboratory astrophysicists to extract quantities such as reaction rates, branching ratios, and activation energies for different chemical and physical processes. The integration of such data into solid phase or gas-grain astrophysical models is key in successfully simulating interstellar environments (Cuppen et al. 2017).

Interstellar ices are a reservoir for the generation of molecules of increasing complexity, both during the ice's formation and its subsequent processing. A current major focus of laboratory ice spectroscopy is the measurement of the spectra of predicted minor components of interstellar ices, such as complex organic molecules (COMs), in preparation for observations with the James Webb Space Telescope (JWST), which will have the sensitivity and spectral resolution to detect such molecules if they are present. Other developments include coupling solid phase vibrational IR

spectroscopy to other techniques, such as gas phase rotational millimeter/submillimeter spectroscopy, in order to monitor the exchange between the ice and the gas phases during processing of the ice (Yocum et al. 2019). In addition to the principal mid-IR spectroscopic range, other spectral regions may also be used for the study of ices relevant to specific astrophysical environments, for example, solid phase terahertz (far-IR/submillimeter) spectroscopy for the study of ices in protoplanetary disks (Min et al. 2016) and near-IR/visible spectroscopy for planetary and/or lunar ices in our own solar system (Gerakines et al. 2005).

Cross-References

- [Absorption Spectroscopy](#)
- [Amorphous Solid](#)
- [Column Density](#)
- [Complex Organic Molecules](#)
- [Dust Grain](#)
- [Electromagnetic Spectrum](#)
- [Evolution, Chemical](#)
- [Gas-Grain Chemistry](#)
- [Ice](#)
- [Infrared Astronomical Satellite](#)
- [Infrared Astronomy](#)
- [Infrared Space Observatory](#)
- [Infrared Spectroscopy](#)
- [Interstellar Ices](#)
- [Jupiter Icy Moon Explorer Mission](#)
- [JWST](#)
- [Laboratory Dust Analogs](#)
- [Molecular Spectroscopy](#)
- [Spectroscopy, Vibrational](#)
- [Water in the Universe](#)

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Interstellar Ices

Emmanuel Dartois¹ and Douglas Whittet²

¹Institut des Sciences Moléculaires d'Orsay, CNRS, Université Paris-Saclay, Orsay Cedex, Orsay, France

²New York Center for Astrobiology, Rensselaer Polytechnic Institute, Troy, NY, USA

Keywords

Astrochemistry · Dust grains · Ice mantles · Interstellar medium · Molecular clouds · Surface chemistry · Photochemistry · Cosmic rays radiolysis · Thermal evolution

Definition

Interstellar ices are volatile molecular solids that accumulate on the surfaces of cold interstellar dust grains. They are composed primarily of H₂O (typically 60–70% by number); other molecules observed or predicted to be present include CO, CO₂, CH₃OH, CH₄, NH₃, O₂, and N₂. Laboratory analog experiments reproducing space environments show that irradiation by photons, energetic particles, and thermal processing of these ice mixtures can lead to production of complex organic species, including amino acids. Interstellar ices

account for a major fraction of all the available CNO group elements in star-formation regions and are presumed to be primary carriers of these elements to protoplanetary disks, where they may become incorporated directly into icy planetesimals or may sublime, and undergo further chemical processing.

History

Ices were discussed as a probable ingredient of interstellar matter as early as 1935, soon after the presence of dust responsible for the extinction of starlight was confirmed (see Whittet 2003 for a review). It was first proposed by Lindblad (1935) that solid particles composed of H₂O, NH₃, and CH₄ could nucleate and grow in interstellar clouds; Jan Oort and Henk van de Hulst (1946) subsequently demonstrated that a realistic size distribution of such particles could account for the observed extinction. Subsequent models developed by Mayo Greenberg (1968) and others proposed that refractory dust particles composed of graphitic carbon or silicates provide nucleation sites for growth of ices in dense clouds, leading to the concept of core-mantle particles. The existence of interstellar ices was confirmed when observational facilities for infrared spectroscopy became available in the 1970s. It has long been suspected, following the development of the “dirty snowball” model for cometary composition in the early 1950s, that comets may inherit some presolar ices from the solar birth cloud, a still actively debated subject.

Overview

Interstellar ices are mainly detected and characterized by means of infrared absorption features that result from the vibrational motion of the molecules they contain and in few cases can be observed in emission in the far infrared implying ice network lower energy modes. Whereas gas-phase molecules produce infrared “bands” in which a vibrational energy level is split into multiple lines by rotation, a solid produces a

vibrational band for each vibrational mode because rotation is suppressed. Solid-state features are generally much broader than gas-phase lines, even at the low temperatures (10–100 K) appropriate to interstellar ices. Most of the important spectral features identified with the ices lie in the wavelength range 2–20 μm ; the most prominent of them is centered at 3 μm and arises from the O-H “stretching” mode of H_2O . An example of an infrared spectrum displaying interstellar ice features is shown below. The ices are observed against a continuum provided by a normal background field star (Elias 16, a K-type red giant) serendipitously located behind a cold core within a dense molecular cloud (Fig. 1).

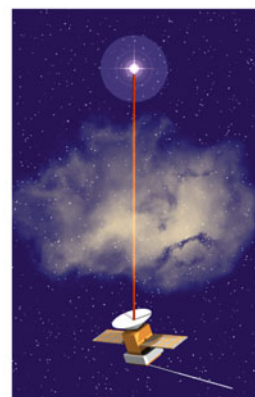
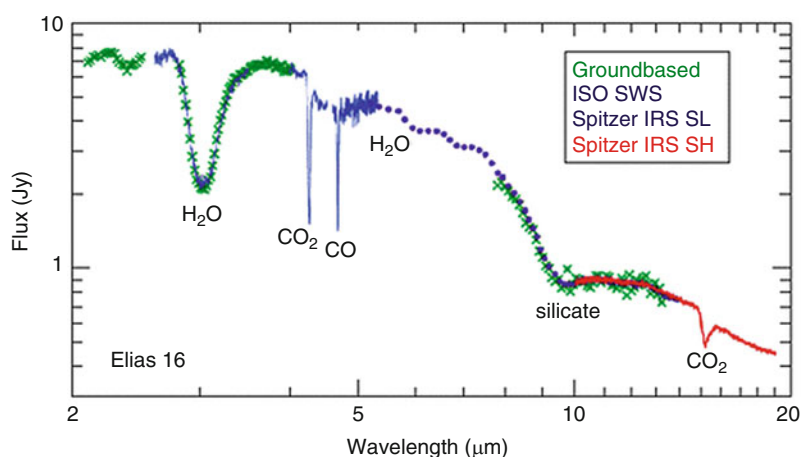
Basic Methodology

Because an observed infrared feature is generally associated with the vibrational mode of a chemical bond rather than a specific molecule, identification is often ambiguous, especially for minor constituents. For example, all organic molecules containing C-H bonds are active in the 3.3–3.6 μm region of the spectrum, and the precise position, width, and shape of the feature produced by a given species depend on both the structure of the

molecule and the nature of the ice matrix in which it is embedded. The absorption profile also changes with the temperature and crystallinity of the ice. Laboratory data for interstellar analogues produced in laboratory experiments (see Fig. 2), simulating the space environment where reside dust grains covered by ice mantles in interstellar space and the different radiations at which are exposed these ice mantles, are therefore essential to aid interpretation of astronomical spectra.

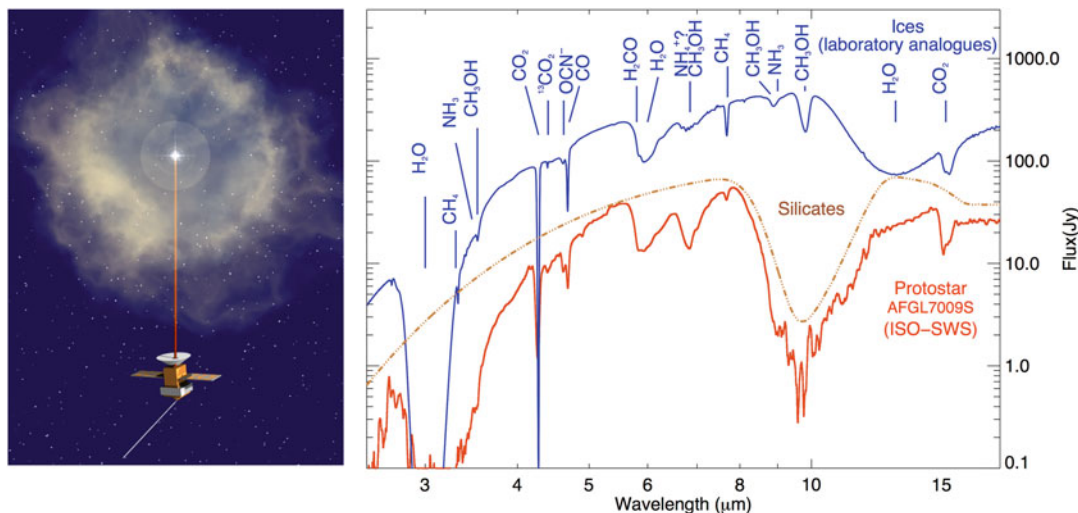
Key Research Findings

Observations of the absorption features attributed to ice constrain the composition of the interstellar ice mantles and provide evidence of variations in both composition and structure with environment (e.g., Gibb et al. 2004; Dartois 2005; Boogert et al. 2015). In the cold, starless cores within interstellar clouds (i.e., regions that are yet to form stars), the ice is dominated by three species: H_2O , CO, and CO_2 . Of these, H_2O is always the most abundant (typically 60–70%). The ubiquity of H_2O requires that it must form in situ, primarily by reactions such as $\text{H} + \text{O} \rightarrow \text{OH}$ and $\text{H} + \text{OH} \rightarrow \text{H}_2\text{O}$ occurring on the surfaces of dust particles, because H_2O molecules formed by gas-phase



Interstellar Ices, Fig. 1 Composite infrared spectrum of Elias 16, a normal red giant star located behind a dense molecular cloud (a sketch of the observation configuration is shown on the right). Data from several instruments are included (the Short Wavelength Spectrometer of the

Infrared Space Observatory, the Infrared Spectrometer of the Spitzer Space Telescope, and ground-based telescopes). Spectral features of H_2O , CO, and CO_2 ices and of silicate dust are labeled. Note that narrow gas-phase lines are unresolved in this spectrum



Interstellar Ices, Fig. 2 Infrared spectrum of AFGL7009S, a massive young protostar located in a dense molecular cloud (right panel, lower trace, from the Short Wavelength Spectrometer of the Infrared Space Observatory). Above is shown a spectrum of a laboratory ice mixture analog, irradiated with ultraviolet photons, showing many spectral features of ices, that are labeled.

The contribution of the dust grains core (the silicates) not simulated in the laboratory is shown in brown. The ices present in the molecular cloud, probed by the protostar observation, are identified by comparing such laboratory analogue spectra to space observations (a sketch of the space observation configuration is shown on the left)

reactions are insufficiently abundant to account for the ice mantles by adsorption (freeze-out) onto the grains. CO is the only condensable gaseous interstellar molecule that is abundant enough to contribute significantly to the ices by direct adsorption. CO molecules sticking to a grain may be oxidized to CO_2 or may be hydrogenated first to HCO , H_2CO (formaldehyde), or CH_3OH (methanol) or chemically evolve in the ice mantle mixtures under the space radiation fields (ultraviolet photons, cosmic ray particles) to produce even more complex molecules. Ice mixtures dominated by H_2O are generally referred to as “polar” ices (i.e., they have a significant dipole moment). In regions of highest density within molecular clouds, ice-mantle growth proceeds also by direct freeze-out of gas-phase molecules, primarily CO. The CO-rich ice mixtures that form in such regions are generally referred to as “non-polar” ices (in reality they have a very small dipole moment). Observations of (e.g.,) the $4.67\ \mu\text{m}$ and $15.3\ \mu\text{m}$ infrared features of CO and CO_2 allow discrimination between the polar and nonpolar components, which display distinct absorption profiles.

Evolution of the ices in regions of active star formation is explored by observing ice features in the spectra of dust-embedded young stellar objects (i.e., protostars or pre-main-sequence stars in molecular clouds) and comparing them with those observed in background field stars that probe quiescent regions of molecular clouds (van Dishoeck and Blake 1998; Whittet 2003; Gibb et al. 2004; Oberg et al. 2011; Boogert et al. 2015). Protostars are typically luminous at infrared wavelengths, and the radiation they emit warms interstellar material in their local environs. Widespread evidence for heating of the ices is found: typically, the abundance of the relatively volatile nonpolar ice is reduced relative to the more robust polar ice due to sublimation; changes in profile shape are also observed and attributed to partial crystallization and segregation resulting from increased mobility of molecules in the ice matrix (e.g., Dartois et al. 1999; Pontoppidan et al. 2008; Poteet et al. 2013).

Heating may also drive chemical reactions by enabling activation energies to be overcome. Evidence for more dramatic changes driven by UV irradiation or particles accelerated to high energy

such as cosmic rays bombardment is also observed in the spectra of some luminous protostars, characterized by the appearance of a feature near 4.62 μm (Soifer et al. 1979; Lacy et al. 1984; Pendleton et al. 1999) attributed to synthesis of CN-bearing (cyanate) molecules in the ices (Bernstein et al. 1995; Elsila et al. 1997; Schutte and Greenberg 1997; Demyk et al. 1998; Hudson et al. 2001; Novozamsky et al. 2001; Raunier et al. 2003; Theule et al. 2011).

The gas-phase medium enriched by the desorbing or sublimating ices can be observed in dense clouds, in warmed interfaces close to nascent stars, in interstellar shocks on dense medium, using powerful radio telescopes (Cazaux et al. 2003; Bonfand et al. 2019; Manigand et al. 2021) and, for abundant ones, infrared observatories.

Future Directions

Interstellar volatiles are important to astrobiology because they represent a major reservoir of raw materials needed to form planets and life (Ehrenfreund and Charnley 2000; Herbst and van Dishoeck 2009). Important goals for future research will be to elucidate key astrochemical pathways toward complex molecule formation in the ices and their sublimates and to determine the extent to which the products survive disk accretion to become incorporated into icy planetesimals in protoplanetary disks. Progress toward solving the ice composition and abundance still unsolved problems requires a synthesis of research in observational astronomy (tighter observational constraints on abundances), laboratory astrophysics (measurement of rate constants and activation energies for key reactions, of energetic processing with photons, ions, thermal, shocks), and mathematical modeling. The development of robust models will allow the organic inventories of interstellar matter in prestellar cores and protoplanetary disks to be accurately constrained. The new-generation telescopes (ground- or space-based), probing protoplanetary disks in formation around other stellar systems, with a high angular resolution and allowing to constrain the composition of gas and ices as a function of the distance to the star

will advance the understanding of the interstellar heritage in disks. This will facilitate meaningful comparisons between interstellar matter and comets, which are accessible examples of icy planetesimals forming beyond the snowline in a protoplanetary disk. The composition study of solar system cosmomaterials (sample return missions, meteorites, interplanetary dust particles travelling in the solar system) that can be collected (with space probes or on Earth) and examined in detail in the laboratory, and which host the heritage of the realization of one particular (our solar system) among many protoplanetary disks of the Galaxy now observed with such generation telescopes with high angular resolution, is also one future direction.

Cross-References

- Absorption Spectroscopy
- Active Site
- Apolar Molecule
- Coagulation, Interstellar Dust Grains
- Comet (Nucleus)
- Dust Cloud, Interstellar
- Extinction, Interstellar or Atmospheric
- Gas-Grain Chemistry
- Ice
- Infrared Space Observatory
- Interstellar Chemical Processes
- Interstellar Dust
- Interstellar Medium
- Molecular Cloud
- Nucleation of Dust Grains
- Photochemistry
- Polar Molecule
- Protostars
- Protostellar Envelope
- Spitzer Space Telescope
- Star Formation, Observations

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Interstellar Medium

Ronald L. Snell

Department of Astronomy, 517 K Lederle
Graduate Research Center, University of
Massachusetts, Amherst, MA, USA

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Atomic gas · Galaxies · Interstellar dust ·
Interstellar gas · Milky Way · Molecular gas ·
Star formation

Synonyms

ISM

Definition

The interstellar medium refers to the tenuous gas and dust that fills the void between stellar systems in galaxies. This gas and dust is not distributed uniformly in interstellar space but displays significant variations in density, temperature, and ionization state. The interstellar medium is held in place by the gravitational force of the stellar component of galaxies. The interstellar medium contains the raw materials out of which new stars are formed, and as stars die, material is returned to the interstellar medium, often violently, enriched by stellar nucleosynthesis. The cycling of material in and out of the interstellar medium plays a critical role in the evolution of galaxies.

Overview

The space between stellar systems in galaxies is called interstellar space, distinct from interplanetary space (the space within a stellar system) and intergalactic space (the space between galaxies). Interstellar space is not empty but is filled with rarefied gas and dust, and this gas and dust is what is commonly referred to as the interstellar medium. Besides gas and dust, interstellar space is also filled with ► [electromagnetic radiation](#) covering a vast range of wavelengths, energetic particles called cosmic rays, and magnetic fields, and these components have a strong influence on the physical properties of the interstellar gas and dust. The elemental composition of the interstellar medium is dominated by hydrogen, with lesser amounts of helium and only trace amounts of the elements heavier than helium. The most abundant of these trace elements, or what astronomers often refer to as the “heavy elements” or “metals,” are oxygen, carbon, and nitrogen. The state of the gas in the interstellar medium ranges from being a nearly fully ionized

plasma to being almost entirely in molecular form. The dust in the interstellar medium consists of small solid particles with a range of sizes, composed of both silicate and carbon grains (see ► [“Interstellar Dust”](#)). By mass, dust represents only about 1% of the interstellar medium; however, about half the mass of the heavy elements is in the form of dust.

The interstellar medium is best studied in the ► [Milky Way](#), where, as in other spiral galaxies, we find most of the gas and dust concentrated to the galactic midplane. The interstellar medium is held in place by the combined gravitational force of the stars in the Galaxy. The thickness of the gas and dust layer, often called the scale height, is determined by a balance between the forces of gravity and gas pressure (both thermal and turbulent), and in the Milky Way this layer is relatively thin compared with the dimensions of the Galaxy.

In the Milky Way, astronomers have identified a number of distinct “phases” of the interstellar medium. These phases of the interstellar medium are characterized by significant differences in the temperature, density, and ionization state of the gas. Six phases of the interstellar medium are recognized, which in decreasing temperature order are (1) the hot ionized medium (HIM), (2) ► [HII regions](#) (where the hydrogen is photoionized, H^+ regions), (3) the warm ionized medium (WIM), (4) the warm neutral medium (WNM), (5) the cold neutral medium (CNM), and (6) the molecular medium (MM). Table 1 summarizes the properties of the gas in each of these phases.

The dominant element, hydrogen, is found in ionized, neutral atomic, and molecular forms in the interstellar medium. The ultraviolet radiation in interstellar space can both dissociate hydrogen molecules and ionize atomic hydrogen. However, most hydrogen-ionizing radiation is localized near HII regions, so neutral atomic hydrogen is an important component of the interstellar medium. Some of the trace elements have ionization potentials smaller than hydrogen (13.6 eV [electron volts]) and can be ionized even in the neutral atomic hydrogen regions. Thus, elements such as carbon (ionization potential 11.3 eV) and iron

Interstellar Medium, Table 1 Properties^a of the gas in the different phases of the interstellar medium. Density is particle density and not mass density

Phase	Temperature (K)	Density (cm ⁻³)	State of hydrogen
Hot ionized medium (HIM)	10 ⁶	0.006	Ionized atomic
HII regions	10 ⁴	1–10 ⁴	Ionized atomic
Warm ionized medium (WIM)	8000	0.03	Ionized atomic
Warm neutral medium (WNM)	6000–8000	0.25	Neutral atomic
Cold neutral medium (CNM)	100	25	Neutral atomic
Molecular medium (MM)	10–20	10 ³ –10 ⁶	Neutral molecular

^aAdopted from Ferrière (2001) and Lequeux (2005)

(ionization potential 7.9 eV) are singly ionized in the CNM and WNM phases. In the densest regions, the molecular dissociating radiation cannot penetrate, and the rate of molecule formation is sufficiently rapid to form ► [molecular clouds](#) (the MM phase). The gas in each of these phases is roughly in thermal equilibrium, where the gas cooling rate per unit volume equals the gas heating rate per unit volume. However, the gas is not in thermodynamic equilibrium with the surrounding radiation field, dust, or cosmic rays. The dominant heating and cooling mechanisms for the gas are different for each of the phases. Since, in general, the cooling rates depend on the square of the gas density, while the heating rates depend linearly on gas density, the equilibrium temperature of the gas decreases with increasing gas density.

In the Milky Way, we have only a rough estimate of the volume occupied by the different phases and their contribution to the total mass of the interstellar medium. It is believed that by volume the interstellar medium is dominated by the lowest density phases (HIM, WIM, and WNM), while by mass, the interstellar medium is dominated by the highest density phases (MM, CNM, and WNM). In the inner regions of the Galaxy (within 8 kiloparsecs [kpc] of the Galactic Center), the mass is dominated by the molecular medium (MM), while in the outer regions of the Galaxy, the mass is dominated by the neutral atomic gas (CNM and WNM). The total mass of the interstellar medium in the Milky Way is uncertain but is estimated to be about 5×10^9 solar masses or about 5% of the stellar mass of the Milky Way (Lequeux 2005).

Basic Methodology

A variety of techniques are used to detect the gas and dust in the interstellar medium. The gas component is probed by observations of ► [spectral lines](#) that can be either in emission or in absorption against a background source of continuous radiation. The gas in the interstellar medium covers a vast temperature range. Since the wavelength or frequency at which emission lines from the gas in the interstellar medium are produced depends on temperature, observations extending from X-ray wavelengths to radio wavelengths are routinely used to probe the various gas phases. We summarize below some of the most common observations of the gas.

The earliest evidence for interstellar gas came from optical observations of bright nebulae. Spectroscopic observations of these bright nebulae by William Huggins in 1864 showed that the light was dominated by emission lines, indicating that these objects (which included both ► [HII regions](#) and ► [planetary nebulae](#)) were composed of diffuse hot gas. We now know that the gas in these bright nebulae is almost entirely ionized, and the prominent emission lines are the optical recombination lines of hydrogen and the forbidden lines of O⁺ (designated by astronomers as OII), O⁺⁺ (OIII), S⁺ (SII), and N⁺ (NII). The hydrogen recombination lines are produced when hydrogen ions recombine with an electron to form an excited electronic state, and this recombination is followed by a series of radiative transitions as the electron cascades down to the ground electronic state, producing an emission line spectrum. In addition, some ions have low-lying electronic

states (O^+ , O^{++} , S^+ , and N^+) that can be readily excited by collisions with electrons and, when they radiatively deexcite, produce observable emission lines at optical wavelengths. These emission lines are called “forbidden lines” since they are intrinsically weak magnetic dipole or electric quadrupole transitions and not the much stronger electric dipole transitions. The observed emission line ratios can be used to determine the density and temperature of the ionized gas in HII regions.

The neutral atomic hydrogen phases of the interstellar medium (WNM and CNM) are too cold for collisions of the gas to excite electronic transitions. The electrons in these atoms are consequently all in their ground electronic state. This neutral component was first detected in the early part of the twentieth century as the interstellar gas absorbed the light of background stars, producing interstellar optical absorption lines in stellar spectra. However, only a few atoms have resonance lines (absorption lines that arise from the ground electronic state) at optical wavelengths; instead most of these lines are in the ultraviolet, so these early observations were limited to only a few chemical elements. The launch of the Copernicus satellite in 1972 provided high-resolution ultraviolet [▶ spectroscopy](#) that permitted astronomers to study the most abundant elements (such as H, O, C, and N) in the mostly neutral atomic interstellar medium. Nevertheless, these absorption line observations are limited to the lines of sight toward relatively nearby bright stars.

The detection in 1951 of the emission from neutral atomic hydrogen at a wavelength of 21 cm provided a new avenue for studying the CNM and WNM phases of the interstellar medium. The ground electronic state of hydrogen is split into two very finely spaced sublevels due to the magnetic interaction between the spin of the proton and the electron. The energy splitting is extremely small, so the upper of the two hyperfine levels is readily excited by collisions even in the coldest phases of the interstellar medium. The subsequent magnetic dipole transition, although very weak, is detectable by radio telescopes. The 21-cm line was the first radio spectral line observed, and it provides the ability to detect

atomic hydrogen anywhere in the Galaxy. Emission from this transition is routinely used to map out the distribution of neutral atomic hydrogen in the Milky Way and other galaxies. The 21-cm line can also be seen in absorption against background radio sources. The combination of both emission and absorption observations allowed astronomers in the 1970s to determine the temperature of the hydrogen gas. These studies provided evidence that the neutral atomic gas in our Galaxy coexisted in both cold (100 K) high-density and warm (6000–8000 K) lower-density phases.

Besides the absorption lines expected to be present due the neutral atomic phase of the interstellar medium, the Copernicus satellite also detected absorption lines from a very highly ionized state of oxygen, O^{++++} (OVI). The high ionization potential of this ion (113 eV) excludes photoionization as an origin, leaving as the only possibility collisional ionization in a plasma with a temperature greater than 300,000 K. About the same time, a series of rocket flights (Wisconsin Survey) mapped the sky at X-ray wavelengths and detected diffuse soft X-ray emission from the interstellar medium. The soft X-ray emission is a combination of spectral line and bremsstrahlung (continuous) emission from a hot plasma. Both the ultraviolet absorption lines seen from high ionization species and the X-ray emission are evidence for a hot, low-density phase of the interstellar medium (HIM) reviewed in Spitzer (1990). Because the absorption line studies are limited to lines of sight toward relatively nearby bright stars and because the soft X-ray emission is readily absorbed by gas in the interstellar medium, we know little about the widespread distribution of the HIM in the Galaxy.

Prior to the detection of carbon monoxide (CO) emission via its pure rotational transition at 2.6 mm in 1970, molecular gas was thought to be only a very minor component of the interstellar medium. Absorption lines from a few simple molecules were detected at optical and ultraviolet wavelengths, suggesting that there was a small fraction of molecules in the neutral atomic phases. However, it was assumed that the ultraviolet radiation would effectively dissociate any molecule that formed. The detection of widespread CO

emission, however, changed this view and revealed a surprisingly new and important component of the interstellar medium that is largely molecular. The CO emission, although widespread, is associated with discrete molecular “clouds.” In these ► [molecular clouds](#), nearly all of the hydrogen is in molecular form. These unexpected large ► [dense clouds](#) can screen dissociating radiation from the cloud interior, allowing for molecules to form. Observations of the rotational lines of various molecular species permit the estimation of the density and temperature of these clouds. The molecular medium is the coldest and densest phase of the interstellar medium. Now well over 150 different molecular species have been detected in the molecular medium (MM) by their rotational transitions at centimeter, millimeter, and submillimeter wavelengths (see ► [“Molecules in Space”](#)).

The presence of free electrons in interstellar space produces a frequency-dependent delay in the pulsed radio signals from pulsars. The amount of time delay, called the pulsar dispersion measure, is directly related to the column density of electrons between the Earth and the pulsar. Observations in the 1970s of the pulsar dispersion measure provided evidence for a widespread distribution of free electrons in the interstellar medium (see review by Ferrière 2001). Later, the development of sensitive Fabry-Perot spectrometers permitted the detection of very extended but weak recombination line and forbidden line emissions at optical wavelengths (Reynolds 2004). These observations suggested the presence of a warm and ionized component of the interstellar medium (WIM). Prior to these observations, it was thought that photoionized gas was restricted to small isolated regions (called Strömgren spheres) surrounding luminous hot stars. However, these observations revealed that about 90% of the photoionized gas in the Milky Way is found in the more widespread WIM (Reynolds 2004).

Finally, the dust component of the interstellar medium can be detected either directly by its thermal emission at infrared wavelengths or by the effects of the intervening dust on the extinction and reddening of starlight. See entry on ► [Interstellar Dust](#).

Key Research Findings

Studies over the past century have revealed a complex multiphase interstellar medium in the Milky Way.

HII Regions

The oldest known component of the interstellar medium is HII (or H^+) regions. These are regions of ionized hydrogen gas surrounding luminous hot massive stars (O and B spectral type stars) which produce copious amounts of hydrogen-ionizing photons. The theory of HII regions dates back to Strömgren (1939), who showed that in ionization equilibrium (number of ionizations within a volume equal to the number of recombinations), the gas surrounding these hot stars will be nearly fully ionized out to a radius, now called the Strömgren radius, and is completely neutral beyond that radius. The size of HII regions depends on the density of the gas being photoionized and the rate at which the central star is producing hydrogen-ionizing photons. The gas in the HII region is heated by the photoionization process and cooled by the forbidden line emission and is typically around 8000 K. HII regions are not an important mass or volume component of the interstellar medium.

Two-Phase Interstellar Medium

The discovery of gas components (WIM, CNM) more pervasive than HII regions (see Methodology) gave rise to the first global theory of the interstellar medium. Field et al. (1969) examined gas in the interstellar medium in both thermal and pressure equilibrium. In their model the gas is heated by the energetic electrons produced by the cosmic-ray ionization of hydrogen. The gas is cooled through the collisional excitation of the fine-structure split levels of the ground electronic states of atoms and ions, such as C^+ and O, followed by a radiative transition that returns the atom or ion to its ground state. The emitted photon carries away kinetic energy, thus cooling the gas. Because the cooling rate has a strong dependence on both density and temperature, Field, Goldsmith, and Habing found that the neutral atomic hydrogen gas could coexist in two

stable phases in thermal and pressure equilibrium, one cold and dense (CNW) and a second warmer and less dense (WNM), in agreement with the combined hydrogen 21-cm emission and absorption observations. From this model developed the concept that the interstellar medium was composed of a “cloud” component (CNM) surrounded by an “intercloud” medium (WNM). Although the interstellar medium is much more complex than this early simple model, this concept is still useful for understanding the neutral atomic gas, and the model has been recently updated by Wolfire et al. (2003).

Three-Phase Interstellar Medium

The existence of a hot “intercloud” medium was first suggested by Spitzer (1956), who argued that such a medium was important for the pressure confinement of interstellar clouds. The UV absorption studies and X-ray observations, discussed earlier, revealed the presence of a very tenuous and hot component of the interstellar medium (HIM) as predicted by Spitzer. These hot interstellar bubbles are created by high-speed shocks produced by ► [supernova](#) blast waves that expand into the interstellar medium (Cox and Smith 1974). Because of the high temperature and low density of these supernova-created bubbles, Cox and Smith suggested that they would cool slowly and thus be relatively long lived. McKee and Ostriker (1977) produced one of the first models of the interstellar medium to incorporate the HIM, and in this model the structure of the interstellar medium was regulated by supernova explosions. McKee and Ostriker suggested that a multi-component interstellar medium resulted, in which a large fraction of the volume of the interstellar medium was filled with these hot bubbles. The fraction of the interstellar medium filled with the HIM has been a source of great debate; estimates as low as 10% to as high as 70% have been suggested. The volume fraction depends on both the frequency and clustering of supernovae and their subsequent evolution in the interstellar medium (Ferrière 2001; Cox 2005).

The model of McKee and Ostriker includes a diffuse ionized layer (WIM) to the WNM

component, ionized by diffuse stellar ultraviolet photons. However, the WIM is observed to be much more extensive than pictured in this early model. The WIM is estimated to occupy approximately 20% of the volume of the interstellar medium within 1 kpc of the galactic midplane (Reynolds 2004). Although the WIM is believed to be photoionized, why hydrogen-ionizing photons are so widespread is not yet well understood. In the traditional view, hydrogen-ionizing photons should all be contained within the Strömgren radius surrounding hot O and B stars in the Galaxy. However, if the hot bubbles produced by supernova explosions are pervasive and interconnected, then it may be possible for hydrogen-ionizing photons produced by hot stars to travel large distances, creating the observed widespread diffuse ionized component to the interstellar medium (Reynolds 2004).

Molecular Clouds

The molecular medium (MM) is the coldest and densest phase of the interstellar medium and, by definition, represents regions where the hydrogen is almost entirely in molecular form. This medium is sufficiently dense that the molecules that form by gas phase and grain surface chemical reactions are shielded against ► [photodissociation](#) by the interstellar ultraviolet radiation field. This gas can be probed by emission produced from excited rotational transitions of molecules that are excited by collisions. Since molecular hydrogen is a symmetric molecule, it does not have a permanent electric dipole moment and hence has only weak electric quadrupole transitions. In addition, molecular hydrogen is a light molecule (small moment of inertia), and therefore the rotational levels are widely spaced in energy, so even the lowest excited rotational levels of molecular hydrogen are rarely excited by collisions in these cold clouds. Therefore, the millimeter and submillimeter wavelength rotational transitions of heavier molecules with permanent dipole moments, such as CO (the next most abundant molecule after molecular hydrogen), are commonly used to measure the distribution of molecular gas in galaxies. Numerous surveys of CO emission have

been obtained that have mapped out the distribution of the molecular gas in the Milky Way (Combes 1991). The molecular and atomic gas components of the Galaxy have different distributions; the molecular gas is much more concentrated toward the center of the Galaxy than the atomic gas. Although the molecular component contains a significant fraction of the total mass of the interstellar medium within 8 kpc of the Galactic Center, it occupies a negligible fraction of the volume.

The molecular medium is made up of discreet units commonly referred to as “molecular clouds.” These molecular clouds are sufficiently dense that self-gravity is important. In fact, it is believed the molecular clouds are close to gravitational equilibrium, where the internal pressure of the molecular gas (which is dominated by macroscopic motions called turbulence and not microscopic thermal motions) is balanced by a combination of the cloud’s self-gravity and the pressure of the external medium. The molecular clouds are observed to be grouped together to form molecular cloud complexes. The masses of these molecular clouds and molecular cloud complexes range from 5 to 2×10^6 solar masses and have sizes that range from 0.2 to 80 pc (Goldsmith 1987). Most of the molecular mass resides in the most massive molecular clouds (Combes 1991). The clouds have a mean particle number density of approximately 1000 cm^{-3} , while the average density of cloud complexes is lower. In the nearest of these molecular clouds, dust mixed with the gas absorbs the light of background stars, and these clouds appear dark – the so called dark clouds (reviewed by Bergin and Taffalla 2007) (see entry on ► [Dust Cloud, Interstellar](#)). Within molecular clouds are denser regions called molecular cloud cores with densities of order 10^4 – 10^6 cm^{-3} , and it is in these cores that the gas is gravitationally collapsing to form new stars. The theory of star formation is complex and was recently reviewed by McKee and Ostriker (2007).

The molecular clouds are also of great interest because of their rich chemistry. Over 150 molecules have been identified in molecular clouds, many of them containing five or more atoms

(See entry on ► [“Molecules in Space”](#)). These complex organic molecular species are of particular relevance for astrobiology, as they may survive the formation of the Solar System and later be delivered to the early Earth by cometary and asteroidal impacts.

Summary

Astronomers believe they have identified all of the major phases of the gas and dust in the interstellar medium and have a reasonable estimate of the physical properties of each of these phases. The picture of the interstellar medium that has emerged is a multiphase interstellar medium in which cooler denser “clouds” (molecular clouds and the CNM) are embedded in a much warmer less dense “intercloud” medium (WNM, WIM, and HIM). The interstellar medium is very dynamic, as supernova explosions carve expanding hot bubbles in the interstellar medium that are relatively long lived. Many believe that supernovae play a dominant role in shaping the interstellar medium. In the atomic gas, both ordered and turbulence motions can produce over-dense regions (“clouds”) where self-gravity can begin to dominate. The densest regions of these clouds can collapse and form new stars (see entries on ► [“Hot Core”](#), ► [“Hot Corino”](#), ► [Star Formation, Observations](#)). Thus, the gas is constantly being cycled between phases of the interstellar medium and in and out of stars.

However, astronomers are far from having a complete understanding of this multiphase interstellar medium in the Milky Way, let alone in other galaxies. Observationally, we need a much better three-dimensional picture of how the various interstellar medium phases are distributed in interstellar space, particularly the CNM, WNM, and HIM phases. Although we know much about the detailed microscopic processes at work in the gas and dust, we lack a detailed theoretical model for the interactions of these phases and how the interstellar medium evolves with time, cycling between phases and ultimately forming stars. Much observational and theoretical work is needed to fully

understand the interstellar medium and the star formation process in galaxies.

Cross-References

- [Absorption Spectroscopy](#)
- [Dense Cloud](#)
- [Diffuse Cloud](#)
- [Dust Cloud, Interstellar](#)
- [Electromagnetic Radiation](#)
- [HII Region](#)
- [Hot Core](#)
- [Hot Corino](#)
- [Interstellar Dust](#)
- [Magnetic Field](#)
- [Milky Way](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)
- [Shock, Interstellar](#)
- [Spectral Line](#)
- [Spectroscopy](#)
- [Star Formation, Theory](#)
- [Supernova](#)

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Interstellar Molecule

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

An interstellar molecule is a molecular species found in the ► [interstellar medium](#), primarily in ► [dense clouds](#) and in the regions surrounding ► [protostars](#) known as ► [hot cores](#) or ► [hot corinos](#). For a detailed description of the currently identified interstellar molecules, see the entry ► [Molecules in Space](#), which also includes circumstellar molecules.

Cross-References

- [Circumstellar Chemistry](#)
- [Dense Cloud](#)
- [Hot Core](#)
- [Hot Corino](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)
- [Protostars](#)

Interstellar Particles

► [Interstellar Dust](#)

Intervening Sequence

► [Intron](#)

Intron

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Intervening sequence](#)

Definition

In interrupted (split) ► [genes](#), intron is a part of the sequence that is present in the primary transcript but absent in the mature ► [RNA](#) sequence. The maturation of the RNA transcript of a split gene implies the specific removal of introns and the fusion of ► [exons](#) throughout the splicing process. Although the splicing involves sophisticated enzymatic machineries, in some cases, the elimination of introns is an autocatalytic process (self-splicing); in other words, it occurs in the absence of proteins since the RNA is catalytic (► [ribozymes](#) of group I introns) in nature.

Cross-References

► [Exon](#)
► [Gene](#)
► [Ribozyme](#)
► [RNA](#)

Io

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Keywords

Galilean satellites

Definition

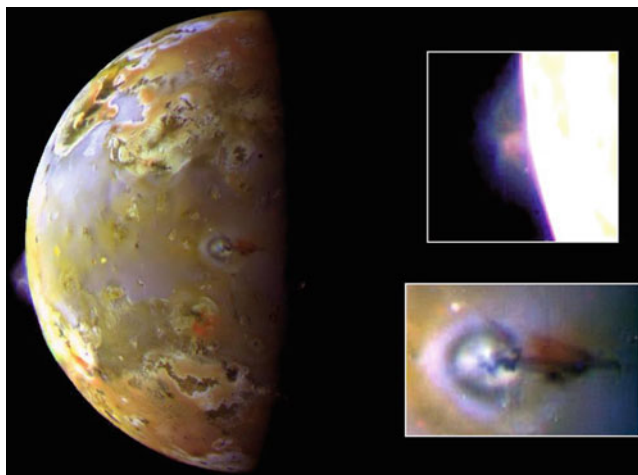
Io, discovered by ► [Galileo Galilei](#) in 1610 and named by Simon Marius (1614), is the Galilean satellite that is closest to ► [Jupiter](#). It orbits at a distance of 421,800 km (or about six Jovian radii) from the planet. With a diameter of 3640 km and a density of 3.5 g/cm³, Io is the densest Galilean satellite. This property is due to its proximity to Jupiter, which generates a strong internal energy due to tidal effects. As a result, in contrast with all other Galilean satellites, Io has lost all its water content.

Overview

Io's surface was revealed by the images of the ► [Voyager 1](#) spacecraft that flew over the satellite in March 1979 at a distance of only 20,500 km (or 11 satellite radii) and provided the first evidence for active volcanism outside the Earth. Io's surface shows no impact craters but several active volcanoes that replenish it on a short timescale. Fifteen years later, Io was explored again with the Galileo orbiter. From these observations, combined with the ► [HST](#) images, a temporal study of the volcanic evolution has been possible (Fig. 1).

The temperature of the active volcanoes can reach 1700 K, while the surrounding surface is at about 130 K. The main detected outgassed product is sulfur dioxide (SO₂), which freezes at the surface in white spots. Depending upon their temperatures, the sulfur compounds are black, red, or yellow. Silicate products are likely to be dominant

Io, Fig. 1 Io as observed by the Galileo spacecraft in 1995; note the volcanic plumes in the insets. (© NASA)



in the erupted magma, as indicated by the high temperature of the volcanoes. Their presence is consistent with models of Io's internal structure that predict a massive core of molten iron and (Fe, S) compounds, with a silicate mantle and crust.

The proximity of Jupiter induces a mechanical deformation due to tidal effects which would be stable in the absence of other satellites. However, due to gravitational perturbations linked to ► [Europa](#) and ► [Ganymede](#) (in resonance with Io), Io's deformation varies along its orbit, inducing a strong mechanical relaxation and heating, especially in the equatorial regions; this is where most of the volcanoes are found.

Io's volcanism produces a stable (although variable) atmosphere of gaseous SO₂ which was first identified in a plume by Voyager 1 in the infrared range and later confirmed from ground-based millimeter spectroscopy. The surface pressure ranges from 3 to 40 nanobars. SO and NaCl have been identified as minor atmospheric components by the same technique. Io's atmosphere is partially ionized by the ultraviolet solar radiation and by high-energy particles. This plasma is driven by the Jovian magnetic field to generate a torus around Jupiter at the distance of Io's orbit; indeed, Io's orbit crosses the Jovian magnetosphere. This torus was first detected through the ► [Ly \$\alpha\$](#) line by the Pioneer spacecraft. Further UV measurements led to the detection of S and O ions, and Na was detected

from visible ground-based observations. Io's torus was also studied in detail by the ► [Ulysses](#) spacecraft as it flew over the Jupiter system in 1992.

Cross-References

- [Europa](#)
- [Galileo Galilei](#)
- [Ganymede](#)
- [HST](#)
- [Jupiter](#)
- [Ulysses Mission](#)
- [Voyager, Spacecraft](#)

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IOM

- [Insoluble Organic Matter](#)

Ion Beams

► [Heavy Atom Beams](#)

Cross-References

► [Affinity Chromatography](#)
 ► [Chromatography](#)
 ► [HPLC](#)

Ion-Exchange Chromatography

Mark Dörr
 University of Southern Denmark, Odense M,
 Denmark

Synonyms

[IEC](#)

Definition

Ion-exchange chromatography (IEC) is a laboratory separation process for the separation of ions and polar molecules based on their charge. It can be used for a multitude of charged molecules, including large molecules, such as proteins and oligonucleotides, and small molecules, such as amino acids. The stationary phase commonly consists of a resin or gel with a covalently linked charged molecule. Depending on the charge, IEC can be either anion- or cation-exchange chromatography. It is often used for protein purification, DNA/RNA oligomer analysis, and water analysis.

History

Ion-exchange chromatography is one of the oldest separation processes described in the literature. In 1850, H. Thompson and J. T. Way treated various clays (as a stationary phase) with ammonium sulfate or carbonate in solution to release calcium. During World War II, ion-exchange chromatography was further developed and played a crucial role in the “Manhattan project” to enrich radioactive elements.

Ion-Neutral Reaction

Ian W. M. Smith
 Chemistry Laboratory, University of Cambridge,
 Cambridge, UK

Keywords

Chemical kinetics · Interstellar medium ·
 Long-range forces · Low temperatures · Rate
 coefficients

Synonyms

[Ion-molecule reaction](#)

Definition

An ion-neutral reaction is a chemical reaction that occurs in a binary collision between one electrically charged species, an ion, and one electrically neutral species. As with ► [neutral-neutral reactions](#), the crucial properties that are sought in kinetic experiments are the *rate coefficient* and its dependence on temperature, denoted by $k(T)$ and, in cases where two or more sets of products are possible, the *branching ratio*, that is, the fractions of the overall reaction that proceed via different channels. For a bimolecular reaction, say $A^+ + B \rightarrow C^+ + D$, the rate of the loss of the ion A^+ , that is, $d[A^+]/dt$, is given by $-k(T) [A^+][B]$, where the square brackets denote concentrations,

The field editor A. Canosa informs that Prof. I. W. M. Smith has unfortunately passed away in 2016. Therefore, the field editor has included some complements along this contribution to maintain it as updated as possible

Ian W. M. Smith: deceased.

usually expressed in cm^{-3} , so that the units of $k(T)$ are $\text{cm}^3 \text{s}^{-1}$.

History

The occurrence of gas-phase ion-neutral reactions has been recognized since the development of mass spectrometry in the early years of the twentieth century. The ready occurrence of such reactions was shown by the detection of ions that could not be formed by the direct ionization of any neutral species that were known to be present. Indeed, such spurious signals could be viewed as a nuisance when the primary purpose of the experiments was to analyze the species present in a mixture of neutral species. Systematic studies of these reactions began in the early 1950s (Herman and Smith 1992). Most of the experimental work on ion-neutral reactions has been on the reactions of positively charged ions (*cations*), which are known to play a key role in the chemistry of the ► [interstellar medium](#). However, the recent discovery of negatively charged ions (► [anions](#)) in the interstellar medium is now stimulating laboratory work on the reactions of these species (Bierbaum 2011; Biennier et al. 2022).

Overview

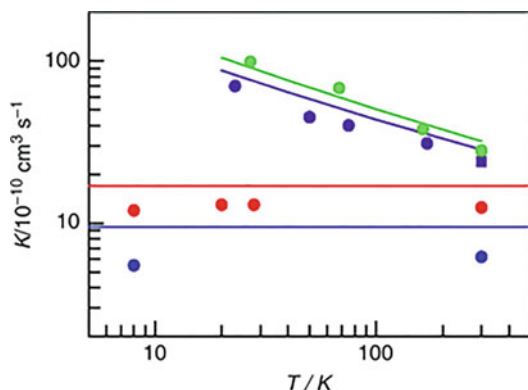
The existence of an electric charge on an ion causes an attractive force between it and a neutral molecule, which is strong and acts over long range, compared with the interaction between two neutral molecules. This force arises between the charge on the ion and an electric dipole which it induces in the molecule and, if the molecule itself possesses a permanent electric dipole, between this dipole and the charge. The existence of these strong forces is frequently sufficient to cancel out any potential energy barrier resulting from rearrangement of the electrons as bonds make and break. Consequently, the rates of ion-neutral reactions are generally controlled by the rate at which the reactants “capture” one another and are brought into close contact by the attractive interaction.

When the neutral molecule does not possess a dipole moment, as is the case for H_2 , N_2 , CO_2 , and CH_4 , the strength of the attraction depends only on the distance apart of the two species, and a simple treatment, usually attributed to Langevin, leads to the prediction that the rate coefficient (using c.g.s-esu units) is given by $k(T) = 2\pi e (\alpha/\mu)^{1/2}$, where e is the electronic charge on the singly charged ion, α is the polarizability of the neutral charged molecule, and μ is the reduced mass, $m_A^+ m_B / (m_A^+ + m_B)$, of the colliding reactants. This formula is (a) easy to evaluate and (b) predict that the rate coefficient for ion-neutral reactions of this kind will not depend on the temperature. However, when the neutral molecule possesses an electric dipole moment, for example, in molecules like H_2O and NH_3 , the treatment of the capture process becomes more complicated, because the force between the reactants now depends not only on their separation but also on the orientation of the dipole with the line joining the centers of the two species. Several theoretical approaches have been adopted. They agree that the *average* attraction becomes stronger as the temperature is lowered and consequently $k(T)$ increases. Formulae fitting this effect have been proposed (Wakelam et al. 2010).

Figure 1 displays the temperature-dependent rate coefficients that have been measured for several ion-neutral reactions, comparing the results for two reactions between He^+ or N^+ ions and the nonpolar molecules N_2 and O_2 with those for two reactions of N^+ with the polar molecules H_2O and NH_3 . The rate coefficients for the first two reactions do not depend on temperature and are fairly close to the values predicted by the Langevin treatment, whereas the rate coefficients for the reactions of N^+ with H_2O and NH_3 increase as the temperature is reduced.

Basic Methodology

Experiments designed to obtain the rate coefficients (and branching ratios) of ion-neutral reactions fall into two main categories (Smith 2011). One is where combinations of electric and magnetic fields are employed to “trap” the ionic



Ion-Neutral Reaction, Fig. 1 Examples of rate coefficients for ion-neutral reactions, comparing results for reactions of ions with nonpolar and polar molecules with one another and with simple predictions. Experimental data for $\text{He}^+ + \text{N}_2$ (●) and $\text{N}^+ + \text{O}_2$ (●) are compared with the respective Langevin predictions, — and —. The rate coefficients for $\text{N}^+ + \text{H}_2\text{O}$ (●) and $\text{N}^+ + \text{NH}_3$ (●, ■) are compared with predictions based on expressions recommended by Wakelam et al. (2010), — and —. The experimental data for $\text{He}^+ + \text{N}_2$ and $\text{N}^+ + \text{O}_2$ are taken from Rowe et al. (1985), those for $\text{N}^+ + \text{H}_2\text{O}$ from Marquette et al. (1985), and those for $\text{N}^+ + \text{NH}_3$ (a) ■ from Marquette et al. (1985) and (b) ● from Rowe et al. (1995)

reactant and observe the rate of its loss by reaction when a neutral molecule is introduced to the reaction cell. In the second method, the ions are injected into a flowing gas, and the loss of the ion is observed when the neutral co-reactant is introduced to the gas flow. As both methods employ mass spectrometric detection, it is, at least in principle, possible to observe product ions and hence to obtain branching ratios.

The earliest form of the trapping methods used ion cyclotron resonance, where ions are constrained by a combination of electric and magnetic fields. After the introduction of the neutral co-reactant and after a selected time delay, the ions are transferred to an “analyzer region” where their (relative) concentration can be monitored (McMahon and Beauchamp 1972). Ion cyclotron resonance experiments were responsible for many of the rate coefficients that were used in early models of the interstellar medium (Prasad and Huntress 1980). Although this method has largely been employed to determine rate coefficients at room temperature, as explained above, the dependence of the rate coefficients for ion-

neutral reactions on temperature is frequently straightforward to predict. Trapping methods to determine rate coefficients at very low temperatures have been developed over a number of years by Dunn (1995), Gerlich (1995, 2008), and their coworkers. These experiments, especially those of Gerlich using a 22-pole trap, enable ions to be stored for minutes, thereby allowing the rate coefficients for very slow processes, such as the radiative association of C^+ with H_2 to form CH_2^+ at 10 K, to be measured.

The so-called flowing afterglow method was pioneered by Ferguson and his coworkers in the 1960s (Fehsenfeld et al. 1966; Dunkin et al. 1968). It is similar to the flow tube methods used to study the kinetics of neutral-neutral reactions, though the gas flows are greater and the gas dynamics must be carefully analyzed to extract rate coefficients. Ions are created at the upstream end of the flow tube, and changes in their concentration are monitored at the downstream end, as neutral reactants are added at one or more points along the flow tube.

There have been two major developments to the basic flowing afterglow technique. The first, originating with Adams and Smith (1976), was the introduction of a quadrupole mass filter between the ion source and the main flow tube. This makes it possible to select the reactant ion and the method is generally known by the acronym SIFT for selected ion flow tube. The second development, which allowed the first measurements of rate coefficients below ca. 90 K, was the invention of the CRESU (Cinétique de Réaction en Ecoulement Supersonique Uniforme or Reaction Kinetics in Uniform Supersonic Flows) technique by Rowe et al. (1984). Some details of this method are given in the entry on “► Neutral-Neutral Reaction.” In the study of ion-neutral reactions, ions were generated by irradiation with an electron beam that crossed the supersonic flow of gas just downstream from the exit of the Laval nozzle. Although the CRESU method has been applied to a limited number of ion-neutral reactions, the results have been invaluable in demonstrating how the temperature dependence of the rate coefficients differs when ions react with nonpolar and polar molecules (see Fig. 1).

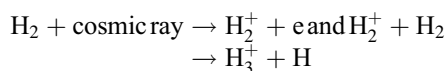
Key Research Findings

Measurements of the rate coefficients for a large number of ion-molecule reactions (Anicich 1993a, b) by the methods described in the previous section have confirmed that, for the majority (but not all) of exothermic reactions, the observed rate coefficients are close to those suggested by the simple capture theories and that the rate coefficients remain approximately the same or increase as the temperature is lowered. The rate coefficients may be lower than the simple predictions in those cases where both the ion and neutral species have unpaired electrons, since then reaction can only occur in the fraction of collisions in which electrons – one from each species – pair up to form a chemical bond.

Applications

Ion-molecule reactions play an important role in the chemistry of the upper levels of the Earth's atmosphere. However, and especially in the context of this encyclopedia, the principal application of the rate coefficients for ion-molecule reactions is in the modeling of the ► [interstellar medium](#), especially the cold (ca. 10 K) cores of dense, dark interstellar clouds, where H_2 is the dominant species present and where many of the known interstellar molecules have been detected.

The chemistry in these regions of the cosmos, which serve as the birthplace of stars, is initiated by the ionization of molecular hydrogen, H_2 , followed by the reaction of the H_2^+ ions that are formed with the relatively abundant H_2 molecules to form H_3^+ :



The proton affinity of H_2 is not very high so the ion H_3^+ can undergo facile ion-molecule reactions in which a proton is transferred from it to a neutral reactant. This occurs with O atoms, C atoms, and N_2 , creating OH^+ , CH^+ , and N_2H^+ and initiating networks of (largely) ion-molecule reactions that

lead, inter alia, to molecules such as H_2O , CH_4 , and NH_3 .

It is worth mentioning that ion-molecule reactions found a practical outlet in analytical technologies since they chemically generate ion products that are identifiers of the neutral partner B. Devices like the selective ion flow tube–mass spectrometer (SIFT-MS) or the proton transfer–mass spectrometer (PTR-MS) and their various derivatives are based on the knowledge of rate coefficients and branching ratios of ion-molecule reactions at room temperature involving either H_3O^+ , NO^+ , or O_2^+ . These tools are presently widely used to identify and quantify trace concentrations of volatile organic compounds (Spanel et al. 2019) in the air outdoors or indoors.

Future Directions

Recent modeling calculations (Wakelam et al. 2010), which identify the reactions that are key in determining the abundances of the major molecular species observed in ► [dense interstellar clouds](#), have shown that reactions of ions with radical atoms are especially important. Such reactions have been studied recently at room temperature in SIFT experiments in which flow-discharge techniques (see section on “► [Neutral-Neutral Reaction](#)”) are used to generate measured concentrations of atoms. The results of these experiments – on reactions of both positive and negative ions – have been reviewed by Snow and Bierbaum (2008). The rate coefficients of such reactions may be lowered if the ion as well as the radical atom has unpaired electrons. Furthermore, although radical atoms cannot possess an electric dipole moment, additional attraction to an ion can arise if the electrons in the atom are not symmetrically distributed around its nucleus, and this can lead to an acceleration in the rate of reaction with an ion as the temperature is lowered. This effect is predicted for the important reaction of O atoms with H_3^+ ions (Bettens et al. 1999; Klippenstein et al. 2010). Experimental confirmation of these predictions is desirable.

Determination of branching ratios (see section “[Definition](#)” above) is also of fundamental

importance for chemical networks trying to mimic the interstellar medium chemistry. Although there is now a great deal of data at room temperature, the temperature dependence of branching ratios is generally unknown and data below 200 K are essentially nonexistent (Biennier et al. 2022). It is often assumed that branching ratios do not depend on temperature but this needs to be verified either experimentally or theoretically. As a matter of example, the reaction of He^+ with methyl formate (HCOOCH_3) is expected to form only $\text{HOCO}^+ + \text{CH}_3$ in astrochemical networks. However, recent experimental investigations (Ascenzi et al. 2019) at high temperature revealed that the $\text{HCO}^+ + \text{CH}_3\text{O}$ route was largely dominant (83%) and other minor channels were also identified forming CH_3^+ (7%), OCH_3^+ (4%), or CH_2^+ (4%) whereas HOCO^+ was totally negligible (<1%). Will the branching ratios be identical at the very low temperatures of dense interstellar clouds? Further laboratory investigations are clearly desirable for this system and many others.

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Langevin Rate Coefficient](#)
- [Molecular Beams](#)
- [Neutral-Neutral Reaction](#)
- [Reaction Rate Coefficient](#)
- [Supersonic Jet Expansions](#)

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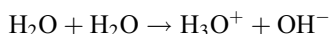
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Ionization Constant

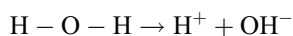
Henderson James Jim CleavesII
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA

Definition

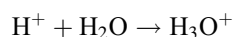
An ionization constant refers to the degree that an ionic bond is dissociated in solution. This can describe many important chemical phenomena, including acid and base dissociation and water self-ionization. The self-ionization of water occurs when two water molecules disproportionate to yield a hydronium (H_3O^+) ion and a hydroxide (OH^-) ion:



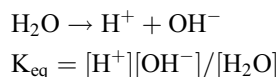
The occurrence of this reaction is evidenced by the electrical conductivity of pure water. The ionization of water actually occurs in two steps. First, the electronegative oxygen atom in water abstracts the electron from an attached hydrogen atom, yielding a proton which may dissociate:



The resulting hydrogen ion (or proton, H^+) may then react with another water molecule to form the hydronium ion:



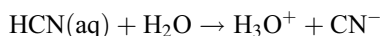
In pure water at 25°C, the concentration of H_3O^+ or OH^- ions at equilibrium is 10^{-7} M. The equilibrium between the ions and the water molecules can be used to define the ionization constant of water:



The concentration of each molecule is expressed in terms of molarity. Substituting the values of 10^{-7} M given above and the molarity of water ($1000 \text{ g L}^{-1} * 1/18 \text{ moles g}^{-1} = 55.5 \text{ M}$) gives an equilibrium constant (the ionization constant) of $1.8 * 10^{-16}$ M. But since the concentration of water is generally nearly constant in most contexts (depending on temperature and ionic strength, though, among other factors), the expression below is typically used:

$$K_w = [\text{H}_3\text{O}^+][\text{OH}^-] = 10^{-14}$$

Acid and base behavior can also be described in terms of ionization constants. Acid dissociation constants, which are a specific type of ionization constant, describe the extent to which an acid dissociates, for example:



At equilibrium, the rates of the forward and back reactions are equivalent, and the concentrations of the products and reactants are essentially constant. Their equilibrium relationship (the acid dissociation constant K_a) can then be expressed:

$$K_a = [\text{H}_3\text{O}^+][\text{CN}^-]/\text{HCN}$$

Similar calculations can be carried out for any compound which tends to dissociate to give ionic species in solution, including salts and metal-ligand complexes.

Cross-References

► [pH](#)

Ionizing Radiation, Biological Effects

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Synonyms

[Biological radiation effects](#)

Definition

Radiation interacts with matter primarily through ionization and excitation of electrons in atoms and molecules. There are two alternative ways of radiation damage to biological key substances: either by direct energy absorption (direct radiation effect) or via interactions with radicals, for example, those produced by radiolysis of cellular water molecules (indirect radiation effect). For direct radiation effect, the mean number of injured molecules, for example, DNA, is directly proportional to the dose. For indirect effects, the number of changed molecules increases with increasing ► [linear energy transfer \(LET\)](#). ► [Mutations](#), cancer induction, and cell death are the most critical biological radiation effects.

Cross-References

- [Biostack](#)
- [Cosmic Rays in the Heliosphere](#)
- [DNA Damage](#)
- [DNA Repair](#)
- [HZE Particle](#)
- [Linear Energy Transfer](#)

- [Mutagen](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Nucleic Acids](#)
- [Radiation Biology](#)
- [Radiation Dose](#)

Ion-Molecule Reaction

- [Ion-Neutral Reaction](#)

IRAS

- [Infrared Astronomical Satellite](#)

IRAS16293-2422

Audrey Coutens

Laboratoire d'Astrophysique de Bordeaux, Pessac, France

Keywords

Star formation · Protostar · Astrochemistry · Prebiotic species · Deuterium fractionation · Large spectral surveys · Atacama Large Millimeter Array · Herschel Space Observatory

Definition

IRAS 16293-2422 is a low-mass ► [protostar](#) located at a distance of 141 (+30, −21) pc (Dzib et al. 2018) in the L1689 cloud, which is part of the Rho Ophiuchi ► [molecular cloud](#) complex. This binary source is formed of the components IRAS 16293A and IRAS 16293B, which are separated by 5.1 arcsec (i.e., 719 AU at 141 pc). This deeply embedded object belongs to the Class 0 stage (André et al. 1993) and is well-known for its richness in ► [complex organic molecules](#) as well as its high ► [deuterium](#) fractionation.

History

This source detected in the 1980s with the ► [Infrared Astronomical Satellite](#) was quickly known for its rich molecular line spectrum (e.g., van Dishoeck et al. 1995). The interest for this protostar strongly increased with the detection of a wide variety of ► [complex organic molecules](#) characteristic of hot molecular cores (e.g., CH₃CHO, CH₃OCHO, CH₃OCH₃, and C₂H₅CN) by Cazaux et al. (2003). It was the first time that such molecules were found in a low-mass ► [protostar](#). To better characterize its molecular content, several large spectral surveys were subsequently observed towards this source:

- The IRAS 16293-2422 millimeter and submillimeter spectral survey (TIMASSS, Caux et al. 2011) at 3, 2, 1, and 0.9 mm with the IRAM 30 m and JCMT single-dish telescopes
- The Chemical HERSchel spectral survey (CHESS, Ceccarelli et al. 2010) with the HIFI instrument on board the ► [Herschel](#) Space Observatory between 480 GHz and 1.9 THz
- A high angular resolution survey of several bands in the 215.6–231.4 GHz and 336.8–353.1 GHz ranges with the Submillimeter Array (Jørgensen et al. 2011).
- The Protostellar Interferometric Line Survey (PILS, Jørgensen et al. 2016) with the Atacama Large Millimeter/submillimeter Array (► [ALMA](#)) between 329 and 363 GHz

These different ► [molecular line surveys](#) led to the most complete molecular census in a Class 0 protostar, which makes IRAS 16293-2422 an astrochemical template for this type of sources.

Overview

Physical Structure

IRAS 16293-2422 breaks up into two protostellar components, IRAS 16293A and IRAS 16293B. A dust filament connects the two protostars

(Pineda et al. 2012; Jørgensen et al. 2016). According to a 3D modelling of the source (Jacobsen et al. 2018), IRAS 16293A (18 solar luminosities) would be more luminous than IRAS 16293B (3 solar luminosities). Some previous high angular resolution observations suggested that IRAS 16293A could be a binary itself with its two components separated by about 1'' (e.g., Chandler et al. 2005). It was, however, not confirmed with recent ALMA observations of the source (Jørgensen et al. 2016). This would, consequently, rather support the presence of a relatively edge-on disk, as suggested by a velocity gradient observed in the North East-South West direction (e.g., Pineda et al. 2012). The lines observed with ALMA towards IRAS 16293B show inverse P-Cygni profiles, which indicates that the gas is infalling in the inner regions of this component. An East-West bipolar outflow and a North West-South East outflow are seen around IRAS 16293A, while no obvious outflow seems to come from IRAS 16293B (Yeh et al. 2008; Kristensen et al. 2013).

Chemistry

Thanks to the numerous spectral surveys carried out towards IRAS 16293-2422, it was found that this low-mass source is as chemically rich as massive hot cores. Most of the first detections of ► [complex organic molecules](#) in solar-type protostars were obtained towards IRAS16293-2422. Some of the detected molecules present a prebiotic interest: for example, the simplest sugar-type molecule, ► [glycolaldehyde](#) (CH₂OHCHO, Jørgensen et al. 2012), the molecules with a peptide-like bond, ► [formamide](#) (NH₂CHO, Kahane et al. 2013) and methyl isocyanate (CH₃NCO, Ligerink et al. 2017; Martin-Domenech et al. 2017), and ► [cyanamide](#) (NH₂CN, Coutens et al. 2018). IRAS 16293-2422 is also famous for its first interstellar detections of ► [chloromethane](#) (CH₃Cl, Fayolle et al. 2017) as well as many deuterated ► [complex organic molecules](#) (Coutens et al. 2016; Jørgensen et al. 2016).

Cross-References

- ALMA
- Chloromethane (CH₃Cl)
- Complex Organic Molecules
- Cyanamide
- Deuterium
- Formamide (NH₂CHO)
- Glycolaldehyde (HOCH₂CHO)
- Herschel Mission
- Infrared Astronomical Satellite
- Molecular Cloud
- Molecular Line Survey
- Protostars

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IRC+10216

Hans Olofsson

Department of Earth and Space Sciences,
Chalmers University of Technology, Gothenburg,
Sweden

Definition

IRC + 10216, also known by its variable star name CW Leonis, is a ► [red giant](#) star on the asymptotic giant branch with a carbon-rich atmospheric composition, i.e., the atmospheric abundance of carbon exceeds that of oxygen. It is probably the most nearby object of its kind, and it loses substantial amounts of matter from its surface. This stellar wind creates a dense circumstellar envelope which is rich in molecules and carbon dust. More than 80 different circumstellar molecular species have been detected, the majority being long, unsaturated, carbon chains of different types (incl. anions) and many of them being unique to the circumstellar medium.

Cross-References

- [Circumstellar Chemistry](#)
- [Molecules in Space](#)

Iridium

Philippe Claeys

Analytical-Environmental & Geo-Chemistry,
Vrije Universiteit Brussel, Brussels, Belgium

Definition

Iridium is a hard, brittle, corrosion-resistant metal with the symbol $_{77}\text{Ir}$. It is one of the platinum group elements (or PGE) – ruthenium, rhodium, palladium, rhenium, osmium, iridium, and platinum – which are highly siderophilic and form

strong bonds with iron. Most of the terrestrial PGE are concentrated in the core, leaving the mantle and crust highly depleted in Ir (ca. 3 and < 0.05 ppb, respectively). In comparison, undifferentiated meteorites (meteorites that have not suffered geological evolution) are enriched in PGE (ca. 200–500 ppb). Elevated PGE concentrations measured in terrestrial rocks can indicate a meteoritic contribution. The detection of the iridium enrichment in the KT Or K-Pg boundary clay layer first found in Gubbio, Italy, and then confirmed all over the world, led to the meteoritic impact hypothesis as a possible cause of the dinosaur extinction. The determination of PGE elemental ratios in impactites can contribute to the identification of the type of impacted meteorite.

Cross-References

- [Chicxulub Crater](#)
- [Crater, Impact](#)
- [Impact Melt Rock](#)
- [Impactite](#)
- [KT Boundary](#)
- [Mass Extinctions](#)
- [Siderophile Elements](#)

Iron

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Iron is a transition element with three natural states of oxidation Fe^0 (metal), Fe^{2+} , and Fe^{3+} . It is abundant in planetary material, mostly as Fe^0 and Fe^{2+} . In the Earth, most iron resides in the metallic core and in the mantle where it forms abundant minerals, with Mg. Under hydrous conditions, Fe^{2+} is highly soluble, whereas Fe^{3+} is

highly insoluble and precipitates as iron (oxi)-hydroxy. In contact with the atmosphere ($\text{H}_2\text{O}-\text{O}_2$) the stable form of iron is Fe^{3+} . Iron sulfides (e.g., ► [pyrite](#)) are highly insoluble. Iron is a fundamental element for life. Iron plays a major role in critical cellular functions like ► [respiration](#), nitrogen fixation, or oxygen detoxification. Under anoxic conditions, iron is generally in its reduced state (ferrous iron, Fe^{2+}) and soluble. In aerobic conditions, iron is generally oxidized (ferric iron, Fe^{3+}) forming different insoluble minerals. At neutral pH, iron is insoluble and non-bioavailable. Consequently, organisms produce iron-binding agents called siderophores that efficiently bind iron and transport it into the cell. Iron is a good ► [electron donor](#), so it can be used as a source of energy, and also is an ► [electron acceptor](#), thus can be used for ► [anaerobic respiration](#). Iron-oxidizing and iron-reducing microorganisms are the base of the biogeochemical cycle of this element. Ferric iron is also a good buffer, controlling the pH at acidic conditions and a protective agent against UV radiation, a property of astrobiological interest. The UV irradiation of ferrous iron, the Fenton reaction, produces very reactive radicals that can damage functional sites of proteins and nucleic acids. Iron is stored in ferritin particles in its oxidized, less reactive form, to protect cells. This protective mechanism is ancestral and universal. Ferritins are found in most organisms from the three domains. Some prokaryotes can grow in the absence of iron like *Lactobacillus plantarum* or *Borrelia burgdorferi*. In these bacteria, Mn^{2+} substitutes for iron as the metal component of enzymes that normally contain Fe^{2+} .

Cross-References

- [Chemolithoautotroph](#)
- [Chemolithotroph](#)
- [Electron Acceptor](#)
- [Electron Donor](#)
- [Electron Transport](#)
- [Iron Cycle](#)
- [Respiration](#)

Iron Carbonate

- [Siderite](#)

Iron Cycle

Ricardo Amils

Departamento de Biología Molecular,

Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Chemolithotrophy · Electron acceptor · Electron donor · Iron · Iron oxidation · Iron reduction

Definition

The ► [iron](#) cycle is the biogeochemical cycle that couples the oxidation and reduction reactions of iron, a key element for life.

Overview

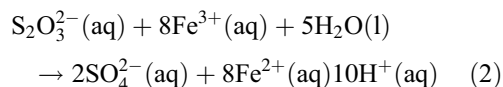
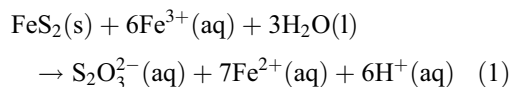
Iron is one of the most abundant elements in the universe. On the Earth's surface and in its crust, iron exists in two oxidation states, ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron. Fe^0 does not exist in nature; it is a major product of industrial activity generated by smelting iron minerals to produce cast iron. The oxidation of ferrous iron can be produced both chemically and biologically through chemolithotrophy. The reduction of ferric iron occurs geochemically and in ► [anaerobic respiration](#), as the result of its use as an ► [electron acceptor](#). Ferric iron precipitates at neutral and alkaline pH as ferric hydroxide.

Iron Oxidation

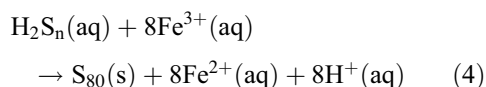
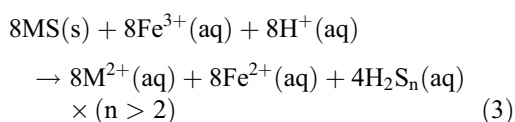
At neutral pH, ferrous iron is oxidized rapidly in the presence of oxygen. Several prokaryotic microorganisms can obtain energy by oxidizing reduced ferrous iron. In neutral habitats, Fe^{2+} can

be oxidized by iron bacteria such as *Gallionella* and *Leptothrix*. In this case, these microorganisms require mechanisms that can compete efficiently with the rapid chemical oxidation produced by oxygen. These microorganisms grow mainly at interfaces between ferrous-rich anoxic groundwaters and air. However, the most extensive microbial iron oxidation occurs at acidic pH, where Fe^{2+} is stable and not subject to spontaneous oxidation. In extremely acidic habitats, the acidophilic chemolithotrophic *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* oxidize Fe^{2+} to Fe^{3+} . Very little energy is produced in this reaction; thus these microorganisms must oxidize large amounts of iron to generate enough energy to grow. *A. ferrooxidans* and *L. ferrooxidans* are phylogenetically, morphologically, and metabolically very distinct. While *L. ferrooxidans* can grow only on Fe^{2+} , *A. ferrooxidans* grows chemolithotrophically on either ferrous iron or reduced sulfur compounds, such as elemental sulfur (S^0).

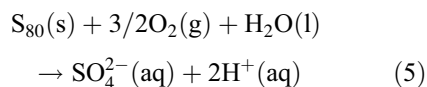
One of the most common forms of iron in nature is ► [pyrite](#). Bacterial oxidation of pyrite is of great environmental (generation of acid mine drainage) and biotechnological (biomining) importance. The mechanisms by which acidophilic chemolithotrophs can obtain energy from mineral sulfides have been a source of controversy for many years. But the demonstration that the ferric iron present in the cell wall and the extracellular polysaccharides of these microorganisms are responsible for the electronic transfer from the insoluble mineral substrate (pyrite) to the electron transport chain has clarified this issue, with important fundamental and applied consequences. As we will see, the oxidation of sulfides is a combination of chemically and microbially catalyzed reactions. The differences observed during the bioleaching of diverse metallic sulfides are a consequence of the chemical attack mechanisms, which depend on the crystallographic structure of the mineral substrates. In nature, three sulfides, pyrite, molybdenite, and tungstenite, can be oxidized by ferric iron through the so-called thiosulfate mechanism shown in Eqs. 1 and 2:



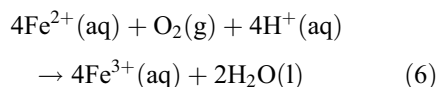
The sulfuric acid produced in these reactions requires only the oxidative action of ferric iron. The rest of the sulfides (sphalerite, galena, chalcopyrite, etc.) undergo oxidation through the polysulfide mechanism (Eqs. 3 and 4):



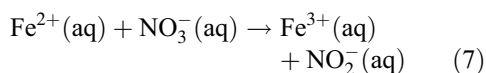
In this case, there is no direct production of sulfate. The elemental sulfur can be further oxidized by sulfur-oxidizing microorganisms generating sulfuric acid according to Eq. 5:



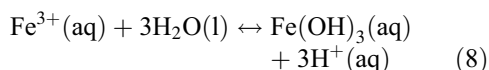
The critical role of iron-oxidizing microorganisms, such as *L. ferrooxidans* and *A. ferrooxidans*, in the bioleaching of metal sulfides is to maintain a high concentration of the oxidizing agent, ferric iron (Eq. 6):



Furthermore, it is now well established that iron can be oxidized anaerobically in the absence of oxygen using nitrate (and probably other compounds) as an electron acceptor (Eq. 7):



In addition, the hydrolysis of ferric iron further releases protons, a buffer reaction that is responsible for the constant pH observed in these systems (Eq. 8):



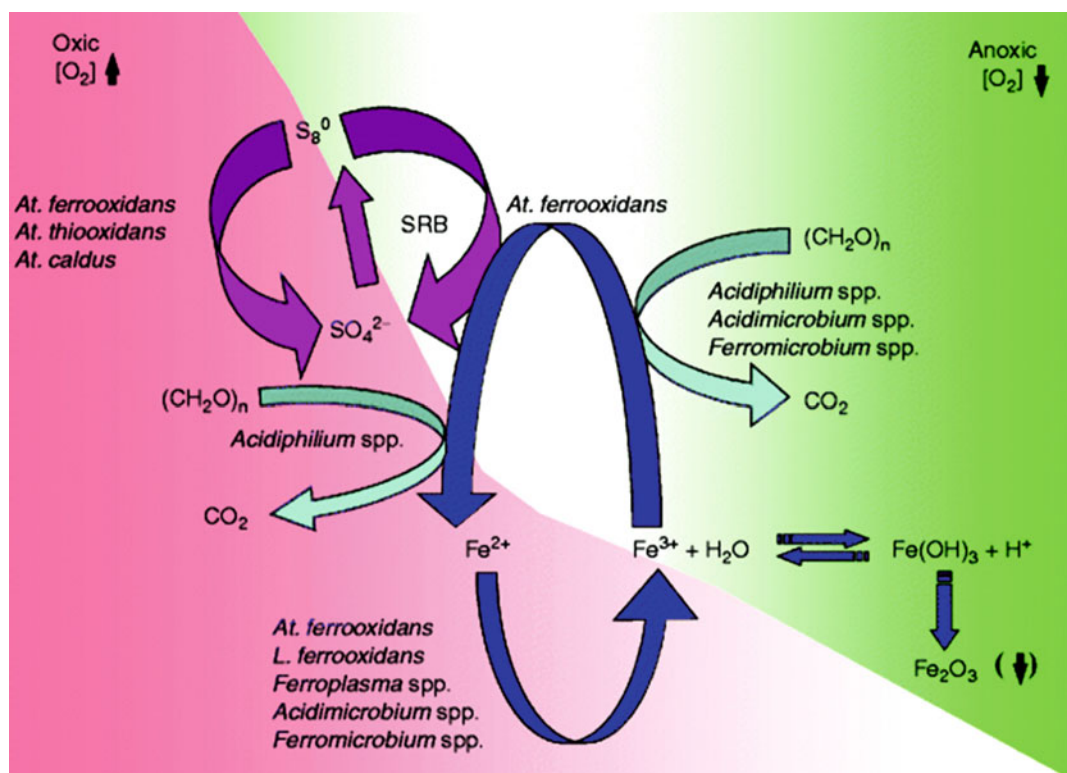
These reactions explain most of the properties observed in different extreme acidic environments, which are under the control of iron (Fig. 1).

Iron Reduction

Many microorganisms can use ferric iron as an electron acceptor (e.g., *A. ferrooxidans*, *Acidiphilium* spp., or *Geobacter metallireducens*, which in anoxic conditions can obtain energy respiring anaerobically). Ferric iron reduction is

common in anoxic environments such as lake sediments and bioleaching heaps. Movement of iron-rich groundwater from anoxic waterlogged soils can result in the transport of large amounts of ferrous iron. When this iron-laden water reaches oxic environments, ferrous iron is oxidized chemically or by iron-oxidizing microorganisms, precipitating ferric compounds. Ferric hydroxide precipitates can interact with reduced organic compounds, like humic acids, to reduce ferric iron back to ferrous iron. Ferric iron can also form complexes with different organic compounds. In this way, iron becomes solubilized and once again available to ferric-reducing microorganisms as an electron acceptor.

In Fig. 1, a display of the iron cycle operating in the Río Tinto basin coupled to a sulfur cycle is shown. Due to their characteristics, the iron and sulfur cycles are considered important model systems of astrobiological interest.



Iron Cycle, Fig. 1 Geomicrobiology of the Río Tinto basin, a geochemical terrestrial analog of Mars, showing the microbial activities associated with the operation of the iron and sulfur cycles

Cross-References

- [Acidophile](#)
- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Biogeochemical Cycles](#)
- [Chemolithotroph](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [Iron](#)
- [Lithotroph](#)

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Iron Isotopes

Franck Poitrasson
Géosciences Environnement Toulouse, CNRS,
Toulouse, France

Keywords

Biomarkers (isotopic) · Isotope geochemistry · Meteorites · Plasma source mass spectrometry · Prokaryotes

Definition

Iron has four naturally occurring stable isotopes: ^{54}Fe , ^{56}Fe , ^{57}Fe , and ^{58}Fe of respective abundances 5.80%, 91.72%, 2.20%, and 0.28%. They are increasingly used to determine the source of the iron present in geological or biological materials and/or to characterize the chemical reactions that may have led to the form of iron under study. The isotopic signature of Fe is particularly sensitive to redox effects, including certain biological reactions such as bacterial dissimilatory iron reduction (DIR).

Overview

Although less variable in abundances than carbon or oxygen stable isotopes, iron isotopes show analytically significant mass-dependent isotopic variations in nature. The geochemical community has investigated the range of Fe isotope compositions in both high- and low-temperature geological environments. Contrary to early expectations, there are no specific biological-type iron isotope signatures. On the other hand, the largest isotopic fractionation was observed for low-temperature redox reactions, and biological dissimilatory iron reduction (DIR) is one of those biological reactions that affect significantly iron isotope compositions. Another requirement for inorganic or organic reactions to leave an isotopic imprint is that the reaction exchange is not complete, that is, not all of the original pool of iron has been consumed. Nature-based and experimentally based astrobiology studies have shown that iron isotopes are particularly useful to study traces of life and/or their environment when used in conjunction with other mineralogical, biological, and chemical indicators.

Basic Methodology

The isotopic composition of iron in natural samples has been measured since the 1940s by electron impact ionization and, more recently, by thermal ionization mass spectrometry (TIMS) after sample dissolution and chemical purification

using anion exchange chromatography. The level of precision reached relative to natural variations rendered the study of Fe isotope signatures of little interest until the end of the twentieth century. The advent of the second generation of multiple collector inductively coupled plasma mass spectrometers (MC-ICP-MS) led to an order of magnitude improvement in analytical precision (Belshaw et al. 2000). This opened the way to an exponential development of these “non-traditional isotopes,” such as iron isotopes. Although the purification chemistry is straightforward and has been known for some time (Strelow 1980), MC-ICP-MS techniques vary among laboratories. Mass bias corrections range from the simple sample-standard-bracketing approach to more sophisticated Cu- or Ni-doping methods. A few groups have also adopted the double spike technique, which remains the only way to determine precise Fe isotope composition by TIMS. Isotopic results are conventionally reported using the delta notation with reference to the IRMM 14 reference material (unfortunately no longer available from the European Institute for Reference Materials and Measurements, Geel, Belgium, but it may be conveniently replaced by the IRMM 524A reference material) that has a composition close to that of chondrites. For example,

$$\delta^{57}\text{Fe} (\text{‰}) = \left(\frac{{}^{57}\text{Fe}/{}^{54}\text{Fe}_{\text{sample}}}{{}^{57}\text{Fe}/{}^{54}\text{Fe}_{\text{IRMM14}}} - 1 \right) \times 10^3$$

and this notation can be equally defined for $\delta^{56}\text{Fe}$. Some groups still report their Fe isotope compositions with reference to average of igneous rocks. Although being isotopically homogeneous, this convention should be abandoned since some igneous rocks depart significantly from this average value (e.g., some granites from the Earth's continental crust; Poitrasson and Freydier 2005), and therefore, this may generate some confusion among nonspecialists.

Key Research Findings

A first important finding is that the iron isotope compositions of igneous rocks that form the

Earth's crust vary very little. As a result, they make a baseline against which low-temperature, superficial biogeochemical processes that display larger isotope variations may be compared to (Beard et al. 2003; Poitrasson 2006). Various field-based, experimental, and especially theoretical studies conducted over the past two decades revealed that the main driving factors generating Fe isotope variations are redox and coordination chemistry changes. For example, the largest equilibrium Fe isotope fractionation among two coexisting iron reservoirs ($\sim 4.5\text{‰}$ in $\delta^{57}\text{Fe}$) was observed between aqueous Fe^{2+} and Fe^{3+} species (Welch et al. 2003; Anbar et al. 2005). The importance of the bonding environment on Fe isotope signatures is best illustrated by theoretical prediction of Fe isotope fractionation between mineral phases holding iron in the same redox state, but with different network-forming anions, such as in sulfide and carbonate minerals (Polyakov and Mineev 2000; Blanchard et al. 2009). Ab initio computations also illustrate the importance of iron coordination chemistry and nature of aqueous ligands to interpret the Fe isotope composition of environmental samples (Fujii et al., 2014). The finding that mass-dependent Fe isotope variation occurs in nature is interesting in itself. Even more important however is the discovery that for the same rocks, the stable isotopes of iron show contrasted fractionation when compared to those of carbon (Matthews et al. 2004). Although not unexpected given the contrasted interatomic bonding environments of Fe and C, this illustrates that the stable isotopes of different elements can trace different processes and/or different properties of the studied reservoirs. As such, combining different isotopic tracers is certainly a promising approach for future research, notably to detect biological activity (Johnson et al. 2008; Severmann and Anbar 2009).

Applications

Since astrobiology aims at looking for traces of life on the early Earth and on planets other than the Earth, one would ideally do precise Fe isotope measurements of extraterrestrial samples to

determine signatures that could be tracking life or at least environmental conditions suitable for life. However, the need for high-precision mass spectrometry methods that were established in terrestrial laboratories over the past decade makes such delicate measurements on robotic missions on other planets impossible at present. Aside for the Moon that has never been prone to the development of life since the beginning of its history given its extreme temperatures, lack of liquid water, and lack of atmosphere, we should wait for sample return missions from other planetary bodies. In the meantime, we have to rely on meteorites thought to come from planets where life may have existed, such as Mars. However, Martian meteorites that belong to the Shergotty, Nakhla, and Chassigny (SNC) class are essentially igneous rocks. Hence, looking for traces of life on those rocks using iron isotopes was unsuccessful (Anand et al. 2006). This was not unexpected given that even if traces of life were searched on bulk terrestrial fresh igneous rocks, the igneous rock Fe isotope signature would have likely overwhelmed the biologically processed Fe. Another limitation is that despite initial expectation (Beard and Johnson 1999), there are, like for carbon isotopes, no unique Fe isotope biological signatures (Anbar et al. 2000). Indeed, inorganic processes may also produce strong Fe isotope fractionation leading to light products, notably when kinetic effects are involved. Hence, the use of Fe isotopes to search for traces of biological activity should necessarily be conducted in conjunction with other mineralogical, chemical, and isotopic indicators.

Astrobiology also looks at extreme terrestrial environments where life may occur despite hostile conditions. This is the case of acid mine drainage waters from the ► [Rio-Tinto-Odiel](#) sulfide deposit basin, southern Spain, that is characterized by anomalously acidic waters ($1.5 < \text{pH} < 3.9$) containing elevated concentrations of dissolved Fe ($>20,000$ ppm). Despite these conditions, bacterial activity occurs. This geological setting is of interest to astrobiologists because it forms specific minerals including ► [jarosite](#) that also occur at the Martian

Meridiani Planum site. Iron isotopes were used by Egal et al. (2008) to study this Spanish site. Although the biological activity imprint could not be detected through Fe isotope compositions, this study combined mineralogical, aqueous geochemistry, and iron isotope determinations to put constraints on the mechanisms that led to the formation of such an extreme geochemical environment on Earth.

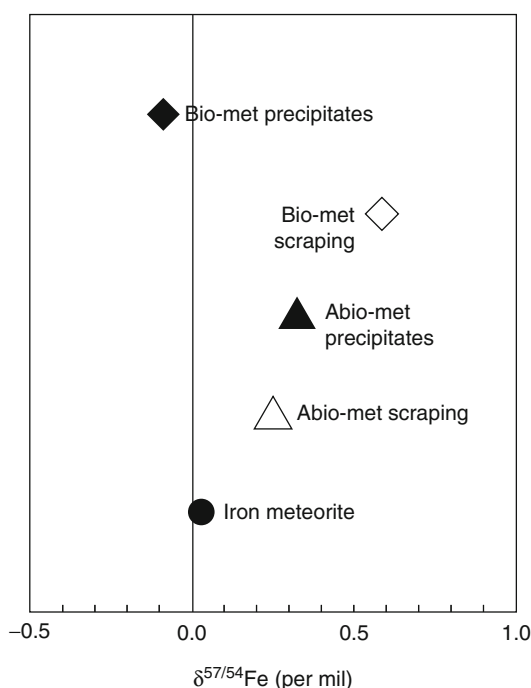
Archean ► [apex cherts](#) from Marble Bar, Western Australia, is another interesting geological case study for astrobiologists since it has been claimed to contain the oldest fossils of microbes found yet on Earth, ca. 3.5 Ga years ago, although this finding generated a lot of debate. Pinti et al. (2007) used iron isotopes to study Fe-Mn-oxyhydroxides containing C and N with a biological-like isotopic signature that occur in these cherts. They found $\delta^{57}\text{Fe}$ values compatible with oceanic hydrothermal precipitation, thereby strengthening the inference that C and N isotope compositions mark 3.5 Ga old biological activity.

Archean banded iron formations (BIFs) are also obvious geological records to look for ancient traces of life. Combining a detailed petrographic study with C, O, and Fe isotope investigations of carbonates from these sedimentary formations led Heimann et al. (2010) to highlight the importance of bacterial dissimilatory iron reduction back to ca. 2.5 Ga ago. Studying again Fe and C isotopes in magnetites and carbonates from BIFs of ca. 2.5 and 3.8 Ga, Craddock and Dauphas (2011) concluded that this bacterial process is in fact recorded in the oldest available sedimentary rocks we have on Earth.

Experimental investigations may also help to study processes that may have occurred on the early Earth. For example, Gronstal et al. (2009) examined experimentally how the first living organisms on Earth, that is, prokaryotes, could have extracted energy by oxidizing metallic iron from meteoritic material. Such a form of Fe, which is nearly nonexistent on the present Earth's surface, was supposedly abundant at that time corresponding to the end of the ► [Late Heavy Bombardment](#), and there was an anoxic atmosphere. Interestingly, these authors found that whereas metal weathering occurred regardless of

the presence of iron-oxidizing bacteria, the weathering products clearly showed isotopically contrasted iron pathways during oxidation with and without bacteria. This suggests that the biological action in meteorite weathering could be highlighted with Fe isotopes (Fig. 1).

Among subsequent experimental studies, Amor et al. (2016) investigated the Fe isotope fractionation during the growth of magnetotactic bacteria and found a unique mass-independent iron isotope fractionation between the culture medium and the bacterially produced magnetites. The next challenge is to find geological formations where this effect can be recorded despite obvious risks of dilution of this isotopic signature in the rock matrix (Amor et al., 2020).



Iron Isotopes, Fig. 1 Products of iron meteorite weathering in aqueous solutions with (Biomet) and without (Abiomet) iron-oxidizing bacteria. Both the weathered layers at the surface of the meteorites (scraping) and precipitates elsewhere in the experimental cell (precipitate) were sampled. Iron isotope composition relative to the starting meteorite shows contrasted Fe isotope signatures for these weathering products with and without bacteria, suggesting contrasted reaction pathways (Error bars within symbols; From Gronstal et al. 2009)

Future Directions

Iron isotopes have not yet been applied frequently to astrobiology problems. More case studies therefore need to be investigated, either experimentally, and from natural examples of extreme terrestrial environments, or of the oldest remains of the early Earth. There are however more fundamental issues that need to be addressed first to be able to fully exploit the potential of iron isotope signatures in this endeavor. In a number of studies, equilibrium isotopic fractionation between phases is taken as a reference against which the observed natural variations may be interpreted. This is especially important in low-temperature environments where kinetic isotope fractionations are more likely to be observed given the sluggishness of chemical reactions under such conditions and therefore the large amount of time required to reach equilibrium. For this, more experimental and numerical determinations of the fractionation factors are required. It is important to conduct both approaches simultaneously since cross-validation of experimental, theoretical, and natural determinations is clearly needed (Hill et al., 2010). Another important development is the need for in situ data. Meteorites and very old terrestrial samples have had a protracted history that generated chemical and isotopic heterogeneity. Producing bulk sample data unveils only a portion of the message. Doing precise and accurate in situ Fe isotope determinations (Horn et al. 2006; Steinhöfel et al. 2010; Czaja et al. 2013) is more likely to fully unfold the history that iron isotopes can tell.

Cross-References

- [Archaeal Traces of Life](#)
- [Banded Iron Formation](#)
- [Biomarkers](#)
- [Isotope](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Jarosite](#)
- [Late Heavy Bombardment](#)
- [Rio Tinto](#)

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Iron Oxidation

Stephanie A. Napieralski, Nathaniel W. Fortney
and Eric E. Roden

University of Wisconsin-Madison, Madison, WI,
USA

Keywords

Chemolithotrophy · Electron donor · Iron ·
Iron Cycle · Mars

Acronyms

FeOB; Iron-oxidizing bacteria

Definition

Iron oxidation is a chemolithotrophic microbial metabolism whereby metabolic energy is generated via the removal of electrons (oxidation) from inorganic ferrous iron [Fe(II)]-containing compounds, resulting in the formation of ferric iron [Fe(III)]-containing compounds.

Overview

Prokaryotic organisms are capable of generating metabolic energy from the oxidation of Fe(II) to Fe(III), often coupled to autotrophic growth (chemolithoautotrophy) (Konhauser et al. 2011). A wide range of environments are present on Earth where microorganisms are known to participate in Fe(II) oxidation (Fig. 1). Due to the rapid rate of abiotic oxidation of soluble Fe(II) by oxygen at neutral pH (Singer and Stumm 1970), several strategies exist for iron-oxidizing bacteria (FeOB) to compete with abiotic oxidation including oxidation of soluble Fe(II) at neutral pH under low-oxygen conditions, oxidation of insoluble Fe(II) mineral phases at neutral pH, oxidation under acidic conditions, and oxidation of soluble or mineral-bound Fe(II) under anaerobic (no oxygen present) conditions. In all of

these cases, rates of the abiotic chemical oxidation are sufficiently low to allow for FeOB to utilize Fe(II) as an energy source. It should be noted that all of the examples of Fe-based microbial life described below have relevance to the potential for life on Mars.

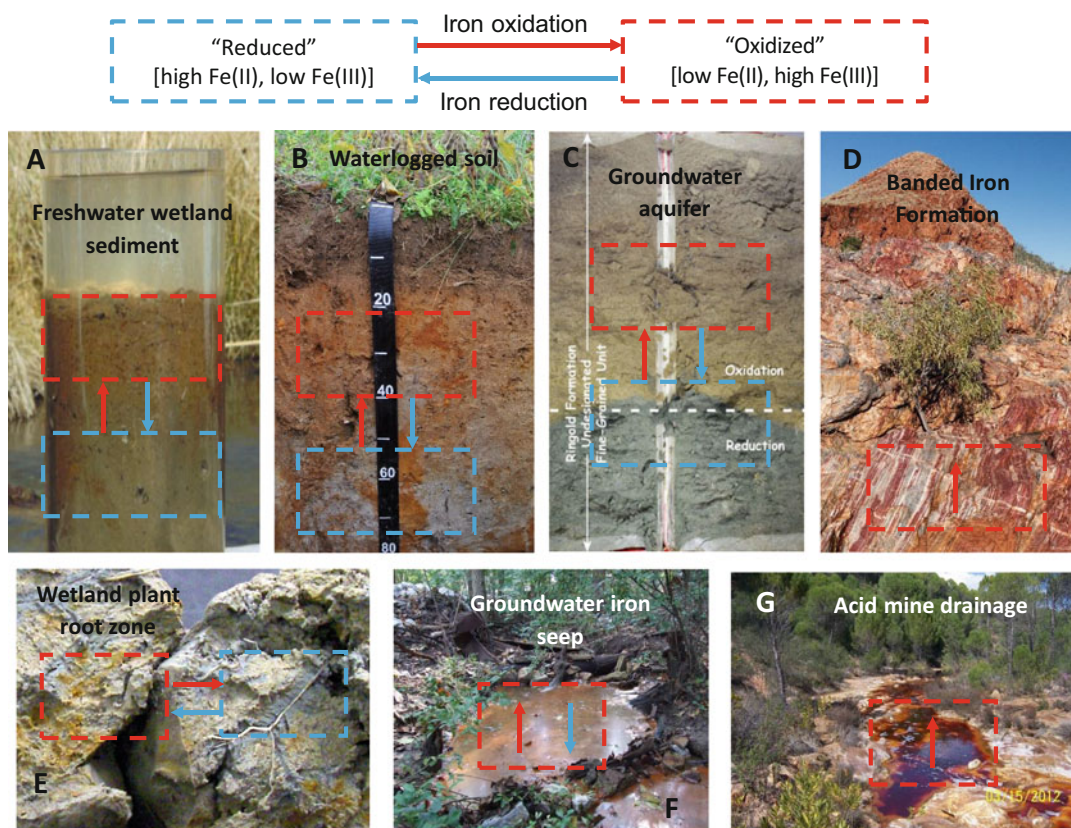
Aerobic Iron Oxidation

At neutral pH under fully aerobic conditions, soluble Fe(II) undergoes rapid chemical oxidation and hydrolysis to form insoluble Fe(III)-(oxyhydr)oxides, limiting the availability of soluble Fe(II) for lithotrophic microbial growth. In order to efficiently compete with chemical oxidation, neutral pH FeOB such as *Gallionella* and *Leptothrix* (Emerson et al. 2010) typically inhabit zones in soils and sediments where reduced ferrous iron-containing fluids meet an overlying aerobic environment, establishing opposing gradients of Fe(II) and oxygen that allow for iron oxidation under low-oxygen conditions:



In addition to the use of soluble Fe(II) as a source of electrons, it has also been demonstrated that FeOB can use solid phase, mineral-bound Fe(II) including the structural iron in biotite (Shelobolina et al. 2012) and clay minerals (Benzine et al. 2013) for lithotrophic growth. Abiotic oxidation of these minerals at neutral pH is sufficiently slow to allow for growth of FeOB, even under fully aerobic conditions.

Under acidic conditions Fe(II) is chemically stable, and acidophilic Bacteria such as *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* (Schrenk et al. 1998) and Archaea such as *Ferroplasma* (Edwards et al. 2000) grow by oxidizing Fe(II) with oxygen as a terminal electron acceptor as in the equation above. Little thermodynamic energy is generated by this reaction; thus these organisms need to turn over large quantities of Fe(II) to obtain enough metabolic energy

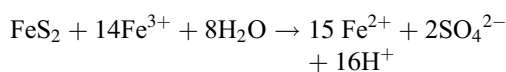


Iron Oxidation, Fig. 1 Examples of environments where iron oxidation (and in some cases reduction; see “► [Iron Reduction](#)”) takes place, including the surface of a freshwater wetland sediment (panel A; E. Roden, unpublished, used with permission), the upper layer of a waterlogged soil (panel B; A. Hartemink, unpublished, used with permission), and an “oxidation/reduction” transition zone in a groundwater aquifer (panel C; reprinted (adapted) with permission from Fig. S4 in Percak-Dennett et al., *Environ. Sci. Technol.*, 2014, 48 (16), pp. 9197–9204. Copyright (2014) American Chemical Society), where Fe(II) enters from a Fe(II)-rich “reduced” zone; Precambrian banded iron formation rocks (panel D; C.M. Johnson, unpublished, used with permission) where Fe(II) from deep ocean water was oxidized in the surface ocean, ultimately leading to the formation of huge Fe-rich geological deposits; a wetland plant root zone (panel E;

adapted with permission from Fig. 1 in Shelobolina et al., *Front. Microbiol.*, 2012, Article 134) where oxygen leaked from plant roots is linked to Fe(II) oxidation; a groundwater iron seep (panel F; adapted with permission from Fig. 2 in Roden et al., *Front. Microbiol.*, 2012, Article 172) where Fe(II) in low-oxygen groundwater comes into contact with atmospheric oxygen and in which both iron oxidation and reduction are known to take place; and an acid mine drainage environment (panel G, W. Burgos, unpublished, used with permission), where Fe(II) derived from pyrite is oxidized under acidic conditions. Dashed boxes indicate zones of Fe oxidation (red arrows)/reduction (blue-green arrows) activity. The presence of both arrows indicates that both oxidation and reduction are taking place; a single vertical red arrow indicates a predominantly Fe-oxidizing environment

for growth. Commonly associated with acid rock drainage where iron sulfide minerals, including pyrite (FeS_2) are oxidized, even a small number of these microorganisms can generate significant quantities of dissolved Fe(III) and sulfate (SO_4^{2-}). This is of high environmental concern, as at extremely acidic pH (≤ 3), soluble Fe^{3+} ,

rather than oxygen, is the dominant oxidant for pyrite (Moses et al. 1987):

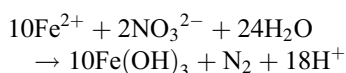


The primary role of acidophilic FeOB is thus to re-oxidize (according to eq. 1) the soluble

ferrous iron that is the product of the above reaction, which can again serve as the oxidant for pyrite, generating more acidity and establishing a self-propagating system.

Chemolithotrophic Anaerobic Iron Oxidation

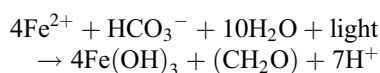
In environments lacking oxygen, oxidants capable of receiving electrons from Fe(II) include Mn(IV) oxides and oxidized nitrogen species including nitrate and nitrite. No organisms are known to couple the oxidation of Fe(II) to Mn(IV) reduction; however chemolithotrophic oxidation of Fe(II) can occur using nitrate as the terminal electron acceptor according to the reaction (Straub et al. 1996):



In contrast to the inherent competition for Fe(II) of aerobic neutral pH FeOB, in nature Fe(II) is not spontaneously oxidized by nitrate; thus nitrate-dependent FeOB do not require mechanism to compete with abiotic oxidation pathways. While autotrophy is widespread among aerobic FeOB, most organisms that couple denitrification to iron oxidation are not autotrophic but rather mixotrophic, oxidizing Fe(II) to gain energy and assimilating preformed organic compounds for cell biosynthesis.

Photosynthetic Anaerobic Iron Oxidation

Anoxygenic photosynthetic Fe(II) oxidation, also known as photoferrotrophy, is a form of photosynthesis that does not produce oxygen (Widdel et al. 1993) and is performed by a diverse group of microorganisms including purple sulfur, purple nonsulfur, and green sulfur bacteria (Camacho et al. 2017). The generalized reaction for photoferrotrophy is:



Photoferrotrophs typically live in anaerobic environments or tolerate small amounts of molecular oxygen where chemical Fe(II) oxidation is limited. Alternatively, they may have a low requirement for light allowing them to live deeper in the water column where Fe(II) concentrations may be higher owing to proximity to a source of replenishment. While their habits are relatively restricted in a modern, oxygenated world, photoferrotrophs are postulated to have played a role in the deposition of ancient iron mineral deposits called banded iron formations in the Precambrian, prior to the oxygenation of Earth's atmosphere (Kappler et al. 2005).

Relevance to Astrobiology

NASA's Mars rover missions have shown conclusively that the surface soils of Mars, commonly known as the "Red Planet," are rich in various types of Fe(III)-bearing mineral phases that are thought to have formed under aqueous conditions early in the planet's history (Squyres et al. 2004) from oxidative weathering of Fe(II)-bearing basalt rocks that dominate the Martian crust (Foley et al. 2003). In some cases the mineralogy indicates formation under acidic conditions (Squyres et al. 2004), whereas other environments had a more neutral pH (Grotzinger et al. 2014). The wide range of Fe oxidation-based microbial metabolisms described above speak directly to the long-acknowledged possibility that oxidation of Fe(II)-bearing phases on early Mars may have been at least partially mediated by life (Jakosky and Shock 1998; Jepsen et al. 2007). Geologists and planetary scientists have speculated openly about the potential for microbial Fe oxidation to have played a role in the formation of Fe(III) oxide (hematite)-rich mineral "berries" that are abundant on the Martian surface (Chan et al. 2004; Ormo et al. 2004) and for Fe-based energy metabolism to have

taken place in ancient aqueous environments characterized by neutral pH and variable oxidation/reduction states of iron and associated elements (e.g., sulfur) in fine-grained sedimentary rocks (Grotzinger et al. 2014). Astronomical analyses suggest that at least some earth-sized exoplanets are likely to be Fe-rich “rocky” bodies (Howard et al. 2013), raising the possibility that Fe-based microbial life could exist on planets in other solar systems.

Cross-References

- [Archaea](#)
- [Autotroph](#)
- [Bacteria](#)
- [Chemolithotroph](#)
- [Electron Donor](#)
- [Hematite](#)
- [Iron Cycle](#)
- [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- [Lithotroph](#)
- [Mars](#)
- [Oxidation](#)
- [Photoferrotrophy](#)
- [Prokaryote](#)

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Iron Oxides, Hydroxides, and Oxyhydroxides

Prachi Joshi and Andreas Kappler
Geomicrobiology, Centre for Applied
Geosciences, University of Tuebingen,
Tuebingen, Germany

Keywords

Reduction-oxidation · Iron cycling ·
Biogeochemical cycles

Synonyms

Iron oxyhydroxides

Definition

Iron oxides, hydroxides, and oxyhydroxides are commonly found minerals that contain ferrous (Fe(II)) and ferric (Fe(III)) iron, oxygen (O), and hydroxyl (OH), widespread in rocks, sediments, and soils. They are highly reactive mineral phases and their formation, transformation, dissolution, and catalytic activity are tightly coupled to various elemental cycles and pollutant transformations.

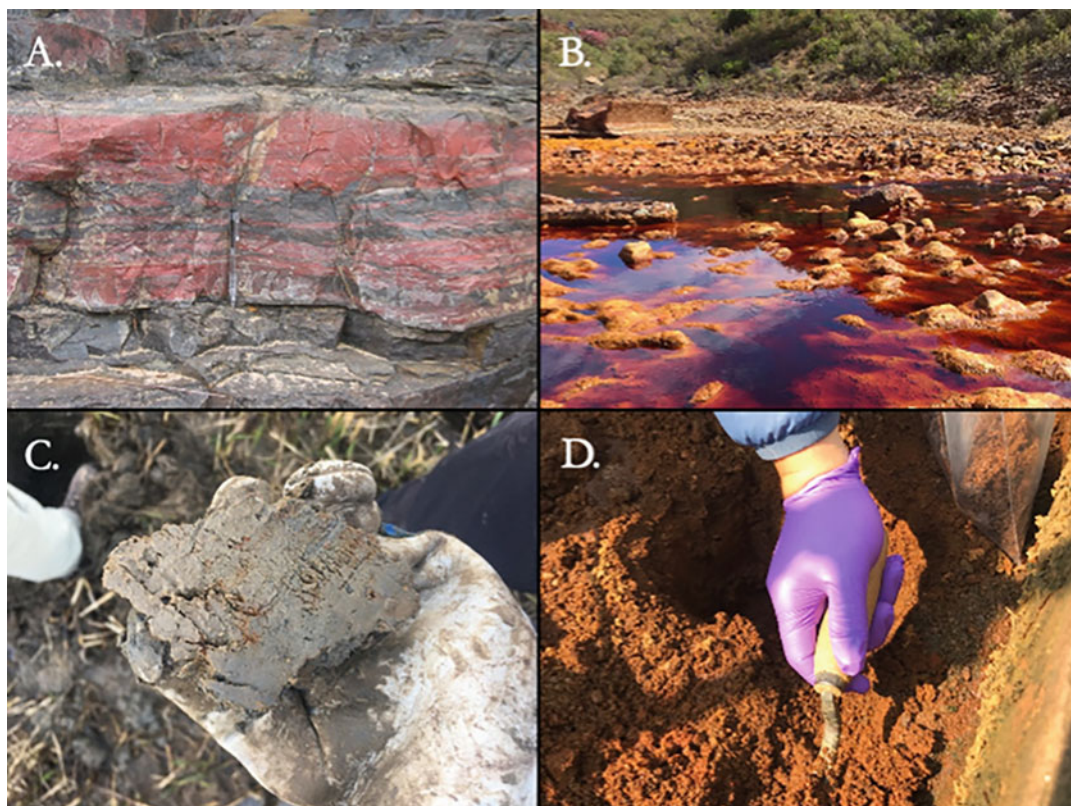
Overview

Iron oxides, hydroxides, and oxyhydroxides are ubiquitous minerals consisting of iron (Fe), oxygen (O), and hydroxyl (OH) found in rocks, sediments, and soils. There are sixteen iron oxides and oxyhydroxides (often collectively referred to as “iron oxides”) (Cornell and Schwertmann 2003). Most iron oxides contain iron in the trivalent state (Fe(III)); only three oxides – wüstite (FeO), magnetite (Fe₃O₄), and Fe(OH)₂ contain iron in the divalent state (Fe(II)). Iron oxides often occur as high surface area nanoscale mineral particles which are highly reactive (e.g., van der Zee et al. (2003)) (Fig. 1).

Iron oxides can be formed by two major pathways: (i) direct precipitation of dissolved Fe(II) or Fe(III), and (ii) transformation from another iron oxide precursor (Cornell and Schwertmann 2003; Schwertmann and Cornell 2008). Dissolved Fe (II) is rapidly oxidized to Fe(III) in the presence of oxygen abiotically at circumneutral pH values (Stumm and Morgan 1970) and microbially at acidic pH values (Blake II and Barrie Johnson 2000) (► [Fe Oxidation](#)). As the solubility of Fe (III) is very low at neutral pH, it tends to precipitate to form Fe(III) oxides. Ferrihydrite, a poorly crystalline iron oxyhydroxide (nominally given as Fe₁₀O₁₄(OH)₂, although the structure has been debated), is often the first product of neutrophilic Fe(II) oxidation and subsequent precipitation (Cornell and Schwertmann 2003). It is considered the precursor to thermodynamically more stable oxides such as goethite (α-FeOOH) and hematite (Fe₂O₃).

Transformation between iron oxide minerals may occur via solid-state recrystallization or dissolution-reprecipitation. For example, goethite is transformed to hematite under dry conditions at high temperatures (Gualtieri and Venturelli 1999). Under ambient, near-surface conditions, reconstructive transformations via dissolution and precipitation in solution are dominant; for example, the recrystallization of ferrihydrite (Fe₁₀O₁₄(OH)₂) to form goethite under reducing conditions (Hansel et al. 2003). Such transformations are suppressed in the presence of organic carbon (Chen et al. 2015) and silica (Anderson and Benjamin 1985), leading to the preservation of ferrihydrite over longer time-scales and at higher temperatures.

All iron oxides tend to sorb macronutrients such as phosphate (Wilson et al. 2004), organic carbon (Kaiser and Guggenberger 2000), and trace elements such as nickel (Jenne 1968). Ferric iron in iron oxides may be used as an electron acceptor in microbial respiration (Lovley and Phillips 1986) (► [Iron Reduction](#)), releasing these nutrients and trace elements into the surrounding water. Similarly, iron oxides may also immobilize inorganic pollutants such as arsenic (Dixit and Hering 2003) and transform organic pollutants such as TNT (Hofstetter et al. 1999). In this manner, iron oxides are tightly coupled to



Iron Oxides, Hydroxides, and Oxyhydroxides, Fig. 1 Iron oxides in natural and engineered environments. (a) Banded Iron Formation from White Mfolozi Gorge, South Africa (3 Ga). (b) Iron oxide-rich water of

the river Rio Tinto, Spain. (c) Orange iron oxide precipitates formed due to oxygenation in paddy soils of Vercelli, Italy. (d) Iron oxide-coated sand in drinking water filters used in Vietnam.

the biogeochemical cycling of several elements and the fate of different classes of pollutants.

Due to their ubiquity and reactivity, iron oxides may act as proxies for the environmental conditions they were formed under as well as post-formational environments. The presence of hematite and goethite on the surface of Mars has provided evidence for the existence of water in the planet's past (Klingelhöfer et al. 2004; Murchie et al. 2009). Observations of magnetite concurrent with Fe sulfides and Fe carbonates in the Martian meteorite ALH84001 have been hypothesized as evidence for biogenic activity on Mars (McKay et al. 1996). In addition to the mineralogy, the trace element and isotopic composition of iron oxides may also provide information about the aqueous chemistry at the time of formation. For example, trace element concentrations in iron

oxide-rich banded iron formations (Fig. 1) (► BIFs) have been used to infer marine phosphate concentrations in the Archean (Bjerrum and Canfield 2002; Konhauser et al. 2007).

Cross-References

- [Banded Iron Formation](#)
- [Biosignature](#)
- [Goethite](#)
- [Hematite](#)
- [Iron Isotopes](#)
- [Iron Oxidation](#)
- [Iron Reduction](#)
- [Magnetite](#)
- [Pyrite](#)
- [Rio Tinto](#)

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Iron Oxyhydroxides

► Iron Oxides, Hydroxides, and Oxyhydroxides

Iron Reduction

Nathaniel W. Fortney, Stephanie A. Napieralski and Eric E. Roden
University of Wisconsin–Madison, Madison, WI, USA

Keywords

Electron donor · Electron acceptor · Iron · Reduction

Acronyms

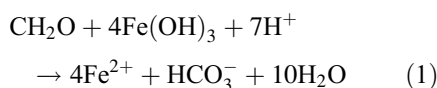
DIR Dissimilatory iron reduction
DIRM Dissimilatory iron reducing microorganisms

Definition

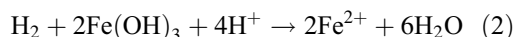
Dissimilatory iron reduction (DIR) is a form of anaerobic (without oxygen) microbial respiration

whereby energy is generated by coupling the oxidation (removal of electrons) of organic matter (chemoorganotrophy) or H_2 (chemolithotrophy) to the reduction (addition of electrons) of ferric iron [Fe(III)]. DIR can be generalized by the following equations, where “ CH_2O ” represents a single unit of organic carbon, and $Fe(OH)_3$ represents an iron oxide mineral phase:

Chemoorganotrophic Fe(III) reduction:



Chemolithotrophic Fe(III) reduction:



Overview

Microbial Fe(III) reduction plays an important role in the biogeochemical iron cycle producing ferrous iron [Fe(II)] which is subject to either microbial or abiotic oxidation (see Fig. 1 in ► “Iron Oxidation”) (Emerson et al. 2012; Konhauser et al. 2011; Lovley et al. 2004; Weber et al. 2006). Furthermore, the activity of dissimilatory iron reducing microorganisms (DIRM) can help remediate metal contamination from subsurface environments. Unlike assimilatory iron reduction where Fe(III) is reduced and transported into the cell for essential biological processes, DIR occurs external to the microbial cell as a means of energy generation (Lovley et al. 2004). Organisms capable of respiring ferric iron are spread throughout multiple clades within the Archaeal and Bacterial Domains of life. Several of these microbial species, the Archaea especially, are thermophilic and hyperthermophilic organisms that appear near the root of the universal phylogenetic tree of life. This has led scientists to hypothesize that DIR is one of the most ancient modes of respiration on Earth (Vargas et al. 1998; Lovley 2004).

Iron Reduction in Modern Environments

Modern DIRM are a diverse group of prokaryotic organisms including members of the

δ -Proteobacteria such as *Geobacter* spp. and *Desulfuromonas* spp., γ -Proteobacteria like *Shewanella* spp., acidothermophiles like *Sulfolobales* and *Acidocaldus* spp., and hyperthermophilic species of *Pyrobaculum* and *Thermotoga*, to name a few (Lovley et al. 2004; Weber et al. 2006). These microbes can be found in numerous environments such as Fe seeps/springs, marine and freshwater sediments and wetlands, and hydrothermal vents (Emerson et al. 2012; Konhauser et al. 2011; Lovley et al. 2004). Typically, DIRM are restricted to the anoxic zones of these environments; however, it has been demonstrated that certain species of *Geobacter* are not only aerotolerant but can grow by O_2 respiration at low concentrations (Lin et al. 2004).

Ferric iron is insoluble at circumneutral pH, and even in acidic environments ($\sim$ pH 3) Fe(III) is predominantly in the form of Fe(III) (oxyhydr)oxide mineral phases. Ferric (oxyhydr)oxides accumulate in the environment when aqueous ferrous iron entering system is rapidly oxidized by atmospheric or dissolved O_2 , or microbial activity (see ► “Iron Oxidation” for more details). Amorphous Fe(III) (oxyhydr)oxides are the preferred form of Fe(III) for DIRM (Lovley and Phillips 1987), although other Fe (III) minerals including clays and more crystalline minerals like hematite and goethite are capable of supporting DIRM (Roden and Zachara 1996). Respiration of Fe(III) presents a problem for microbial energy generation given that in most situations, the Fe(III) used for respiration is in the form of insoluble minerals external to the cell. DIRM have evolved extracellular electron transfer (EET) mechanisms to overcome this problem. Electrons released within the DIRM by the oxidation of organic matter or H_2 are passed through a series of EET proteins in the cell cytoplasm, periplasm, and membrane(s) and ultimately deposited on Fe(III) outside the cell (Shi et al. 2016). In cases where direct cell to mineral contact is not possible, DIRM utilize soluble electron shuttling proteins (*Shewanella* spp., *Geothrix* spp.) or external cell structures called nanowires (*Geobacter* spp.) to complete the electron transfer conduit to Fe(III) (Lovley et al. 2011).

Iron Reduction on Early Earth

Aerobic respiration, the coupling of the oxidation of organic matter to the reduction of O₂, is the most energetically favorable microbial metabolism on modern Earth. However, on early Earth, electron acceptors such as O₂ existed at a fraction of the concentration we have today. Therefore, early microbial life evolved to utilize alternative electron acceptors such as ferric iron. The oceans of early Earth were anoxic and iron would have remained soluble in its reduced, ferrous, form unless acted upon by chemical oxidation, by ultraviolet radiation from the sun, or by direct or indirect microbial oxidation by photoferrotrophic or oxygenic photosynthetic organisms, respectively. The resulting Fe(III) (oxyhydr)oxide minerals that settled to the ocean floor in close proximity to hydrothermal vents would have provided microorganisms with ideal conditions to couple the oxidation of H₂-rich hydrothermal fluids to the reduction of freshly precipitated Fe(III) (oxyhydr)oxides. Elsewhere input of organic matter from photosynthetic organisms was likely available for DIRM, thereby creating ideal sedimentary conditions for Fe(III) reduction (Lovley 2004). Geologically we can see signature of this process in the deposits known as banded iron formations (Cloud 1965; Johnson et al. 2008; Konhauser et al. 2011; Konhauser et al. 2005).

Relevance to Astrobiology

Microorganisms capable of DIR inhabit diverse environments ranging from the extreme to tolerable by human standards. Scientists studying “extremophile” DIRM have gained insight into the evolution of this ancient metabolic process and the evolution of early microbial life itself. Furthermore, DIRM isolated as part of these studies have helped expand what we consider to be the habitable range for life on Earth and possibly other planets. One specific strain, a hyperthermophilic Archaeon called strain 121, is capable of growing at temperatures up

to 121 °C using Fe(III) oxides as a terminal electron acceptor for respiration (Kashefi and Lovley 2003). Indirect evidence has also suggested that DIRM expand our understanding of the physical and geological habitable zone for terrestrial life. Thermophilic DIRM have been recovered from deep subsurface environments (Roh et al. 2002) and micrometer sized magnetite grains have identified at depths of almost 7 km within the crust (Gold 1992). Magnetite is a known byproduct of DIR (Jimenez-Lopez et al. 2010), and the size and composition of the mineral has been cited as having a microbial origin. The ability of DIRM to thrive in hydrothermal and deep crustal environments raises an exciting potential as researchers consider the possibility of life beyond Earth. Along these lines, it has been speculated that magnetite and other Fe-containing minerals (e.g., siderite) detected in the Martian meteorite known as ALH84001 may have arisen from DIR activity early in Mars’ history (McKay et al. 1996). Potential energy sources for such metabolism include reduced gases such as hydrogen and carbon monoxide of both subsurface (Mumma et al. 2009) and atmospheric (Weiss et al. 2000) origin. As in the case of Fe(II) oxidation, DIR-based microbial life is a premier candidate for life on recently identified Earth-size Fe-rich “rocky” exoplanets (Howard et al. 2013).

Cross-References

- ▶ [ALH 84001](#)
- ▶ [Anaerobe](#)
- ▶ [Archaea](#)
- ▶ [Bacteria](#)
- ▶ [Banded Iron Formation](#)
- ▶ [Biogeochemical Cycles](#)
- ▶ [Chemolithotroph](#)
- ▶ [Chemoorganotroph](#)
- ▶ [Extremophiles](#)
- ▶ [Goethite](#)
- ▶ [Hematite](#)
- ▶ [Iron Cycle](#)
- ▶ [Iron Oxidation](#)
- ▶ [Iron Oxides, Hydroxides, and Oxyhydroxides](#)

- Magnetite
- Mars
- Siderite
- Thermophile

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Iron Spar

- Siderite

ISA

- Italian Society of Astrobiology

ISM

- Interstellar Medium

ISO

- Infrared Space Observatory

ISO (Normative Organization)

Catharine A. Conley
NASA Headquarters, NASA Ames Research
Center, Washington, DC, USA

Synonyms

[International Organization for Standardization](#)

Definition

The International Organization for Standardization is a network of national standards institutes from 165 countries. It sets standards for almost all service, industrial, and commercial activities. These standards are used as a common basis to describe activities related to space by most of the space agencies either to design instruments, rockets, and spacecraft or to manage projects. For planetary protection, these standards are used to define levels of biosafety or microbiological procedures.

Cross-References

► [Biological Safety Level](#)

Isochron

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale
Supérieure de Lyon, Lyon Cedex 7, France

Definition

An isochron refers to a curve or a surface that describes the state of multiple systems with the same age. In ► [geochronology](#), an isochron is a straight line describing how a particular isotopic ratio changes in response to radioactive decay. For instance, the abundance of ^{143}Nd in rocks increases

upon decay of their ^{147}Sm content. When several minerals precipitate from the same magma, their $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios form an isochron with a slope that can be converted into an age. An isochron typically requires that all of the synchronous systems involved formed with the same $^{143}\text{Nd}/^{144}\text{Nd}$ ratio and that no Sm or Nd were subsequently lost or added.

Cross-References

- [Decay Constant](#)
- [Geochronology](#)
- [Radioactivity](#)
- [Radiogenic Isotopes](#)
- [System Solar Formation, Chronology of](#)

Isochrone

Sylvia Ekström
Observatoire Astronomique de l'Université de
Genève, Faculté des Sciences, Université de
Genève, Versoix, Switzerland

Definition

Isochrones are theoretical tracks in the ► [Hertzsprung-Russell diagram](#) (HRD) defining the position occupied by stars of a given age. Isochrones are used to determine the age of a ► [stellar population](#), typically a star cluster: on an isochrone, the smaller mass stars may still lie on the main sequence, while the higher mass stars have already left the main sequence to become red giants. The determination of the mass of the stars that are precisely at the turnoff from the main sequence gives the age of the cluster.

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Main Sequence, Star](#)
- [Stellar Evolution](#)
- [Stellar Populations](#)

Isocyanatomethane

- [Methyl Isocyanate \(CH₃NCO\)](#)

Isocyanic Acid

- [HCNO Isomers](#)

Isoelectric Point

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[IEP](#); [pI](#)

Definition

The isoelectric point is the pH at which a molecule or surface carries no net electrical charge. Many molecules are zwitterions, containing both positive and negative charges. The net charge on the molecule is governed by the pH of the surrounding medium. The pI is the pH value at which the molecule carries no net electrical charge, and thus the negative and positive charges are equal. For a doubly charged species containing both negative and positive charges, for example an ► [amino acid](#) with only one ► [amine](#) and one carboxyl group, the pI is simply the sum of the pK_a's of the two ionizable groups divided by 2. The terms isoelectric point (IEP) and point of zero charge (PZC) are often used interchangeably, although they have subtle differences.

For surfaces, in the case when the surface charge-determining ions are H⁺/OH⁻, the net

surface charge is affected by the pH of the surrounding liquid medium. The pI then is the pH value of the solution at which the surface carries no net charge, that is, positive and negative charges are canceled out.

Many biological molecules, such as ► [proteins](#), contain both positively and negatively charged functional groups on their component amino acid side chains at physiological pH. At a pH below their pI, proteins carry a net positive charge; at pH values above their pI, they have a net negative charge.

Cross-References

- [Amine](#)
- [Amino acid](#)
- [Carboxylic acid](#)
- [Protein](#)
- [Zwitterion](#)

Isofulminic Acid

- [HCNO Isomers](#)

Isolation Mass

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux, CNRS,
Universite de Bordeaux, Bordeaux, France

Definition

In planet formation, the isolation mass is the mass a planet reaches after having accreted all the ► [planetesimals](#) in its ► [feeding zone](#).

Cross-References

- [Feeding zone](#)
- [Hill Radius/Sphere](#)

Isoleucine

Kensei Kobayashi

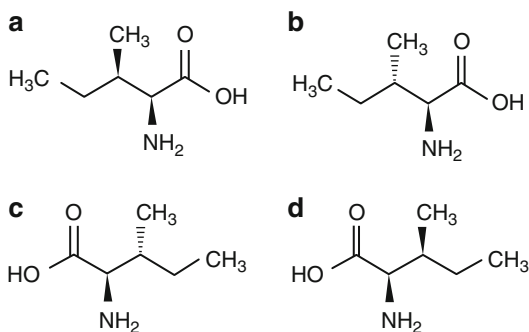
Yokohama National University, Yokohama, Japan

Definition

Isoleucine is one of the 20 protein amino acids. Isoleucine's three-letter symbol is Ile and one-letter symbol is I. Its molecular formula is $C_6H_{13}NO_2$, which gives a molecular weight of 131.17. Its isoelectric point (pI) is 6.02. Isoleucine has many ► [isomers](#): one which is also present in ► [proteins](#), ► [leucine](#) (side chain: $-CH_2CH(CH_3)_2$), and 29 other isomers. Isoleucine has two asymmetric carbons: α -carbon and β -carbon, giving four ► [stereoisomers](#): L-isoleucine (Fig. 1a), D-isoleucine (Fig. 1b), L-*allo*-isoleucine (Fig. 1c), and D-*allo*-isoleucine (Fig. 1d). Only L-isoleucine is present in proteins, and it is widely distributed in the biosphere. It has been identified in extracts from carbonaceous chondrites and among the products of spark discharge experiments in gas mixtures containing methane.

Cross-References

- [Amino Acid](#)
- [Isomer](#)
- [Leucine](#)
- [Protein](#)
- [Stereoisomers](#)



Isoleucine, Fig. 1 Stereoisomers of isoleucine

Isomer

Robert Hazen

Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Definition

Isomers are molecules that have identical molecular formulas but different structural formulas. In constitutional isomers, the atoms are connected in different sequences, as in the case of the two C_2H_6O isomers, dimethyl ether (CH_3-O-CH_3) and ethanol (CH_3CH_2-OH). Similarly, butane and methyl propane (isobutane) are constitutional isomers (conformers) of C_4H_{10} . ► [Stereoisomers](#), by contrast, are molecules with identical formulas and the same atomic connectivity but which differ in their spatial arrangements. Stereoisomers can be further divided into conformational isomers (conformers), which can transform one to the other by a rotation around single bond, and configurational isomers (including chiral molecular pairs), which do not transform one to the other without breaking at least one bond.

Cross-References

- [Enantiomeric Excess](#)
- [Stereoisomers](#)

Isoprenoids

Ross H. Williams

CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology, University of Maryland, College Park, MD, USA
NASA Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, MD, USA

Keywords

Archaea · Bacteria · Biosignatures · Carotenoids · Eukaryotes · Hopanoids · Lipids · Molecular fossils · Steroids

Synonyms

Terpenoids

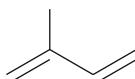
Definition

A diverse class of organic compounds constructed from multiple (2 to 10^3) C5 isoprene units (Fig. 1) linked into larger molecules having linear or ringed structures. Isoprenoids are ubiquitous in biology and are observed as molecular fossils in ancient bitumen, oil, and kerogens of the geological record. Isoprenoids are lipid compounds common in ► **membranes** of ► **archaea**, ► **bacteria**, and eukaryotes included in many proteins and are critical to a wide variety of cellular functions. Examples of isoprenoids include the phytol side chain of chlorophylls and diagenetic products (such as phytane; Fig. 2), squalene, biphytane, tocopherols, carotenoids, aryl isoprenoids, hopanoids, and steroids.

Overview

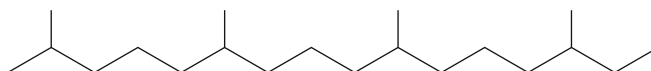
Formation of isoprenoids occurs via polymerization of Δ^3 -isopentenylidiphosphate (IDP), a five-carbon product of both the mevalonic acid (MVA) and non-mevalonic (also referred to as the MEP) pathways. Eukaryotes and archaea utilize the MVA pathway, while the majority of bacteria utilize the MEP pathway. Consequently, isoprenoids tend to have carbon numbers in increments of five (e.g., C20, C25, C30, C35, C40 acyclic isoprenoids of archaea or C20, C25, C30 highly branched isoprenoids of diatoms).

Isoprenoids, Fig. 1 The C5-isoprene subunit (2-methyl-1,3-butadiene) used in the biosynthesis of all isoprenoids



Isoprenoids with different carbon numbers are the result of post-synthesis modifications. The C5-incremental molecular pattern is an example of a generic biosignature resulting from a shared precursor (i.e., isoprene) used in biosynthesis. Isoprenoids and similar molecular patterns have not been observed in meteorites or experimental products of abiotic Fischer–Tropsch reactions.

Isoprenoids are distributed across different phylogenetic groups and all three domains of life, though particular compound groups are observed in association with specific organisms or environmental conditions. Among the cyclic members, the group of triterpenoids (C30) is widely distributed as hopanoids and steroids. Hopanoids are only found in ► **bacteria**, though not all bacteria synthesize them. Steroids are present in all eukaryotes. Acyclic isoprenoids are the hallmark lipids of archaea, though they are found in bacteria and eukaryotes as well. Archeol (diphytanylglycerol), caldarchaeol (dibiphytanyl – diglycerol – tetraether), C20-croctane (2,6,11,15-tetramethylhexadecane), C25-PMI (2,6,10,15,19-pentamethylcosane), biphytane, and other >C20 acyclic isoprenoids are produced specifically by archaea. The most common isoprenoids in sediments are C19-pristane and C20-phytane, which may be derived from a variety of precursor compounds including phytol of cyanobacterial and green plant chlorophylls, tocopherols from plant and phytoplanktonic, and >C20 acyclic isoprenoids from archaea. Isoprenoids are dominantly hydrocarbon skeletons with attached functional groups that are lost during diagenesis and thermal maturation leaving the hydrocarbon skeletons for potential preservation in the rock record. Given the ability for the isoprene units to join in either a head–head or a head–tail configuration, a great variety of structures can be made during cyclization. This allows the possibility of a stereochemical preference to be an additional indicator of biologic activity.



Isoprenoids, Fig. 2 The structure of C20-phytane (2,6,10,14-tetramethylhexadecane), a common isoprenoid found in sediments

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Biomarkers](#)
- [Eukarya](#)
- [Eukaryotes, Appearance and Early Evolution of](#)
- [Hopanes, Geological Record of](#)
- [Hydrocarbons](#)
- [Kerogen](#)
- [Membrane](#)
- [Molecular Fossils](#)
- [Steranes, Rock Record](#)

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Isotope

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

Two ► [nuclides](#), e.g., ¹⁶O and ¹⁸O, are isotopes of the same element (here oxygen), if their nucleus has the same number of protons (same charge) but a different number of neutrons (different mass numbers). Because their electronic shells must balance the nuclear charge, isotopes have the same electronic configuration and, hence, very similar chemical properties. Isotopes can be either stable or radioactive. Stable isotopes are those

isotopes that do not spontaneously undergo radioactive decay. Radioactive isotopes are those with an unstable nucleus that stabilizes itself by emitting ionizing radiation (decay). Radiogenic isotopes are produced by the decay of radioactive isotopes. With few exceptions, even-number isotopes are more abundant than odd-number isotopes. The uncertainty principle requires the existence of a mass-dependent vibrational zero-point energy, which accounts for subtle differences in the chemical properties of the isotopes of the same element. This is the basis of the stable isotope geochemistry of light elements (H, C, N, O, S, etc.).

Cross-References

- [Hydrogen Isotopes](#)
- [Iron Isotopes](#)
- [Isotopic Ratio](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Nitrogen Isotopes](#)
- [Oxygen Isotopes](#)
- [Stable Isotopes](#)
- [Sulfur Isotopes](#)

Isotope Biological Markers

- [Isotope Biosignatures](#)

Isotope Biosignatures

Sümeyya Eroglu¹, Christophe Thomazo^{2,3} and Harald Strauss¹

¹Westfälische Wilhelms-Universität Münster, Institut für Geologie und Paläontologie, Münster, Germany

²UMR CNRS 5561 Biogéosciences, Université de Bourgogne, Dijon, France

³Institut Universitaire de France, Paris, France

Keywords

Biosignatures · Biomarkers · Isotopes · Traces of life · Biogeochemical cycles

Synonyms

Biomarker; Biotic isotope fractionation; Isotope biological markers; Isotopic traces of life

Definition

The term biosignature (or biomarker) *sensu stricto* refers to any physicochemical signature directly derived from the activity of living organisms, which can provide evidence for life. In geology and astrobiology, this includes stable isotope signatures measured directly on organic matter and metabolic by-products (i.e., minerals and fluid inclusions) derived from anabolic and catabolic reactions and preserved in the rock record.

Overview

In the search for biosignatures on Early Earth and beyond, the stable isotopic compositions of carbon (C), nitrogen (N), sulfur (S), and iron (Fe) are most commonly used. They can provide key information not only on the biological origin of substances, but also on the pertinent metabolic pathways of formation and degradation of organic matter and related biominerals, as well as environmental conditions at the time of deposition (see ► “Biomarkers”). They are also useful tools for reconstructing the evolution of biogeochemical cycles for a given element through geologic time. The relevance of using stable isotopes as biosignatures hinges on the fact that life fractionates isotopes in a diagnostic way that is different to other abiotic physicochemical processes. This arises from the activity of enzymes, which help organisms to drive desirable but thermodynamically unfavorable reactions by coupling them to a favorable one. In most cases, for the same reaction (same reagents and products), biotic and abiotic pathways differ strongly in the mechanism and number of steps involved, and therefore in speed, yield, and in the magnitude of stable isotope fractionation (see ► “Stable Isotopes”). Here, we review the basic methodology and present possible interpretations of stable isotope data in our search for biosignatures on the Early Earth

(see ► “Archaeal Traces of Life”). To illustrate this concept, examples for applications of established isotopic biosignatures (C, N, S, and Fe) are provided as well as limits and cautions when dealing with the biosignatures in the rock record.

Basic Methodology

The present state-of-the-art method to study isotopic compositions of any potentially biodegraded materials is isotope ratio mass spectrometry (IRMS). The principle of IRMS is based on the separation of the different isotopes of one chemical species (e.g., for nitrogen, measured as N₂ gas: ¹⁴N¹⁴N, ¹⁵N¹⁴N, and ¹⁵N¹⁵N) according to their differences in mass/electric charge ratio (*m/z*). Measurements are performed on purified gas molecules introduced directly into the IRMS (e.g., SO₂ or SF₆ for sulfur), or on a solution vaporized in a plasma chamber (e.g., Fe-HNO₃ for iron) using a multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS). Micro- to nanoscale *in situ* measurements can be performed by coupling a laser (laser ablation technique) to the mass spectrometer, or by using secondary ion mass spectrometry (SIMS). Because of its design, the respective instrument (i.e., mass spectrometer) measures isotope ratios (e.g., ¹³C/¹²C, ³⁴S/³²S, ¹⁵N/¹⁴N, and ⁵⁶Fe/⁵⁴Fe for carbon, sulfur, nitrogen, and iron, respectively), with results always calibrated against an international standard (e.g., V-PDB for carbon [Craig 1957], V-CDT for sulfur [Jensen and Nakai 1962], AIR for nitrogen [Mariotti 1984], and IRMM-14 for iron [Taylor et al. 1992]) and expressed in the δ -notation as ‰ in parts per thousand (see ► “Delta, Isotopic”).

Key Research Findings

Carbon isotope ratios (¹²C/¹³C) were first measured on various terrestrial and extraterrestrial materials, for example, meteorites, sediments, plants, and oils (Nier and Gulbransen 1939; Murphy and Nier 1941). The earliest measurements demonstrate the diagnostic potential of depleted C isotope compositions in modern and fossilized

organic material relative to inorganic carbonate ($\delta^{13}\text{C} \approx 0\text{‰}$) as biological signals (see ► [“Carbon Cycle, Biological”](#)). Fundamentally, this represented the first use of an isotopic biosignature (Wickman 1941). Subsequently, Wickman (1952) and Craig (1953) showed that plants are systematically depleted in ^{13}C due to the preferential assimilation of the light ^{12}C isotope, and also that the magnitude of fractionation depends on plant ecology and fixation pathway (e.g., C_3 versus C_4 metabolisms). Following these discoveries, isotopic biosignatures were extended to other elements related to microbial metabolisms such as nitrogen, sulfur, and iron. On the Early Earth, anaerobic pathways including denitrification (see ► [“Nitrogen Cycle, Biological”](#)), dissimilatory iron reduction (DIR) (see ► [“Iron Reduction”](#)), microbial sulfate reduction (see ► [“Sulfate Reduction”](#)), and methanogenesis/methanotrophy have been identified in the rock record using the isotopic biosignature approach (for a recent review, see Lepot 2020). These biosignatures are archived in organic material (e.g., kerogen or graphite), in the bulk rock (e.g., banded iron formations, cherts, stromatolites, and microbial mats), and associated minerals formed as metabolic by-products (e.g., pyrite, barite, and Fe-(oxyhydr)oxides). Importantly, potential abiotic sources of “biological-like” signatures need to be evaluated (e.g., Guilbaud et al. 2011), as well as the extent of postdepositional alteration due to metamorphism that can overprint primary (i.e., sedimentary) isotope signatures (e.g., van Zuilen et al. 2003, 2007; Ueno et al. 2002) (see ► [“Biosignatures, Effect of Metamorphism”](#)). Accordingly, multiple sulfur isotope signatures ($^{33}/^{32}\text{S}$, $^{34}/^{32}\text{S}$, $^{36}/^{32}\text{S}$) (see ► [“Fractionation, Mass Independent and Dependent”](#)) contained in barite and pyrite from the 3.48 Ga Dresser Formation (Pilbara craton, Western Australia) have been identified to be one of the earliest and commonly accepted isotopic traces of microbial sulfur reduction (Philippot et al. 2007; Ueno et al. 2008) (see ► [“Dresser Formation, Traces of Life”](#)). Evidence for methanogenesis in lacustrine settings as early as 3.0 Ga (Lalla Rookh Sandstone, Western Australia) is based on strongly depleted $\delta^{13}\text{C}$ signatures in kerogen (Stüeken and Buick 2018).

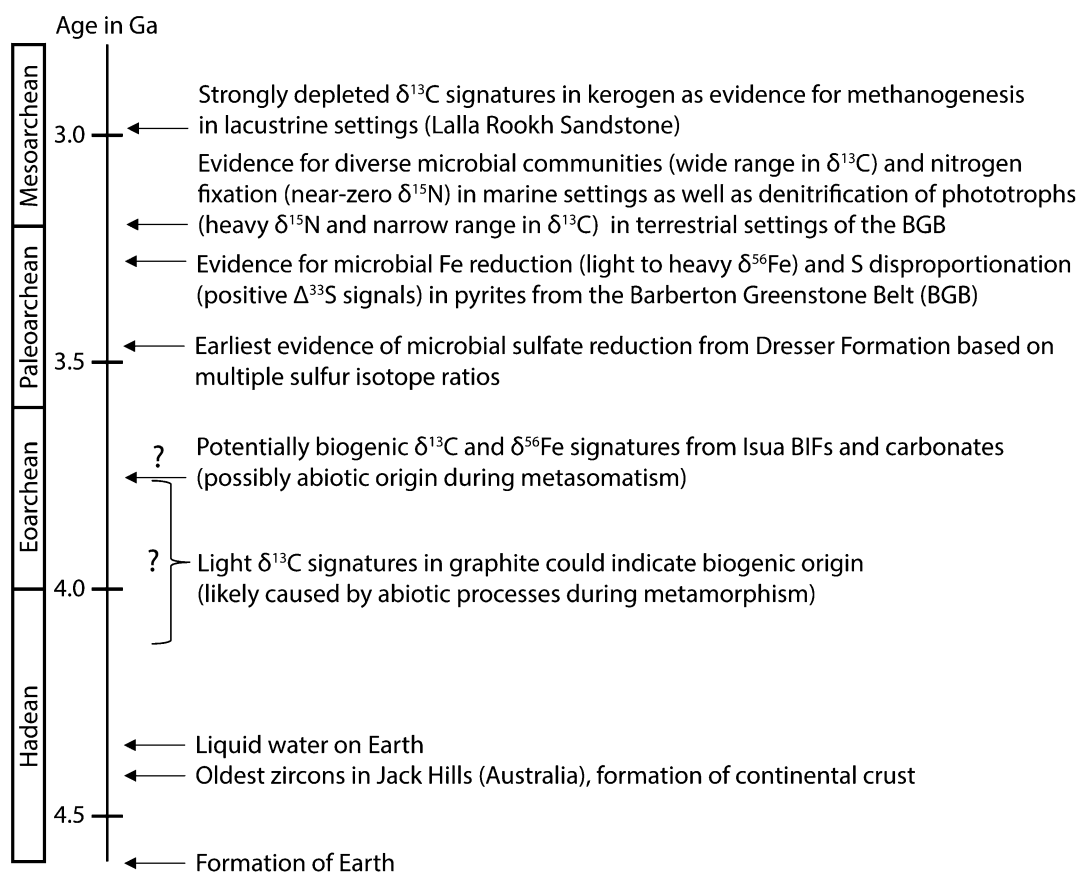
There are inferences on earlier microbial life based on $\delta^{56}\text{Fe}$ and $\delta^{13}\text{C}$ signatures from banded iron formations and carbonates of the 3.77 Ga old Isua Supracrustal Belt (West Greenland) (Craddock and Dauphas 2011; Czaja et al. 2013; Rosing 1999) (see ► [“Isua Supracrustal Belt”](#)). However, the rock record of the Isua Supracrustal Belt has been affected by intense metamorphic and hydrothermal overprints, which cannot be ruled out to have caused such signatures (van Zuilen and Van Kranendonk 2019). Similarly, microbial life as early as 4.1 Ga ago has been proposed based on light $\delta^{13}\text{C}$ signatures found in graphite from rocks of Akilia Island (>3.83 Ga; Greenland) (Mojzsis et al. 1996), Nuvvuagittuq supracrustal belt (>3.75 Ga; Canada) (Papineau et al. 2011), Saglek Block (~ 3.95 Ga; Canada) (Tashiro et al. 2017), and Jack Hills (~ 4.1 Ga; Western Australia) (Bell et al. 2015) but were potentially formed or modified by abiotic processes during metasomatism (e.g., Lepland et al. 2011) (Fig. 1).

Applications

Isotopic Biosignatures Indicating Microbial Life on an Early Earth: Recent Studies from the Barberton Greenstone Belt

There are few low-grade metamorphosed sedimentary successions on Archean cratons which are suitably preserved for the search for Archean microbial life. The 3.6–3.2 Ga old Barberton Greenstone Belt in South Africa hosts some of these localities (see ► [“Barberton Greenstone Belt, Traces of Early Life”](#)). It contains the Swaziland Supergroup, which includes several volcanic sedimentary mixed successions of the Onverwacht Group (3.55–3.26 Ga), the Fig Tree Group, and Moodies Group (3.28–3.21 Ga) (Lowe and Byerly 2007).

In a comprehensive study of Marin-Carbonne et al. (2020), pyrites from the Mendon Formation (upper Overwacht Group) were analyzed in situ regarding their Fe and S isotope compositions. Pyrites occur within a 3.28–3.26 Ga old sedimentary section, mainly composed of black and ferruginous gray cherts, which were deposited



Isotope Biosignatures, Fig. 1 Formation of a habitable Earth and overview of earliest signs of microbial life based on isotope biosignatures. (See text for further details and references)

under quiet water conditions (Lowe and Byerly 1999; Trower and Lowe 2016). The cherts are finely laminated and show some well-preserved primary sedimentary features, but have been affected by post-diagenetic metamorphism and late fluid circulation, resulting in a number of secondary quartz, carbonate, and chlorite veins. Indeed, a combination of scanning and transmission electron microscope analyses shows that some pyrites recrystallized during post-diagenetic processes. In contrast, in situ trace element analyses imply that other pyrites were not affected by these processes, but were instead formed during sedimentary diagenesis. The authors conclude that fluid circulation caused recrystallization in some of the analyzed pyrites without significantly altering the original trace element signatures. This study shows that a careful consideration of post-

diagenetic processes is crucial in order to evaluate the reliability of isotope biosignatures. In this case, pyrites not only showed evidence for mass-independent S isotope signatures (positive $\Delta^{33}\text{S}$) but also Fe isotope signatures clustering around -1.8% and $+1\%$ in different pyrite populations. As there is no systematic change in Fe isotope signatures, which could be related to post-diagenetic overprint, the authors propose that these signatures indicate partial and total Fe reduction due to microbial DIR. This inference is supported by associated $\delta^{13}\text{C}$ signatures ranging between -26 and -32% consistent with fossil biomass. Pyrite has therefore likely been formed from iron monosulfides and elemental sulfur, the latter originating from volcanic sulfur-bearing molecules, delivered in an O_2 -free atmosphere as is indicated by positive $\Delta^{33}\text{S}$ signatures and

further processed by microbial-driven disproportionation in the sediment. Nevertheless, the investigated pyrite populations were affected later by S-rich and Fe-poor hydrothermal fluids, resulting in recrystallization and the absence of $\Delta^{33}\text{S}$ signals in the pyrite rims. In summary, the study by Marin-Carbonne et al. (2020) conclusively shows Fe- and S-based isotope biosignatures from Paleoarchean times and successfully unravels primary biological signals from later abiotic processes.

Recently, Homann et al. (2018) studied the 3.2 Ga old Moodies Group, an alluvial to shallow-marine deposit that contains fossilized terrestrial as well as marine microbial mats in its sedimentary rock record (see ► “Moodies Group, Microbial Mats”). The succession shows a transition from mainly alluvial to shallow-marine sandstones. Microbial mats are well preserved due to early silicification and low-grade metamorphism based on Raman analyses. Petrographic observations can distinguish between mats growing in fluvial-dominated and tidal-influenced environments. These different depositional environments are reflected in the carbon isotope composition of organic carbon, and in the bulk nitrogen isotope composition of selected samples. Terrestrial microbial mats show, on average, $\delta^{13}\text{C}_{\text{org}}$ values of -21.2‰ and $\delta^{15}\text{N}$ values of $+4.3\text{‰}$. In contrast, shallow-marine mats display, on average, $\delta^{13}\text{C}_{\text{org}}$ values of -27.4‰ and $\delta^{15}\text{N}$ values of $+1.8\text{‰}$. The authors conclude that these signatures reflect different biogeochemical cycling of carbon and nitrogen controlled by the depositional environment and associated microbial ecology. The C/N ratios are indistinguishable in both sediment types, suggesting that secondary metamorphic processes did not modify elements, and by extension isotope biosignatures of these sediments. In more detail, a wide range of $\delta^{13}\text{C}_{\text{org}}$ values in the marine sediments (-33.9‰ to -21.3‰) can be explained by a variety of carbon fixation pathways of, e.g., phototrophs, methanogens, and sulfate reducers, while near-zero $\delta^{15}\text{N}$ values indicate atmospheric nitrogen fixation. In contrast, carbon fixation in terrestrial sediments was likely dominated by phototrophs, as being shown by a narrow $\delta^{13}\text{C}_{\text{org}}$ range

(-23.6‰ to -17.9‰), while heavy $\delta^{15}\text{N}$ signatures indicate denitrification on land, based on the assumption that the atmosphere is a source of abiotically fixed nitrogen (Fig. 1).

Future Directions

The search for traces of microbial life in the Earth’s early rock record is continuously advanced by a better understanding of the coetaneous environmental conditions, improvements in the methodology, experimental work, and studies of modern analogues. These modern analogues include stromatolites, or other microbial mats (see ► “Shark Bay, Stromatolites of”) in restricted aqueous settings, or biological soil crusts in arid terrestrial settings. The latter have been analyzed for their bulk C and N isotope composition (Thomazo et al. 2020) and results are consistent with isotopic signatures of terrestrial microbial mats from the Precambrian (Homann et al. 2018). Importantly, these findings can be extended to astrobiology and search for microbial life on other planets, whereby current research is focused on future in situ measurements and Mars sample return missions (see ► “Mars Analogue Sites”). In this context, extreme microbial environments on Earth, e.g., hydrothermal pools in Iceland, could be used as modern analogues for biogeochemical processes and eventually help to identify isotope biosignatures on Mars (e.g., Moreras-Marti et al. 2021).

Cross-References

- [Archaeon Traces of Life](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Biomarkers](#)
- [Biosignatures, Effect of Metamorphism](#)
- [Carbon Cycle, Biological](#)
- [Delta, Isotopic](#)
- [Dresser Formation, Traces of Life](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Iron Isotopes](#)
- [Iron Reduction](#)

- [Isua Supracrustal Belt](#)
- [Mars Analogue Sites](#)
- [Moodies Group, Microbial Mats](#)
- [Nitrogen Cycle, Biological](#)
- [Nitrogen Isotopes](#)
- [Shark Bay, Stromatolites of](#)
- [Stable Isotopes](#)
- [Sulfate Reduction](#)
- [Sulfur Isotopes](#)

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Isotope Effect

- [Kinetic Isotope Effect](#)

Isotope Fractionation

- [Isotopic Fractionation \(Interstellar Medium\)](#)

Isotopes of Chromium

- [Chromium Isotopes](#)

Isotope-Selective Photolysis

- [Self-Shielding Effects on Isotope Fractionation](#)

Isotopic Effect

- [Kinetic Isotope Effect](#)

Isotopic Exchange Reaction

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Chemical reaction · Isotope

Definition

An isotopic exchange reaction is an ion-molecule reaction that can transfer heavy isotopes between molecules at low temperatures by virtue of the zero-point energy difference between reactants and products.

Overview

An example of the isotopic exchange reactions that are very important in interstellar chemistry is the process $\text{H}_3^+ + \text{HD} \rightarrow \text{H}_2\text{D}^+ + \text{H}_2$, which is ► [exothermic](#) in the forward direction by ~ 230 K but ► [endothermic](#) by the same amount in the reverse direction. Therefore, at low temperatures, D nuclei from plentiful HD molecules, when incorporated in H_2D^+ , can be transferred to other neutral molecules by ion-molecule reactions. This can make, for example, the abundance ratio DCN/HCN in cold molecular clouds very much larger than the cosmic D/H ratio. Other ion-molecule reactions can proceed at low temperatures to fractionate astrophysical molecules in the rarer isotopes ^{13}C , ^{15}N , and ^{18}O .

Cross-References

- [Endothermic](#)
- [Exothermic](#)
- [Interstellar Chemical Processes](#)
- [Ion-Molecule Reaction](#)
- [Isotope](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)

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Isotopic Fractionation (Interstellar Medium)

Thomas J. Millar and Paul M. Woods
Astrophysics Research Centre, School of
Mathematics and Physics, Queen’s University
Belfast, Belfast, Antrim, UK

Keywords

Big Bang · Deuterium · Isotopes ·
Nucleosynthesis · Star formation

Synonyms

Isotope fractionation

Definition

Isotopic fractionation in the ► [interstellar medium](#) refers to the result of chemical processes that selectively incorporate heavier isotopes into a molecule due to zero-point energy effects.

Overview

Isotopes are variants of an atom that contain different numbers of neutrons and hence have different mass. Thus, the element carbon has three isotopes, ¹²C, ¹³C, and ¹⁴C, containing six, seven, and eight neutrons, respectively. Naturally occurring isotopes are made through the processes that create the elements. In the Big Bang, which formed the lightest elements, H, He, Li, Be, and B, nucleosynthesis formed isotopes of all these, ¹H, ²H (D), ³He, ⁴He, ⁶Li, ⁷Li, etc. Indeed, the relative abundance observed for these isotopes, when allowance is made for their destruction since the

Isotopic Fractionation (Interstellar Medium), Table 1 Isotopic abundance ratios in the local interstellar medium (LISM). The abundance ratios are accurate to about 10%

Element	Symbol	Relative abundance in LISM
H	¹ H	1
	² H (D)	1/67,000
C	¹² C	1
	¹³ C	1/77
N	¹⁴ N	1
	¹⁵ N	1/450
O	¹⁶ O	1
	¹⁷ O	1/2,000
	¹⁸ O	1/550
Si	²⁸ Si	1
	²⁹ Si	1/20
	³⁰ Si	1/30
S	³² S	1
	³³ S	1/138
	³⁴ S	1/22

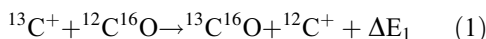
universe was created, is one of the most powerful tests of Big Bang models. When incorporated into molecules, isotopes enable more accurate information to be deduced from astronomical observations of molecular transitions, particularly at radio, millimeter, and infrared wavelengths, as well as act as probes for stellar nucleosynthesis. Table 1 lists the isotopes of the six most common elements that have been detected in interstellar molecules, together with an estimate of their galactic abundance relative to the most abundant isotopic form. Note that these values are representative of the local interstellar medium, although some are known to depend on local star formation activity and thus vary with galactic radius and can be significantly different from values measured in the solar system.

Basic Methodology

Molecular line astronomy, that is, the observation of rotational and ro-vibrational transitions in molecules, is the main means by which we can probe the formation of stars deep in the interstellar clouds in which they are born. In particular, rotational transitions, which have energies equivalent

to a few tens of degrees Kelvin, are well matched to the kinetic temperature of the molecular gas, 10–100 K. Very high-resolution spectrometers, coupled with large surface area radio and submillimeter telescopes on dry mountain tops, such as the James Clerk Maxwell Telescope on Mauna Kea in Hawaii, have been used to detect thousands of transitions in around 150 molecules, not counting isotopologues. (An isotopologue, an “isotopic analogue,” is the name given to a molecule with one or more of its constituent atoms replaced by one of its less abundant isotopes.) When several transitions of the same species can be detected at high spectral resolution, it is possible to derive temperatures, number densities, and kinematics. These physical parameters can be most accurately determined when the emission (or absorption) line is optically thin, that is, when a transition occurring anywhere in the molecular cloud can be observed. Unfortunately, this is often not the case. The lowest rotational transitions of the most abundant molecule observed in the millimeter range, carbon monoxide (CO), are often optically thick, meaning that emission/absorption arises in the surface layers of the cloud and not from the dense core where stars are born. Isotopes allow us to overcome, to a great extent, this “black veil.” Thus, while the transitions of the most common CO isotope, $^{12}\text{C}^{16}\text{O}$, can be very optically thick, those of $^{12}\text{C}^{18}\text{O}$, commonly written C^{18}O , which is around 550 times less abundant (see Table 1), are optically thin and, despite its lower abundance, still observable in interstellar clouds.

The use of isotopologues to derive physical parameters is widespread in molecular astronomy but is less useful in determining abundances of the main isotopic species due to a process called “isotopic fractionation,” which selectively incorporates heavier isotopes into a molecule due to zero-point energy effects. We consider first the fractionation of ^{13}C in CO when the bulk of carbon is in singly ionized form, C^+ , as commonly occurs, for example, in the edges of ► [molecular clouds](#). In this case the ion-neutral isotopic exchange reaction:



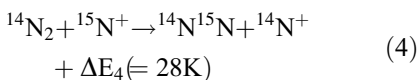
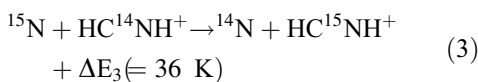
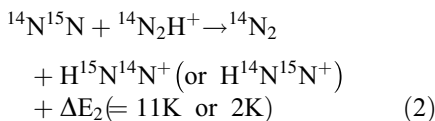
is exothermic in the forward direction and endothermic in the reverse direction due to the fact that ^{13}CO has a slightly lower zero-point energy, by $\Delta E_1/k \sim 35$ K, than ^{12}CO . In steady state, the abundance ratio of $^{13}\text{CO}/^{12}\text{CO}$, $R(^{13}\text{CO})$ can be written as:

$$\begin{aligned} R(^{13}\text{CO}) &= (k_f/k_r)R(^{13}\text{C}^+) \\ &= R(^{13}\text{C}^+) \exp(\Delta E_1/kT) \end{aligned}$$

where T is the kinetic temperature of the molecular gas. Hence, at the low temperatures, ~ 20 K, expected in the outer regions of molecular clouds, the isotopic ratio in ^{13}CO can be enhanced by a factor of about 6 and at 10 K by a factor of about 30. In fact, such a large enhancement is unlikely to occur since the chemistry is more involved than described by the simple equation above. Most importantly, regions in which C^+ is abundant must be pervaded by a UV radiation field sufficiently strong to keep the bulk of carbon in ionized form. This radiation field, however, also photodissociates CO and its isotopologues. Since photodissociation of CO proceeds via absorption of line photons, CO self-shields against destruction with the less abundant isotopologues less able to shield and therefore they are destroyed faster than the main isotopic form. The detailed ratio of CO to its minor isotopes thus depends on a competition between the isotope exchange reaction, which enhances the ^{13}C content in CO, and photodissociation, which decreases it. Nevertheless, the fact remains that the ^{13}C content of CO can be larger than the underlying “cosmic” ratio, although typically by a factor of less than 2. The enhancement of ^{13}C in CO, and hence its depletion in C^+ , has consequences for other molecules that form from these species. Thus, molecules formed from CO, such as HCO^+ , will carry an enhanced ratio while molecules formed from C^+ , such as CH^+ , will carry a lower ratio. It is not just gas-phase species that can carry these anomalies. Molecules formed from CO when it freezes out on to dust grains, for example, H_2CO , CO_2 , and CH_3OH , should also have enhanced isotopic ratios in ^{13}C . The study of isotopic ratios in grain ices, or in molecules evaporated from such

ices in hot molecular core regions, thus provides a potentially powerful probe of studying how individual molecules may form on grain surfaces.

In a second case, low-temperature fractionation of ^{15}N with respect to ^{14}N can occur. For instance, cometary values of $^{14}\text{N}/^{15}\text{N}$ are typically ~ 150 , while terrestrial and protosolar values are much larger (272 and 440, respectively). In models of molecular clouds, fractionation proceeds through reactions such as:

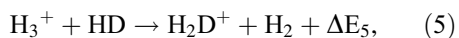


As in the case for carbon, nitrogen fractionation occurs through ion-molecule reactions, making the chemistry of He^+ significant: the fractionation timescale in the interstellar medium is essentially dictated by the availability of the helium ion, which typically destroys those molecules with which it reacts. In regions of high He^+ abundance (e.g., regions where CO has been depleted), the production of $^{15}\text{N}^+$ initiates an enrichment of nitrogen hydrides (such as ammonia) through reactions with H_2 , starting with $^{15}\text{N}^+ + \text{H}_2 \rightarrow ^{15}\text{NH}^+ + \text{H}$ and continuing until $^{15}\text{NH}_3^+ + \text{H}_2 \rightarrow ^{15}\text{NH}_4^+ + \text{H}$. This sequence is tempered by the ortho-to-para ratio of H_2 , as discussed below, which can affect the circulation of $^{15}\text{N}^+$ back into N_2 via reaction (4). Nitriles are fractionated via reaction (3). The disparity between $^{14}\text{N}/^{15}\text{N}$ ratios for CN and HCN in comets is further evidence for HCN not being the sole parent of CN in these environments.

Key Research Findings

Since isotopic fractionation occurs due to zero-point energy differences, the biggest effect occurs

in the exchange of D and H since this causes the largest increase in reduced mass in a molecular system. Indeed, enhancements of up to 10 orders of magnitude are seen in some deuterated molecules, about 30 of which have been detected in interstellar clouds, including doubly and triply deuterated species. In cold dense clouds, the reservoirs of D and H are HD and H_2 , with an underlying ratio $R(\text{HD}) = 2R_D \sim 2-3 \times 10^{-5}$, where R_D is the cosmic ratio of D to H, $\sim 1-1.5 \times 10^{-5}$. The most important isotopic exchange reaction in these clouds is the reaction of H_3^+ , formed by the cosmic-ray ionization of H_2 , with HD:



where the precise value of the exothermicity, ΔE_5 , has contributions from both enthalpy and entropy and depends on the rotational energies of the reactants. For all species in their ground states, $\Delta E_5/k \sim 230\text{ K}$. Assuming steady state, then the abundance ratio of $\text{H}_2\text{D}^+/\text{H}_3^+$ becomes:

$$R(\text{H}_2\text{D}^+) = R(\text{HD}) \exp(\Delta E_5/kT).$$

For a gas temperature of 10 K, one sees that the theoretical enhancement of the cosmic ratio, R_D , becomes extremely large as the rate coefficient of the reverse reaction in Eq. 5 goes to zero. In fact, the enhancement does not grow exponentially large at low temperatures because other reactions destroy H_2D^+ , including dissociative recombination with electrons and proton or deuteron transfer with neutrals, and act to limit the ratio. Taking these reactions into account gives a crude estimate of the enhancement factor, $S(T)$, as:

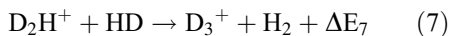
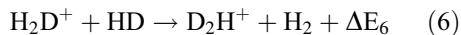
$$\begin{aligned} S(T) = 1 / \Big[&\exp(-\Delta E_5/kT) + (k_e/k_f)f(e) \\ &+ (k_M/k_f)f(M) \Big] \end{aligned}$$

where k_f is the forward rate coefficient of reaction Eq. 5, k_e is the dissociative recombination rate coefficient of H_2D^+ , and k_M is the rate coefficient for reaction of H_2D^+ with neutral species M. Here, $f(X)$ represents the fractional abundance of

species X relative to molecular hydrogen. Typically, the value of k_e is about 100 times larger than those of ion-neutral reactions. The enhancement obtained thus depends not only on the temperature but also on the relative abundances of electrons and reactive neutrals. Since the value of $f(e)$ is two to three orders of magnitude less than that of $f(M)$ in molecular clouds, it is reactions with M that determine the level of enhancement below 20 K. In fact because of its low proton affinity, H_3^+ (and H_2D^+) reacts with almost all neutral species in molecular clouds, with the exception of H, H_2 , He, N, and O_2 . For the case in which neutral abundances, $f(M)$, have their maximum values, given by the elemental abundances of C, N, and O, enhancements of up to 1,000 can occur. For the case where abundances are decreased by 100, to simulate freeze out on to cold grain surfaces, enhancements greater than 10,000 can occur, that is, $R(H_2D^+)$ can be larger than unity. For temperatures greater than about 25 K, the first term in the denominator dominates, and the enhancement falls off exponentially with increasing temperature.

Such large enhancements in the deuterium fractionation in H_2D^+ are transferred to other molecules through deuteron transfer, which is assumed to occur statistically in one-third of all reactive collisions. Thus, DCO^+ and N_2D^+ , for example, should show – and indeed do show – extremely large enhancements in cold, dense cores that have undergone some depletion of molecules, the most important of which is CO because of its large underlying abundance, on to grain surfaces.

In cases where such depletion is enhanced, the formation of doubly and triply deuterated molecules becomes possible. In the equation above for the enhancement of H_2D^+ , the species M implicitly includes HD since H_2D^+ (and D_2H^+) can also react with this species.



where the exothermicities have the same dependencies as ΔE_5 and values of ~ 187 K and 159 K,

respectively. One sees that, in certain circumstances – very low temperatures and heavy depletion of neutral species – D_3^+ can be more abundant than H_2D^+ and therefore potentially a more important deuteron donor since it transfers a deuteron on every reactive collision. In regions characterized by such conditions, corresponding to the gas in star-forming regions immediately before nuclear burning in protostars commences, observations of molecular line emission from H_2D^+ and D_2H^+ , both of which have a small electric dipole moment, may be the only feasible means of studying the physics of star formation.

Gas-phase chemistry initiated by these and other fractionation reactions drives very efficient enhancements in deuterium. For example, triply deuterated ammonia has been observed with an abundance relative to normal ammonia of $\sim 10^{-3}$, some 11 orders of magnitude greater than the statistical ratio. A similar effect is found in triply deuterated methanol, while the D_2CO/H_2CO abundance ratio has been measured to be as large as 0.4 in some clouds. While gas-phase reactions involving the deuterated versions of H_3^+ are important, grain surface reactions may also play a significant role in enhancing isotopic fractionation – it is noteworthy that the molecules showing the largest deuterium fractionation, NH_3 , H_2CO , and CH_3OH , are all thought to form efficiently in cold ice mantles on dust grains. The large fractionation in H_3^+ gives rise, upon dissociative recombination with electrons, to a large enhancement in atomic deuterium. Collisions of atomic D with cold grains then lead to an enhancement of D/H on grain surfaces and to enhancements in the species that form there.

The effect of considering the ortho and para states of H_2 can be significant (ortho signifying aligned nuclear spins and para signifying anti-parallel spins of the hydrogen nuclei). In cold interstellar environments, the zero-point energy difference between the nuclear spin states of H_2 (about 170 K) is enough to allow some slightly endoergic reactions, for example, that with N^+ , to proceed with H_2 in its $J = 1$ (ortho) state. Following on from this, if the ortho-to-para (OPR) ratio is high (i.e., the higher energy

state is dominant), production of H_2D^+ in reaction (5) can be inhibited, and the D/H ratio in H_3^+ can be lower than expected. Typically, this ortho-to-para ratio is 3 at high temperatures. Ortho to para conversion, however, occurs efficiently at low temperatures in the interstellar medium, for example, via $\text{H}^+ + \text{o-H}_2 \rightarrow \text{H}^+ + \text{p-H}_2$, meaning that in the diffuse ISM, the OPR is about 1.

Cross-References

- [Gas-Grain Chemistry](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Ion-Molecule Reaction](#)
- [Molecular Cloud](#)

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Isotopic Fractionation (Planetary Process)

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

The term *isotope fractionation* refers to subtle variations of isotopic abundances among coexisting solids, liquids, and gases. It can both take place at equilibrium and reflect kinetic effects. It can be mass dependent, when its amplitude is a monotonic function of the isotope masses, or else be mass independent. It is normally given in delta (δ) units, which represent the relative deviation of a particular isotopic ratio in a particular sample with respect to this ratio in a reference material.

History

American physical chemist Harold C. Urey (1947) and chemists J. Bigeleisen and M.G. Meyer (1947) must be credited for the first theoretical prediction of isotopic fractionation. J. M. McCrea (1950) calibrated the fractionation of ► [oxygen isotopes](#) between coexisting carbonates and liquid water.

Overview

Isotope fractionation results from slightly different chemical properties among the isotopes of the same element. These variations are large enough (typically 0.1–10‰, where ‰ indicates permil) to be measured by mass spectrometry. They occur both at equilibrium and under the effect of kinetics. The isotopic properties of a molecule reflect its share of the different sorts of energy: translational, rotational, and vibrational. Isotope fractionation results from the Heisenberg uncertainty principle: the separation distance between two bonding atoms (e.g., O and H in OH) cannot be

that of the potential energy minimum as both the position and the velocity would be fixed. The minimum of vibrational energy is reached for the mass-dependent *zero-point energy* $\frac{1}{2} h\nu$, where h is the Planck constant and ν the vibration frequency. There is no zero-point energy for rotational energy, and the incidence of zero-point translational energy is negligible. Because vibrational energy varies inversely with the square root of the mean mass of the vibrating pair (heavy atoms vibrate less rapidly than light atoms), such an effect is referred to as *mass-dependent isotope fractionation*. Heavy isotopes prefer the low-energy states, which explains why liquid water is preferentially enriched in ^{18}O and ^2H (also represented with the notation “D”) over ^{16}O and H, respectively. Likewise, oxides (CO_2 , NO_2 , SO_2) tend to concentrate the heavy isotopes at the expense of the corresponding reduced species (CH_4 , NH_3 , H_2S). The symmetry of interacting molecules also plays a major role.

Isotopic variations of H, O, C, N, and S are commonly reported in the delta (‰) notation, e.g., $\delta^{18}\text{O}$, which is the relative excess of ^{18}O over ^{16}O in a particular sample with respect to a reference material (see Delta Notation entry).

Isotope fractionation varies with temperature, e.g.,

$$1000 \ln \alpha^{18\text{O}}(\text{quartz/water}) \\ \approx \delta^{18}\text{O}_{\text{quartz}} - \delta^{18}\text{O}_{\text{water}} = A/T^2 + B$$

where T is in Kelvin, $\alpha^{18\text{O}}$ is the ratio of $^{18}\text{O}/^{16}\text{O}$ in coexisting quartz and water, and A and B are constants (most often B is zero). Isotope fractionation is therefore most noticeable at ambient temperatures and is still significant in the crust ($<600^\circ\text{C}$). Isotope fractionation is greatly enhanced by distillation processes. Fractionation during analysis is often referred to as *mass bias*.

Understanding biological and physical isotopic fractionation processes is fundamental for discriminating the isotopic signature of elements such as C, N, S, and Fe preserved in the rock record and deciphering whether these signatures have a biological or abiological origin. Isotopic fractionation is also important for discriminating

sources of elements in the universe. An important astrobiological example is the D/H ratio (the isotopic ratio between [▶ deuterium](#) and hydrogen), which varies in hydrogenated molecules preserved in planetary bodies depending on the temperature at which water molecules exchange between a vapor and a solid phase. The D/H ratio is a valuable marker of the carrier phase of water on Earth (comets vs. meteorites), because these different bodies formed and hydrated at different distances from the Sun.

There is considerable discussion at this time about whether different planets have the same isotope abundances, notably for metals. The abundance of neutron-rich isotopes, such as ^{48}Ca , ^{54}Cr , and ^{50}Ti , clearly varies across the Solar System, but the isotope proportions of other elements such as Zn and Rb may vary as well. It is now believed that these isotope heterogeneities predate the formation of the Solar Nebula. For many elements, isotope abundances in the Moon and the Earth differ from those of [▶ chondrites](#). The Moon and the Earth have comparable isotope compositions for most elements, except for the element Zn. This issue is the topic of active research.

Cross-References

- ▶ [Deuterium/Hydrogen Ratio](#)
- ▶ [Distillation, Rayleigh](#)
- ▶ [Fractionation, Mass Independent and Dependent](#)
- ▶ [Hydrogen Isotopes](#)
- ▶ [Iron Isotopes](#)
- ▶ [Isotopic Ratio](#)
- ▶ [Nitrogen Isotopes](#)
- ▶ [Oxygen Isotopes](#)
- ▶ [Stable Isotopes](#)
- ▶ [Sulfur Isotopes](#)
- ▶ [Urey's Conception of Origins of Life](#)

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- [Isotopic Fractionation \(Planetary Process\)](#)
- [Nitrogen Isotopes](#)
- [Oxygen Isotopes](#)
- [Stable Isotopes](#)
- [Sulfur Isotopes](#)

Isotopic Isomer

- [Isotopomer](#)

Isotopic Ratio

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

Isotopic ratio refers to the ratio of the atomic abundances of two isotopes of the same element, e.g., $^{18}\text{O}/^{16}\text{O}$ or $^{143}\text{Nd}/^{144}\text{Nd}$. An advantage of using ratios rather than absolute abundances of a particular nuclide is a better precision. Comparing the two signals ^{143}Nd and ^{144}Nd can be done at the ppm (one part in one million) precision level, i.e., two to three orders of magnitude more precisely than the counting of either nuclide individually.

Isotopic ratios change as a result of (1) thermodynamic fractionation, (2) radioactive ingrowth, (3) the presence of nucleosynthetic compounds, and (4) spallation reactions. Ratios of a radiogenic isotope (e.g., ^{143}Nd) to a stable isotope (e.g., ^{144}Nd) are used in geochronology and provide information on the geochemistry of sample source environment; ratios of stable isotopes provide information about temperatures and sources.

Cross-References

- [Fractionation, Mass Independent and Dependent](#)
- [Geochronology](#)
- [Hydrogen Isotopes](#)
- [Iron Isotopes](#)
- [Isochron](#)

Isotopic Traces of Life

- [Isotope Biosignatures](#)

Isotopolog

Steven B. Charnley
Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

Isotopologs are molecules that differ only in the isotopic composition of their constituent atoms, for example, HDO and H₂O, where D (deuterium) is ^2H . Astrochemists sometimes use isotopomer as a synonym for isotopolog, although chemists normally define isotopomers to mean ► [isomers](#), which have the same number of each rare-isotopic atom but with these atoms differing in their positions in the molecule.

Cross-References

- [Isomer](#)
- [Isotope](#)

Isotopomer

Weifu Guo
Carnegie Institution of Washington, Washington, DC, USA

Synonyms

[Isotopic isomer](#)

Definition

Isotopomers (the term being a contraction of *isotopic isomer*) are chemical compounds (molecules, ions, radicals, etc.) that have the same number of each isotopic atom (same isotopic formula) but differ in the positions of isotopes. They are either *constitutional isomers* (e.g., $\text{CH}_3\text{-CDH-CH}_3$ vs. $\text{CDH}_2\text{-CH}_2\text{-CH}_3$), or *isotopic stereo-isomers* (e.g., (*R*)- vs. (*S*)- $\text{CH}_3\text{-CHDOH}$, or (*E*)- vs. (*Z*)- $\text{CH}_3\text{-CH=CHD}$). An isotopomer should not be confused with an *isotopologue* (a compound with the same chemical structure but with a different isotopic composition). For International Union of Pure and Applied Chemistry official definitions, see Minkin (1999) Glossary of terms used in theoretical organic chemistry. Pure Appl Chem 71:1919–1981.

Cross-References

- ▶ [Isomer](#)
- ▶ [Isotopolog](#)

Isovaline

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Isovaline is an α -amino acid that rarely participates in biochemical processes. It has been detected in the Murchison and other meteorites, in many instances with a significant L-enantiomeric excess. It is an isomer of the biologically important amino acid valine. It has been proposed that it is synthesized prebiotically via a ▶ [Strecker synthesis](#) from methyl ethyl ketone and ammonium cyanide. Since the α -proton in isovaline is replaced with a methyl

group, the kinetics of aqueous ▶ [racemization](#) are extremely slow, and thus it has been suggested that the ▶ [enantiomeric excess](#) of L-isovaline represents an initial chiral synthetic bias, which has subsequently been lost in the α -proton containing ▶ [amino acids](#). Isovaline is, however, found in some fungal antibiotic peptides; thus, it cannot be considered a strict marker of abiological synthesis.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Chirality](#)
- ▶ [Enantiomeric Excess](#)
- ▶ [Racemization](#)
- ▶ [Strecker Synthesis](#)

ISRO, India

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Indian Space Research Organization](#)

Definition

India began space activities in the early 1960s as a nonaligned country. Various committees were created to support the national effort in developing launchers and satellites. In 1969, ISRO was created as part of the Nuclear Energy Department and became an independent organization in 1972. In 1975, the program launched Aryabhata, the first Indian satellite, and since then, it has produced the Polar Satellite Launch Vehicle (PLSV) to launch satellites for remote sensing. The Geosynchronous Satellite Launch Vehicle (GSLV) is able to send up to 2 t in geosynchronous transfer orbit. In 1984, an Indian astronaut flew on board the Russian Salyut 7 space station. India is now turning to space sciences and

exploration, and current ISRO activities are spread among more than 20 laboratories or centers across India. In 2008, India sent the Chandrayaan-1 to orbit the Moon, and in 2014, India's Mars Orbiter Spacecraft successfully achieved an orbit around Mars.

For further information, see <https://isro.gov.in>

ISS

► [International Space Station](#)

ISSI

Jean-Pierre Bibring
Institut d'Astrophysique Spatiale, Université
Paris Sud, Orsay, France

Synonyms

[International Space Science Institute](#)

Definition

The International Space Science Institute (ISSI) was established in 1995 as an institute of advanced studies where scientists from all over the world meet in a multi- and interdisciplinary setting to reach out for new scientific horizons. The institute organizes workshops as well as working groups and forums. Thereby, the institute offers space to scientists, ground-based observers, experimenters, theoreticians, and modelers, providing opportunities to work together and to analyze and compare data from a multitude of sources. Because data are collected from a variety of spacecraft and ground-based facilities, interdisciplinary meetings enable scientists to extract or create more science with little additional expenditure. More than 6200 individual scientists from 60 countries have participated in ISSI activities during the first 25 years of its existence and published the results in scientific publications. The institute is managing several publications

covering all the fields of space sciences, among others, the Space Sciences Series of ISSI (SSSI) and the ISSI Scientific Report Series.

The institute is based in Bern (Switzerland). The staff is headed by an executive director and includes three additional scientific directors and five scientists. The present permanent staff is around 15 people.

Strategies of Life Detection, O. Botta, J. Bada, J. Gómez Elvira, E. Javaux, F. Selsis, R. Summons (Eds.), published in August 2008, and Geology and Habitability of Terrestrial Planets, K.E. Fishbaugh, P. Lognonné, F. Raulin, D.J. Des Marais, O. Korablev (eds.), published in September 2007, are two examples of early activities of ISSI related with astrobiology.

Further information: www.issibern.ch

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ISSOL

Antonio Lazcano
Facultad de Ciencias, UNAM, Mexico, DF,
Mexico

Keywords

Astrobiology · Origins of life

Synonyms

[International Astrobiology Society](#); [International Society for the Study of the Origin of Life](#)

Overview

Following the first International Conference on the Origin of Life on Earth held in 1957 in

Moscow organized by A. I. Oparin under the auspices of the International Union of Biochemistry and the second international conference held at Wakulla Falls, USA, with the support of ► [NASA](#) and Institute for Space Biosciences of the Florida State University. during the 1970 conference that took place in Pont-à-Mousson, France, the organizational meeting for the founding of the International Society for the Study of the Origin of Life (ISSOL) took place. Its first president was the Soviet scientist Alexander I. Oparin whose work during the first half of the twentieth century opened the possibility of transforming the study of the origin of life from mere speculation into a workable research program capable of unifying disparate facts and observations from widely different fields within a coherent explanatory framework provided by a Darwinian view.

Although numerous origin of life meetings had been held following the 1957 Moscow conference, most of them had a regional character and limited scope. Because of this, it was decided that the first ISSOL meeting, which took place in 1973 in Barcelona, was also named the 4th International Conference on the Origin of Life. The recognition of the scientific significance of the field of astrobiology, as promoted by NASA and adopted by scientists in many countries, led in 2005 to a change of name which transformed the society into ISSOL: The International Astrobiology Society.

ISSOL currently has some 500 members from more than 20 countries, two of whom received Nobel Prizes in 2009, Jack W. Szostak in Physiology and Medicine and Ada Yonath in Chemistry. The society's official journal is *Origins of Life and Evolution of Biospheres (OLEB)*.

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Isua Greenstone Belt

► [Isua Supracrustal Belt](#)

Isua Supracrustal Belt

Minik T. Rosing

Nordic Center for Earth's Evolution, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark

Keywords

Amitsoq · Archean · Earth's early crust · Early life · Faint young sun · Isua · Late Heavy Bombardment

Synonyms

[Isua greenstone belt](#); [Isuakasia](#)

Definition

The Isua supracrustal belt is the largest contiguous complex of Eoarchean supracrustal rocks (formed at or near the Earth's surface) known on Earth. It is located ca. 150 km NE of Greenland's capital Nuuk, in West Greenland.

History

Since the establishment of the Geological Survey of Greenland in 1946, geological investigations of West Greenland shifted gradually from investigations of individual mineral deposits to mapping of the general geology. By the early 1970s, the main framework of West Greenland's geology was laid

out. An orogenic belt was identified around 66°N, the so-called Nagssuqtoqidian orogen, characterized by Paleoproterozoic penetrative deformation and metamorphism of a preexisting Precambrian basement, still preserved toward the south (Noe-Nygaard and Ramberg 1961; van Gool et al. 2002). South of 61°N, the old basement was again overprinted by deformation and metamorphism during the Paleoproterozoic and the accretion of a juvenile magmatic arc onto the old continent. This Ketilidian orogen also hosted the alkaline Gardar igneous province (Ussing 1912; Garde et al. 2002) emplaced around 1,300 Ma ago (Vanbreem and Upton 1972). The Archean cratonic basement sandwiched between these two orogenic belts is known as the Archean Block.

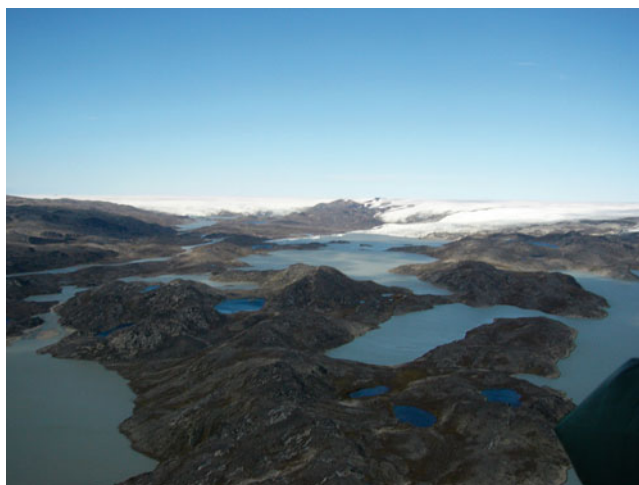
The Achaean Block is dominated by Eoarchean and Meso-Neoarchean amphibolite and granulite-facies felsic gneisses (Bridgwater et al. 1970; Griffin et al. 1980). The gneiss complex around Nuuk (previously Godthåb) can be divided into two domains based on the presence or absence of a suite of mafic dikes named Ameralik dikes (McGregor 1968) that contain characteristic plagioclase megacrysts. The so-called Amitsoq gneisses contain mafic dikes or mafic enclaves that represent deformed fragments of such dikes. The other gneiss suite, named the Nuuk (or Nûk) gneisses, contains no Ameralik dikes and was inferred to have been emplaced later than the intrusion of the dikes (McGregor 1973). In 1971,

a suite of the ► [Amitsoq gneisses](#) was dated and produced an age of 3,650 Ma (Black et al. 1971). This exceeded by far any age obtained on terrestrial material before and established the Nuuk area as home to the oldest rocks known on Earth. The two gneiss domains turned out to be dominated by gneisses with ages centered around 3,600 Ma for the Amitsoq gneisses (Moorbath et al. 1972; Baadsgaard 1973, 1976) and around 3,000 Ma for the Nuuk gneisses (Pankhurst et al. 1973). Both gneiss complexes also contain inclusions and contiguous belts of supracrustal rock (rocks formed at or near the Earth's surface). In both terranes, the supracrustal rocks appeared to pre-date the gneisses, because the granitoid precursors to the gneisses were commonly intrusive into the supracrustal rocks. The supracrustal assemblage in the Amitsoq gneisses was named the Akilia association, and the supracrustal rocks within the Nuuk gneisses were called the Malene supracrustals (McGregor 1973; Gill and Bridgwater 1976).

During the late 1960s, prospectors carried out aeromagnetic surveys of the west coast of Greenland and identified a strong magnetic anomaly at Isua near the margin of the Inland Ice 150 km NE of Nuuk (Kurki and Keto 1966) (Fig. 1). This anomaly turned out to be caused by a large deposit of quartz-magnetite banded-iron formation (BIF). Mapping showed that the BIF formed part of a large arcuate belt of supracrustal rocks some

Isua Supracrustal Belt,

Fig. 1 The Isua landscape is barren with excellent exposure due to the high elevation and the proximity to the Greenland Ice Cap. The mountain peak in the background is “Iron Mountain,” a large quartz-magnetite banded-iron formation deposit



30 km in length and up to 4 km in width (Bridgwater and McGregor 1974; Allaart 1976). The Isua BIF gave an age of 3,770 Ma (Moorbath et al. 1973), the oldest age obtained for any rock on Earth at that time. From field relations, the Isua supracrustals and the Akilia association occupy the same chronostratigraphic position since both are older than the enveloping Amitsoq gneisses. Further isotopic age determinations supported this observation and showed that at least some of these supracrustal rocks are more than 3,800 Ma old (Baadsgaard et al. 1984; Nutman et al. 1984, 2002).

The collage of tectonic panels of different ages and origins in the Nuuk region has been placed into a model of Archean terrane accretion by Nutman et al. (1989). The oldest assemblage of rocks, which included the Amitsoq gneisses and the Isua and Akilia association of supracrustal rocks, was defined as the Itsaq Gneiss Complex (Nutman et al. 1996, 2000, 2002). Eoarchean rocks with ages >3,600 Ma have also been identified along the northern boundary of the Archean Block in the so-called Aasivik terrane (Rosing et al. 2001), but little is known about this terrane at present.

Overview

The scientific attention paid to the Eoarchean complexes around Nuuk and the Isua and Akilia supracrustals is probably unparalleled in the world of geology. The research has focused on two main avenues. One was the state of chemical differentiation of Earth by the Eoarchean, and the other was the characterization of the early Earth's surface environments and the search for traces of life on the young planet.

Early Earth Differentiation

Earth has undergone continued differentiation (see ► [“Earth, Formation, and Early Evolution”](#)) into distinct chemical reservoirs such as the granitic continental crust, the basaltic oceanic crust, the depleted mantle from which the crust was extracted and the atmosphere and the oceans where the volatile components from the depleted

mantle are concentrated. The Amitsoq gneisses and the Isua and Akilia supracrustal rocks became a prime target for the development and use of isotopic tracers to document the timing and extent of differentiation of the young Earth. If radioactive mother isotopes and their radiogenic daughter isotopes have different compatibilities in the mantle during melting, the timing and extent of melting will be reflected in the isotopic composition of both the residual mantle and the rocks formed from the melt, and the isotopic dissimilarity will be more pronounced with time. Given this insight, a number of isotopic systems were applied (see ► [“Geochronology”](#)) on Isua rocks to establish the extent and history of differentiation of Earth (see ► [“Earth, Age of”](#)) by the earliest Archean (U-Th-Pb (Moorbath et al. 1975), ^{147}Sm - ^{143}Nd (Hamilton et al. 1978), Lu-Hf (Blichert-Toft et al. 2000), La-Ce (Shimizu et al. 1988), ^{146}Sm - ^{142}Nd (Boyet et al. 2003; Caro et al. 2003). The conclusions drawn from these isotope studies were that there still was some chemical heterogeneity inherited from early differentiation of Earth preserved in the mantle at Isua time. These heterogeneities could have been established during an early magma ocean episode and subsequently progressively erased by mantle convection and back mixing of protocrust into the mantle. Another conclusion was that a depleted mantle reservoir similar to the present-day source of mid-ocean-ridge basalt was present even during the earliest Archean.

Traces of Life and Early Earth Surface Conditions

Already in 1979, the German geochemist Manfred Schidlowski (Schidlowski et al. 1979) proposed that the ratio between the two stable isotopes of carbon ^{13}C and ^{12}C found in ancient sedimentary rocks could be used to identify the presence of life in Earth's early oceans. This is because living organisms incorporate ^{12}C more efficiently than ^{13}C when they form organic matter from ambient CO_2 and therefore leave the ocean and atmosphere enriched in ^{13}C and organic-rich sediments depleted in ^{13}C . He used this principle on carbonate rocks and graphite from Isua under the assumption that the carbonate

represented the carbon isotopic composition of the early Archean ocean and the graphite represented metamorphosed organic matter (Schidlowski et al. 1979). Later geologic studies at Isua, however, showed that the carbonates were formed from circulating brines during metamorphism and that the graphite studied by Schidlowski was also secondary in origin (Rosing et al. 1996). The search for traces of early life in the Archean of West Greenland continued. In 1996, Mojzsis et al. reported the presence of ^{13}C -depleted graphite inclusions from apatite crystals in the supracrustal rocks from Akilia Island, near Nuuk (Mojzsis et al. 1996). In 1999, Rosing reported that shales from Isua contained abundant sedimentary ^{13}C -depleted carbon (Rosing 1999; van Zuilen et al. 2003) (Fig. 2). There has been an ongoing and continued controversy over the credibility of these claims for the presence of life during the earliest part of Earth's history, and research into this topic is still ongoing along many different avenues of study.

The Isua supracrustal sequence also carries information about the surface conditions on the young Earth. Most significantly, water-lain sediments attest to the presence of a liquid hydrosphere, most probably the existence of oceans, from at least 3,800 Ma ago. The Isua supracrustal rocks have also been analyzed for traces of the so-called ► **Late Heavy Bombardment**, which cratered the Moon, and possibly also affected

Earth in a dramatic way at the time of deposition of the Isua sediments. However, this search has given no clear evidence for extraterrestrial material in the Isua rocks (Schoenberg et al. 2002; Frei and Rosing 2005).

The Composition of the Isua Supracrustal Belt

Soon after the discovery of the Isua supracrustal belt, several lithologic units were identified (Keto and Kurki 1967; Allaart 1976). The belt is outlined in the field by a prominent erosion-resistant ridge, which is dominated by a chloritic amphibolite unit characterized by a distinctive amphibole sheave texture. This unit was called the Garbenschiefer Formation, and its protolith was generally believed to be a sill-like mafic intrusion. The BIF that originally had given the supracrustal belt away forms a very large body at the northeast termination of the belt under the Inland Ice, but this unit can also be traced more or less continuously along the full extent of the belt. In early maps, this BIF was lumped with various other lithologies into a "quartzitic sequence." Bordering on the BIF is a thick unit of carbonate and calc-silicate-rich rock which commonly grades into carbonate-rich mica schists. This unit was called the carbonate formation and was believed to represent a change in sedimentary facies in the same sedimentary basin that gave rise to the BIF. Along most of the length of the belt, felsic schists and two-mica gneisses are common. At many localities, these

Isua Supracrustal Belt,

Fig. 2 Well-preserved Bouma sequence with alternating graphite-rich black shale and gray turbidite sediments. The black shale contains abundant fine particles of carbon with $\delta^{13}\text{C} \sim -25$, most likely derived from living organisms



rocks display a diamictic structure. At one locality, large felsic “boulders” stand out from a slightly darker, carbonate-rich matrix. This rock was called the “bomb rock,” and fiamme-like textures were described from the alleged felsic volcanic bombs. For this reason, this felsic formation was believed to be dominated by volcanic rocks. Along the margin of the belt, black amphibolite forms the predominant lithology and was often referred to as the amphibolite formation. The distribution of lithologies gave the impression of a sequence of lithologies that was repeated by folding along an arcuate axial plane tracing the center of the supracrustal belt. It was assumed that the belt formed a rim syncline enveloping a central gneiss dome, following the style that was seen in the classical granite-greenstone terranes of Australia (Keto and Kurki 1967). Another prominent suite of lithologies is ultramafic rocks, which occur as serpentinites, talc-anthophyllite-magnesite schists, and dunites. These rocks occur as discontinuous layers and lenses within the sequence and do not appear as a single unit. In the northeastern termination of the belt, the distinctive garbenschiefer unit (see above) also occurs in a separate splay along the inner perimeter of the belt and is separated from the rest of the belt by a distinctive topographic lineament. This was considered a separate segment of the belt, which also included a mica schist unit and a felsic unit. The formations of the main belt were allocated to a so-called A sequence, and the rocks in the small separate domain were allocated to a “B sequence.” This understanding of the geology of Isua permeated the literature (Nutman et al. 1984) and formed the basis for the 1:40,000 geological map published by the Geological Survey of Greenland in 1986 (Nutman 1986). Many of the main features of the belt were surprisingly well understood in these very early works, and the main lithological subdivision has remained almost unchanged during the more than 40 years passed since the discovery of Isua. In terms of describing the makeup of the Isua belt, subsequent work has mainly proposed new interpretations of the protoliths to the present lithologies and increased the detail of their geochemical description.

Metamorphism, Deformation, and Metasomatism

It was readily observed that the rocks at Isua were generally strongly deformed (James 1976) and had experienced penetrative amphibolite-facies metamorphism (Allaart 1976; Gill and Bridgwater 1976; Nutman et al. 1984). The contact between the orthogneiss complexes that envelop the belt was identified as predominantly tectonic, and it was concluded that a suite of mafic dikes that transect both the Isua supracrustals and the gneisses were equivalent to the Ameralik dikes defined in the Godthaabsfjord region. Boak and Dymek (1982) presented a detailed study of the metamorphic overprint on the supracrustals. With increasing intensity of geochemical studies of the supracrustals and especially the advent of new isotopic tracers and age determination protocols, it became increasingly obvious during the 1970s and 1980s that many lithologies had not remained closed geochemical systems during deformation and metamorphism. It was first noted that alkali metals had been mobile (Gill and Bridgwater 1979; Baadsgaard et al. 1986), but also the Sm-Nd and Lu-Hf isotopic systems showed clear signs of disturbance (Gruau et al. 1996; Frei et al. 2002; Polat et al. 2003). Rosing et al. (1996) proposed that the Isua supracrustals had been pervasively metasomatized and that the carbonate-calc-silicate formation was not a stratigraphic unit of sedimentary origin, but rather represented a wide variety of different lithologies transformed by transient silica-undersaturated carbonic fluids derived from devolatilization reactions in the ultramafic rocks (Rosing and Rose 1993; Rose et al. 1996). Inherent in this reinterpretation of the lithologic variation within the supracrustal belt was the breakdown of the interpretation of the Isua belt as a tight syncline folded into an open arc, as the symmetry of formations about a central axial plane trace was no longer apparent when the metasomatic overprinting was considered.

Recent developments in the understanding of the tectonic construction of the Isua belt include the proposal that the Isua belt formed as an accretionary complex, which shares many similarities with the Phanerozoic accretionary complexes of

Isua Supracrustal Belt,
Fig. 3 Pillow structure in metabasalt from Isua. The pillow basalts occur in association with sheeted dikes, gabbros, and ultramafic rocks in an assemblage similar to modern ophiolite complexes



Japan (Komiya et al. 1999). This suggestion allowed for the realization that the Isua belt might be composed of tectonic panels of slightly different early Archean ages and origins (Nutman et al. 1997) and that the package included ocean-floor sequences similar to Phanerozoic ophiolites (Furnes et al. 2007) (Fig. 3). A new updated 1:20,000 geologic map constructed on the basis of a composite origin of the Isua supracrustal belt has been presented by Nutman and Friend (2009).

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Isuakasia

- [Isua Supracrustal Belt](#)

Itabirite

- [Banded Iron Formation](#)

Italian Society of Astrobiology

John R. Brucato
Astrophysical Observatory of Arcetri, Florence,
Italy

Synonyms

[ISA](#)

Definition

The Italian Astrobiology Society (SIA) was founded in 2006 by a team of astronomer,

biologist, chemist, geneticist, and medicine scientists with the scope to promote scientific research on astrobiology in Italy. The SIA is a non-profit scientific association of researchers cultivating the study of the origin, evolution, and distribution of life in the Universe. The SIA has a national and independent nature free from any government, organization, or political party. It is open to every expert with documented scientific interests in astrobiology.

The main objectives of SIA are:

- To promote the progress of Astrobiology knowledge
- To promote and coordinate the fundamental and applied research
- To stimulate the collaboration between various scientific disciplines
- To promote and favor the relationships with other international organizations
- To set up relationships with analogous associations
- To favor the development of new technologies for terrestrial and space applications
- To promote new methods of searching for signs of life
- To promote and coordinate activity of higher educations
- To promote meetings and conferences
- To favor the sharing of knowledge for educational aims
- To preserve the scientific interests of astrobiology

Cross-References

- [EANA](#)
 ► [European Astrobiology Institute](#)
 ► [ISSOL](#)
 ► [NAI](#)

Italian Space Agency

- [ASI](#)

Itokawa Asteroid

Anny-Chantal Levasseur-Regourd
Sorbonne Univ., Campus P. & M. Curie /
LATMOS, Paris, France

Synonyms

[Asteroid 25143](#)

Definition

Itokawa (25143) is a near-Earth stony (S-type) asteroid. This object has been the first asteroidal target for a sample return mission, the ► [JAXA Hayabusa](#) mission. Itokawa is likely a contact binary. It is small (major axes 530 m, 290 m, and 210 m) and has a rotation period of about 12.13 h. Its density is rather low ($\approx 1950 \text{ kg m}^{-3}$), meaning that it is porous. This asteroid could indeed have been built from loose-packed rocks held together by gravity, after an impact on a larger parent body. It presents a significant topographic diversity, with boulders on rough terrains and a featureless central area of fine dust particles forming a smooth regolith in gravitational lows. Such results are of importance when considering orbital deflection techniques to be implemented if a similar asteroid was discovered on a collision course with the Earth.

Samples analyses have identified more than 1000 dust particles retrieved from Itokawa, with sizes mostly below 100 micrometers. They consist of minerals (e.g., olivine, pyroxene, plagioclase, and troilite), with water typically in low-calcium pyroxene grains, and a low content of organics (e.g., nanocrystalline graphite and disordered polyaromatic carbon). Their composition appears to be quite comparable to that of ordinary chondrites.

Cross-References

- [Asteroid](#)
- [Bennu Asteroid](#)
- [Hayabusa Missions](#)

- [JAXA](#)
- [Near-Earth Objects](#)
- [Ryugu Asteroid](#)

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Itsaq Gneiss Complex

- [Amitsoq Gneisses](#)

IUPAC

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[International Union of Pure and Applied Chemistry](#)

Definition

IUPAC, the International Union of Pure and Applied Chemistry, defines itself as “the global

organization that provides objective scientific expertise and develops the essential tools for the application and communication of chemical knowledge for the benefit of humankind and the world.” It was originally formed in 1919 in response to the need for international standardization in chemistry, including nomenclature for both inorganic and organic chemistry, standardization of atomic weights and physical constants, and tables of the properties of matter. At present, the scientific work of IUPAC is divided among eight divisions: physical and biophysical chemistry,

inorganic chemistry, organic and biomolecular chemistry, polymers, analytical chemistry, chemistry and the environment, chemistry and human health, and chemical nomenclature and structural representation. Among the activities of IUPAC is the sponsoring of IUPAC projects, which should be related to the needs of chemists in the entire world, should be relevant to the needs of mankind, and can be addressed by an international team that IUPAC can assemble. The national chemical societies of more than 50 countries are affiliated with IUPAC.

JABC, Japan

Motohide Tamura
The University of Tokyo and Astrobiology
Center, Mitaka, Tokyo, Japan

Synonyms

[Japan Astrobiology Consortium](#)

Definition

Nearly 4000 exoplanets have been discovered and confirmed within the last 20 years or so. The diversities of those planets have greatly expanded our view of the universe based on astronomical observations and theories. Earth sciences have also made significant progress in understanding our life-harboring planet. With these advances in astronomy and Earth sciences, as well as expansions in the fields of biology, such as extremophiles and biochemistry, the field of astrobiology is expected to grow significantly in the twenty-first century.

Based on this background, in 2012, the Tokyo Institute of Technology established the Earth-Life Science Institute (ELSI) as a World Premier International Research Center Initiative (WPI) of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. ELSI's research mission is to elucidate how our

planet was formed and how its early environment allowed for the rise of initial life and its subsequent evolution to complexity.

In 2015, the Astrobiology Center (ABC) was established under the National Institute of Natural Sciences (NINS). Since NINS is an inter-university research institute corporation, ABC is not only advancing their research projects but also providing observational instruments to astrobiology researchers throughout the country, in addition to promoting joint research programs and funding. It also utilizes the development of astrobiology and other related fields as opportunities for international cooperation.

In 2016, both ELSI and ABC agreed to establish the Japan Astrobiology Consortium (JABC). In the future, more institutes in Japan are expected to join. JABC's mission is summarized as follows:

- To be a contact point for international astrobiology collaborations
- To be a core of domestic collaborations on astrobiology
- To promote personal exchanges for researchers and students
- To host international conferences and summer school programs on astrobiology
- To support the Japanese Astrobiology Network mailing list

Through these activities, JABC aims to expand and develop the astrobiology field in Japan.

Cross-References

- [Astrobiology](#)
- [Atmospheric Retrieval for Exoplanets](#)
- [EANA](#)
- [Exoplanet, Detection, and Characterization](#)
- [NAI](#)

Jack Hills (Yilgarn Craton, Western Australia)

Simon Wilde

School of Earth & Planetary Sciences, Curtin University, Perth, WA, Australia

Keywords

Continental crust · Hadean · Neoproterozoic · Oceans · Western Australia · Zircon

Definition

Jack Hills is the name of a low range of hills located in the Murchison District of Western Australia, approximately 800 km north of Perth. Since 1986, the area has been internationally known as the site of the world's oldest minerals. These are detrital zircon grains up to 4404 Ma old.

Overview

A ► [zircon](#) grain with a portion recording an age of 4404 ± 8 Ma (2σ) was extracted from a conglomerate on Eranondoo Hill in the central Jack Hills. Published in 2001 (Wilde et al. 2001), this age was ~ 130 Ma older than the previous oldest known crystal on Earth, also reported from the same site in 1986 (Compston and Pidgeon 1986). Prior to that, the oldest known zircon crystals (~ 4150 Ma) were obtained from Mt. Narryer, located ~ 60 km southwest of Jack Hills (Froude et al. 1983). A concordant U-Pb zircon age of 4463 ± 17 Ma (2σ) was obtained from another Jack Hills zircon, but this was shown to be

spurious due to mobility of radiogenic lead during a later thermal event (Ge et al. 2018).

Both Jack Hills and Mt. Narryer are located in the Narryer Terrane, which occupies an area of $\sim 30,000$ km² in the northwestern part of the Archean Yilgarn Craton of Western Australia (Spaggiari et al. 2007; Wilde and Spaggiari 2007; Kemp et al. 2018). The Jack-Hills belt is approximately 90 km long and has a sigmoidal shape. Deformation is extensive, and the contacts of the belt with adjacent deformed granites and gneisses are all sheared, so that its original disposition is obscured. The oldest known rock in Australia (3731 ± 4 Ma) is tonalitic gneiss, collected 3 km south of the Jack Hills (Nutman et al. 1991). Overall, the ages of granitoids at Jack Hills closely match those obtained from Mt. Narryer, with a spread of U-Pb dates from 3.70 to 3.30 Ga for the older components and ages of 2.65 Ga for younger monzogranites that intrude the older granitoids. The latter may locally intrude the belt itself, although the contacts are now sheared. The older granitoids record discrete age peaks at 3.75–3.65 Ga, 3.50 Ga, and at 3.30 Ga, interpreted to define major magmatic events. The oldest group of ages may record the time of extraction of the earliest tonalites from a garnet-amphibolite source. The presence of 3.3 Ga zircon rims around older cores in several sedimentary rocks indicates multiple recycling of the earliest granitoids (Cavosie et al. 2004). Importantly, evidence for 3.3 Ga-old magmatic activity appears to be restricted to the southern side of the Jack Hills belt, suggesting that the belt may lie along a major suture zone within the Narryer Terrane.

The belt itself consists of weakly metamorphosed sedimentary rocks that include ► [banded iron formation](#) (BIF), ► [chert](#), siltstone, quartzite, sandstone, and conglomerate, together with thin units of mafic and ultramafic rocks. These units have been grouped into three packages or associations (Wilde and Pidgeon 1990): (a) chemical sedimentary rocks consisting of BIF and chert, together with mafic schist (amphibolite), and minor ultramafic intrusions, that are developed along both the northern and southern margins of the belt; (b) a pelite-semipelite association characterized by quartz-biotite, quartz-chlorite, and

andalusite-bearing schists, with local mafic and ultramafic schists, which were possibly part of a turbidite sequence that now forms most of the central part of the belt; and (c) mature clastic sedimentary rocks that occur in a more restricted sequence comprising conglomerate, sandstone, quartzite, and siltstone, developed in the central and northern parts of the belt. Until 2002, all sedimentary rocks in the Jack Hills belt were considered to have been deposited in the late Mesoproterozoic to early Neoproterozoic, since no zircon younger than ~ 3.1 Ga had been recorded from the samples. However, concordant late Archean and Paleoproterozoic zircons were discovered in some of the clastic metasedimentary units with ages ranging from 2736 ± 6 to 1576 ± 22 Ma (Cavosie et al. 2004) and were also recorded in rare volcanic units interleaved with the sediments (Wilde 2010). This indicates that younger sedimentary and volcanic units are tectonically interleaved with the Archean units. It is difficult to distinguish the Archean metasedimentary rocks from the Proterozoic ones in the field, due to their lithological similarity and the effects of later deformation but a geochronological traverse through the Jack Hills belt (Wang and Wilde 2018) established that at least 12% of the rocks were Proterozoic.

The main source of ancient zircons for which Jack Hills is internationally known is the Eranondoo Hill site, commonly referred to as the W74 or Discovery site (Fig. 1), where a specific conglomerate unit yields $\sim 12\%$ zircon with ages >4 Ga, making it the richest source of Hadean material currently known on Earth. The zircon crystals are structurally complex, and a range of ages can commonly be obtained from different domains within a single crystal, attesting to their long and complex history. However, because oscillatory zoning of igneous origin defines pristine magmatic domains in many grains, the original source rocks are widely considered to be plutonic igneous rocks (Cavosie et al. 2006; Harrison et al. 2017), possibly of the **tonalite-trondhjemite-granodiorite** series (TTG) (Blichert-Toft and Albarède 2008; Nebel et al. 2013; Bell et al. 2016). **Oxygen isotope** data from such oscillatory-zoned domains in several zircon grains



Jack Hills (Yilgarn Craton, Western Australia), Fig. 1 Simon Wilde (left) and John Valley (right) standing behind the metaconglomerate of the W74 site, Jack Hills, where the oldest detrital zircons on the Earth were discovered

(including the oldest) reveal elevated values ($\delta^{18}\text{O}$ up to 7.4‰), indicating that they crystallized from the melting of preexisting supracrustal material that had undergone interaction with low-temperature liquid water (Wilde et al. 2001; Peck et al. 2001; Cavosie et al. 2005). Such zircons thus represent the earliest evidence for both **continental crust** and oceans on Earth. Furthermore, isotopic analyses reveal that some of these zircons have fractionated lithium isotope ratios that are much more variable than those recorded from fresh igneous rocks. Values of $\delta^7\text{Li}$ below -10% are present in zircons as old as 4300 Ma, suggesting that highly weathered regolith was being sampled by these early magmas (Ushikubo et al. 2009). This provides further evidence that the parent magmas of the ancient zircons incorporated material that was itself derived from the surface weathering and erosion of preexisting rock in the presence of liquid water, supporting

the hypothesis that continental crust and oceans existed at ~ 4300 Ma, within 250 Ma of the formation of Earth. This requires relatively cool temperatures at the Earth's surface between 4400 and 4325 Ma (Valley et al. 2002; Valley 2005). Additional studies of lutetium and hafnium isotopes in ancient zircons reveal that the precursor material that gave rise to the melts in which the ancient zircons crystallized had a history extending back to ~ 4.5 Ga, extremely close to the age of the Earth itself (Kemp et al. 2010). The original host-rock of the detrital Hadean zircons at Jack Hills is controversial, ranging from melts derived from a crystallized magma ocean (Kemp et al. 2010) to S-type granite (Harrison et al. 2005). It has been established from Lu-Hf systematics that they could not be derived from a single source (Wang and Wilde 2018) and that many host rocks had a felsic to intermediate composition. This ties-in with a recent study of zircons ranging in age from 4.3 Ga to 3.3 Ga that established there was no secular change in trace element values over this time span (Turner et al. 2020). Modeling of these data suggests an andesitic host, similar to those formed in modern subduction settings (Turner et al. 2020), with this lack of change from the Hadean to the Meosoarchean leading to the suggestion that plate tectonics might have operated in the Hadean. Collectively, these data point to the early development on Earth of both continents and oceans and require fairly rapid cooling following accretion, melting, and crystallization of any magma ocean that may have been present: the "Cool Early Earth" hypothesis (Valley et al. 2002).

The nature and significance of inclusions in Jack Hills zircon are also controversial, with some workers suggesting they are primary (Hopkins et al. 2008, 2010) and others maintaining they are secondary (Rasmussen et al. 2011). This has important ramifications since graphitic carbon inclusions have been interpreted to be of biogenic origin (Bell et al. 2015), whereas the association of graphitic carbon with CO_2 inclusions has alternatively been interpreted to indicate a later metamorphic origin (Menneken et al. 2017). Similarly, iron-rich inclusions in Jack Hills zircon as old as 4.2 Ga were

interpreted to provide evidence of an ancient magnetic field (Tarduno and Cottrell 2013; Bono et al. 2018) and the presence of a Hadean geodynamo, whereas Weiss et al. 2015, 2018) concluded they were the result of later re-magnetization. Whichever is correct for the above examples, it is true to say that no "inclusion" amenable to dating has proven to be older than the host zircon grain.

Basic Methodology

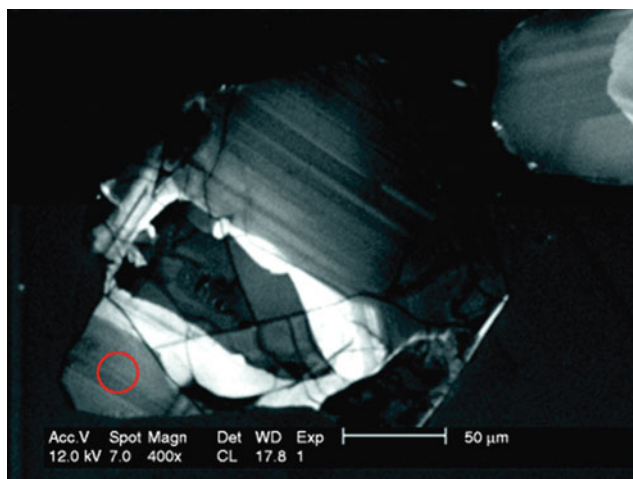
Virtually all the key data acquired from the Jack Hills and Mt. Narryer region that has relevance to the early Earth comes from isotopic analysis of individual zircon crystals. In the absence of any rocks on Earth older than 4.03 Ga (► [Acasta Gneisses](#) in the Northwest Territories of Canada), these zircon crystals, together with a few from other localities around the world, are all that remains of the first 500 Ma of Earth's history (Iizuka et al. 2006; Paquette et al. 2015; Miller et al. 2018; Byerly et al. 2018). With recent improvements in analytical techniques and instrumentation, it is now possible to determine in situ U-Pb, Lu-Hf, O, C, Ti, Li, and many other trace elements and isotopes with reasonable accuracy on portions of crystals only a few microns in diameter. Further advances are to be expected in the coming years.

Key Research Findings

Jack Hills in Western Australia contains the oldest known components of the Earth's crust; a portion of a zircon crystal with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 4404 ± 8 Ma (2σ) (Fig. 2). In addition, zircon crystals ~ 4.3 Ga old show elevated $\delta^{18}\text{O}$ values and strongly negative $\delta^7\text{Li}$ values, indicating they grew during melting of a protolith that evolved through weathering and interaction with liquid water at the Earth's surface, possibly in a CO_2 -rich atmosphere. Lu-Hf isotope data from the zircons suggest the earliest crust may have formed as early as ~ 4.5 Ga, close to the age of the Earth itself (Harrison et al. 2005; Kemp et al. 2010).

Jack Hills (Yilgarn Craton, Western

Australia), Fig. 2 Photo of the oldest zircon at site W74, Jack Hills, Yilgarn Craton (Western Australia). The ancient crystal was imaged in cathodoluminescence prior to the second analytical session that identified the 4.404 Ga portion (in red). (Photo Simon Wilde)



Applications

The Jack Hills zircons constitute the main database for study of the first 500 Ma of Earth's history (► [Hadean](#); ► [Earth, Formation and Early Evolution](#)). As such, they represent a unique inventory and, when other areas containing Hadean zircons are discovered, they provide the standard used for comparison.

- [Oceans, Origin of](#)
- [Oxygen Isotopes](#)
- [Regolith, Terrestrial](#)
- [Shale](#)
- [Silicate Minerals](#)
- [Tonalite-Trondhjemite-Granodiorite](#)
- [Water, Delivery to Earth](#)
- [Zircon](#)

Future Directions

Further work at Jack Hills can provide answers to the following problems: (1) the exact nature of the host rocks of the ancient zircon crystals, (2) whether any remnants of those rocks are still present in the area, (3) the veracity or otherwise of a Hadean magnetic field, and (4) if there are any true inclusions older than the Hadean zircon hosts.

Cross-References

- [Acasta Gneiss](#)
- [Amphibolite Facies](#)
- [Archean Tectonics](#)
- [Earth, Formation, and Early Evolution](#)
- [Geochronology](#)
- [Hadean](#)
- [Mafic and Felsic](#)

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James Webb Space Telescope

► [JWST](#)

Janssen (55 Cancrī e)

► [55 Cancrī](#)

Japan Aerospace Exploration Agency

► [JAXA](#)

Japan Astrobiology Consortium

► [JABC, Japan](#)

Jarosite

Alessandro Airo
Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Synonyms

[Utahite](#)

Definition

Jarosite is a ferric hydrous sulfate mineral with the chemical formula of $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ that has a trigonal crystal system and belongs to the group of ► [alunite](#). This ochre-yellow or brown mineral forms under aqueous, acidic, and oxidizing conditions through, e.g., ► [weathering](#) of volcanic rocks in the presence of acidic, sulfur-rich fluids or by oxidation of sulfide minerals in acid drainage environments.

The Mössbauer spectrometer on Mars Exploration Rover Opportunity has detected up to 10 wt% of jarosite in the sedimentary rocks at *Meridianum Planum* (Klingelhöfer et al. [2004](#)). This discovery was insofar a breakthrough, as it constrained the chemistry of the aqueous paleoenvironment with respect to its redox potential (being oxidizing) and its pH (being acidic). Furthermore, it is known that jarosite rapidly decomposes under humid conditions over geologic time, which suggests that the aqueous period of jarosite formation was followed by predominantly dry conditions (Elwood Madden et al. [2004](#)).

Cross-References

► [Sulfates, Extraterrestrial](#)

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Jasper

► [Chert](#)
► [Jaspilite](#)

Jaspilite

Kurt O. Konhauser and Ernesto Pecoits
Department of Earth and Atmospheric Sciences,
University of Alberta, Edmonton,
AB, Canada

Synonyms

[Jasper](#)

Definition

Jaspilite is a banded compact siliceous rock consisting of interbanded jasper (red ► [chert](#)) and ► [hematite](#). In Australia, the term jaspilite was commonly applied to Precambrian iron formations of Western Australia, but ► [banded iron formation](#) (BIF) is now generally used.

Cross-References

- [Banded Iron Formation](#)
- [Chert](#)
- [Hematite](#)

JAXA

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Japan Aerospace Exploration Agency](#)

Definition

On October 1, 2003, the Institute of Space and Astronautical Science (ISAS), the National Aerospace Laboratory of Japan (NAL), and the

National Space Development Agency of Japan (NASDA) were merged into one independent administrative institution to be able to perform all their activities in the aerospace field as one organization, from basic research and development to utilization. The independent administrative institution is the Japan Aerospace Exploration Agency (JAXA).

This administration manages 17 facilities across Japan as well as overseas offices. From the Tanegashima Space Center, national rockets H-II are regularly launched. Through JAXA, Japan is a major partner of the international space station and contributes with the KIBO scientific module. The H-II Transfer Vehicle (HTV) is JAXA's unmanned cargo transfer spacecraft that delivers supplies to the International Space Station (ISS).

The first Japanese citizen to fly in space was a journalist, Toyohiro Akiyama, who flew on the Soviet Soyuz TM-11 in December 1990, while the expenses (around 14 million USD) were paid by a broad-casting company. JAXA has ten professional astronauts of staff, who are supporting experiments onboard the ISS.

JAXA's missions with relevance to astrobiology include those to Halley's comet (Suisei and Sakigake), to the asteroid 25143 Itokawa ("Hayabusa") which returned some grains of surface material to the Earth in 2010, and more recently Hayabusa2, which sampled material from the asteroid 162173 Ryugu. Ryugu is a more primitive-type asteroid than Itokawa and presumably contains organic material. Hayabusa2 successfully returned its samples to Earth in December 2020. The mission of Hayabusa2 has been extended to at least 2031, when it will hopefully rendezvous with asteroid 1998 KY₂₆.

Cross-References

- [Comet Halley](#)

1847 JB

- [6 Hebe](#)

Jeans Criterion

Daniele Galli

INAF Osservatorio Astrofisico di Arcetri, Largo
E. Fermi 5, Italy

Keywords

Gravitational instability · Gravitational collapse · Free-fall timescale · Fragmentation · Interstellar cloud · Protoplanetary disk

Definition

The Jeans criterion describes the condition for the onset of *gravitational instability* in a medium of density ρ and temperature T .

Perturbations of size larger than the Jeans length $\lambda_J = \pi c_s / (G\rho)^{1/2}$, where $c_s = (k_B T/m)^{1/2}$ is the sound speed, are unstable and collapse under their own self-gravity. The criterion is applicable to interstellar clouds supported by gas pressure against gravity.

History

The criterion was first derived in 1902 by the British physicist James H. Jeans (1877–1946). See Jeans (1902) and Jeans (1928).

Overview

The Jeans criterion is central to the process of star formation. Consider the simple case of an *interstellar cloud* supported against its own gravity by gas pressure alone. If the cloud is sufficiently massive, gravitational attraction can overwhelm the support provided by gas pressure. The cloud then becomes gravitationally unstable, and can collapse to form stars. The Jeans criterion gives the value of the maximum mass (or size) of a cloud in equilibrium under the balance of gravity and pressure. It can also be applied to the formation of giant planets in a *protoplanetary disk*.

Equivalent formulations of the Jeans criterion can be derived from the *virial theorem*, or from the stability analysis of spherical self-gravitating equilibrium models. The simplest derivation is from the analysis of the propagation of small-amplitude waves in a homogeneous isothermal gas with density ρ and temperature T . A perturbative analysis shows that density perturbations of small wavelength propagate like sound waves with speed $c_s = (k_B T/m)^{1/2}$. However, because of the gravitational attraction, the velocity of wave propagation decreases with increasing wavelength. Above a critical wavelength $\lambda_J = \pi c_s / (G\rho)^{1/2}$, called the Jeans length, wave propagation is not possible: the amplitude of disturbances extending over scales larger than λ_J increases exponentially with time. This is the *gravitational instability*. The mass M_J contained inside a radius equal to λ_J is called the Jeans mass, and is the maximum mass that can be in equilibrium under a balance of gravity and pressure.

The Jeans criterion is frequently adopted to estimate whether a molecular cloud (or a part of it) is gravitationally stable or not, and, in the latter case, to estimate the typical size of fragments that can be formed as a consequence of the cloud's collapse. Very often, since giant molecular clouds are supported by turbulent motions rather than by gas pressure, the sound speed c_s in the expressions for the Jeans length and Jeans mass, is replaced by the average turbulent speed, a procedure justified on the basis of the *virial theorem*. However, the inclusion of the effects of turbulence, rotation and magnetic fields on the gravitational instability requires a more detailed analysis.

It must be stressed that the Jeans criterion provides a necessary, but not sufficient, condition for cloud collapse. If the gravitational energy released by the collapse is not radiated away but converted into thermal energy, the temperature (and therefore the pressure) of the cloud rises, halting the collapse. Molecular clouds can efficiently radiate the excess energy, maintaining an approximate constant temperature during the initial phase of collapse. As long as the cloud's pressure is overwhelmed by gravity, the collapse occurs on a *free-fall time* $t_{\text{ff}} = \lambda_J / c_s = \pi / (G\rho)^{1/2}$. It must also be noted that the Jeans length in a collapsing cloud

becomes smaller as the cloud density increases. This allows parts of the clouds (e.g., density inhomogeneities) to become in turn gravitationally unstable, leading to cloud *fragmentation*. Suggested readings: Binney and Tremaine (2008), Stahler and Palla (2004).

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Free-Fall Time](#)
- [Gravitational Collapse, Stellar](#)
- [Hydrostatic Equilibrium](#)
- [Molecular Cloud](#)
- [Protoplanetary Disk](#)

References and Further Reading

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James Hopwood Jeans (1877–1946), an English astrophysicist. The process corresponds to the probability for a molecule with a speed larger than the planet's ► [escape velocity](#), to travel a distance larger than the atmospheric ► [scale height](#) without colliding with another molecule. The average thermal velocity of a molecule in a gas is proportional to the square root of the temperature and inversely proportional to the square root of its mass, while the escape velocity increases with the mass of the planet. One concludes that a planet will more rapidly lose its atmosphere if it is of a low mass and if its upper atmosphere is hot and made of light elements such as hydrogen and helium. In the solar system, ► [giant planets](#) which are massive and rather cold do not lose their hydrogen atmosphere, while smaller planets, close to the Sun and less massive, did lose their initial hydrogen.

Cross-References

- [Hydrodynamic Escape](#)
- [Scale Height](#)

Jeans Escape

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Thermal escape](#)

Definition

The Jeans escape phenomenon is one of the mechanisms by which a planet can lose gradually some constituents of its atmosphere. It is named after

Jet Propulsion Laboratory

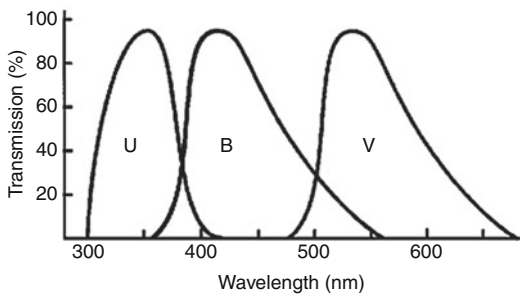
- [JPL](#)

Johnson UVB Bandpasses

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The Johnson UVB bandpasses (Fig. 1) are the bandwidths of the three filters called



Johnson UBV Bandpasses, Fig. 1 The Johnson UBV bandpasses

U (ultraviolet), B (blue), and V (visual) in the widely used astronomical photometric system defined by Harold Johnson (1921–1980) and William Morgan (1906–1994). Those three colors are especially useful to build the Hertzsprung-Russell (HR) diagram that permits astronomers to classify stars. The central wavelengths and bandwidths are given in the table:

Filter name	Central wavelength (nm)	Bandwidth (nm)
U	365	68
B	440	98
V	550	89

The reference flux in each band is such that the U, B, and V magnitudes are identical for an A0 star such as Vega.

Cross-References

- [Color Index](#)
- [Hertzsprung-Russell Diagram](#)
- [Magnitude](#)

Jovian Planets

- [Giant Planets](#)

JPL

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Jet Propulsion Laboratory](#)

Definition

The Jet Propulsion Laboratory (JPL) is the follow-on of Von Karman’s laboratory established in the 1930s at the California Institute of Technology to work on aeronautics and physics. Several students by this time were attempting to work on and launch rockets. Many members of this so-called suicide squad were the founders of the present Jet Propulsion Laboratory.

The Jet Propulsion Laboratory (JPL) is a research and development center managed by the California Institute of Technology for the US National Aeronautics and Space Administration (► [NASA](#)). JPL’s primary function is the construction and operation of robotic planetary spacecraft, though it also conducts earth orbit and astronomy missions. It is also responsible for operating NASA’s Deep Space Network for communication with spacecraft. JPL has been involved with a very wide range of solar system and astronomy missions relevant to astrobiology, often in collaboration with other space agencies such as ► [ESA](#). Among such missions are Cassini-Huygens, the Mars Exploration Rovers, the infrared ► [Spitzer Space Telescope](#), and missions relevant to exoplanets such as the ► [Kepler](#) space telescope.

Beyond Mars, the JPL has had a lot of achievements over much of the robotic exploration of the solar system, from the earth’s orbit (Explorer-1) to the Moon’s (Ranger and Surveyor probes) and to the far end of the solar system (Voyager and Dawn).

Approximately 6,000 people are working at JPL itself, and there are typically a few thousand additional contractors at any given time.

Cross-References

- [Cassini-Huygens Space Mission](#)
- [ESA](#)
- [Exoplanets, Discovery](#)
- [Kepler](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)
- [Spitzer Space Telescope](#)
- [Viking](#)

3 JUNO

- [Juno](#)

Juno

Ivanka Pelivan
Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Synonyms

3 JUNO

Definition

Juno is one of the larger main-belt asteroids with an estimated average diameter of about 240 km. It is also one of the largest stony (S-type) asteroids. With an albedo of 0.24 Juno is at the bright end of a typical S-type asteroid. Juno orbits the Sun at an average distance of 2.67 AU with an orbital period of 4.36 years. The orbit is moderately inclined but has an eccentricity of 0.255 which is higher than that of Pluto. Juno has a rotation period of 7.21 h.

Absorption spectra show a surface composed of iron-bearing silicates and reveal a region of relatively low apparent brightness. This feature can be interpreted as large impact crater >100 km in diameter or a fresh ejecta blanket due to a geologically young impact.

History

Juno was discovered by German astronomer Karl L. Harding in 1804. Juno was the third asteroid discovered.

Cross-References

- [Asteroid Belt, Main](#)

Jupiter

Thérèse Encrenaz
LESIA, Observatoire de Paris, PSL, CNRS,
Sorbonne Universités, Université Paris Diderot,
Meudon, France

Keywords

Giant planets

Definition

Among the Giant planets, Jupiter is the most massive and also the closest to the Sun; it orbits at 5.2 AU from the Sun. Its mass is 318 times the terrestrial mass and its diameter is 11 times the terrestrial one, which corresponds to a density of 1.31 g/cm^3 . As the other giant planets, Jupiter was formed in the outer solar system by the accretion of a core with a rock/ice composition followed by the collapse of the surrounding nebula, mostly composed of hydrogen and helium but also containing more refractory elements. It is widely

agreed that Jupiter formed rapidly, within a few million years, in the outer solar system beyond the snowline which marks the condensation of ices in the protosolar disk. Jupiter has a tenuous ring system and 69 satellites (as of 2018), regular and irregular ones. The regular satellites were formed in the equatorial plane of the planet after the collapse of the surrounding subnebula. They include the four Galilean satellites (Io, Europa, Ganymede, and Callisto) discovered by Galileo Galilei in 1610. The irregular satellites are probably captured distant asteroids.

Overview

Early Observations

As one of the brightest objects in the sky, Jupiter has been known since Antiquity. Its astronomical observation started in 1610 with the first observations by Galileo Galilei. A few decades after the discovery of the Galilean satellites, the band and zone structure of Jupiter, induced by its fast rotation period (9 h 55 min), was observed. In 1664, Robert Hooke identified the Great Red Spot (GRS) which was studied in detail by Giovanni Domenico Cassini in the following years. Since then, the planet has been continuously monitored, showing, in particular, the stability of the GRS over more than three centuries.

Atmospheric compounds were first identified by spectroscopy in the twentieth century: CH₄ and NH₃, minor components but strong spectroscopic absorbers, were identified by Wildt in 1932. Hydrogen, the dominant species but less active spectroscopically, was expected to be present on a theoretical basis but was not detected until 1961. Since the 1970s, the development of infrared spectroscopy has led to the detection of a long list of minor constituents (PH₃, GeH₄, SiH₃, CO, C₂H₂, C₂H₆, ...). It must be noted that most of these species have been detected from ground-based observations. In 1994, the collision of the Shoemaker-Levy comet with Jupiter provided astronomers with a unique opportunity to study in real time the response of an atmosphere to a major meteoritic impact. Many new molecules

were formed by shock chemistry (H₂O, CO, CS, OCS, HCN, ...), some of them remaining detectable in the following years.

Another major result of the ground-based exploration of Jupiter was the discovery, in the 1950s, of a strong radio-emission, both in the decimeter and decameter range. This nonthermal emission was interpreted as the signature of a magnetic field, a result which was later confirmed by space exploration.

The Space Exploration of Jupiter

Jupiter and Saturn were first encountered by the two spacecraft Pioneer 10 and Pioneer 11, in 1973 and 1974, respectively. They sent the first high-resolution images of the atmospheric structure and the first in situ exploration of the Jovian magnetosphere. This first step was followed by the very successful Voyager missions, which consisted of two identical spacecraft which flew by the four giant planets between 1979 and 1989. Jupiter was visited by Voyager 1 and Voyager 2 in 1979. Among the many discoveries of the Voyager mission, one should quote the unexpected complexity of the Jovian cloud structure, the evidence for a tenuous ring system around the planet, the evidence for active volcanism on Io, and the surface diversity of the other Galilean satellites. Several other small satellites were also discovered.

After these flybys, a more ambitious mission, including an orbiter and an atmospheric descent probe, was dedicated to the exploration of the Jovian system. In 1995, NASA's Galileo orbiter approached the planet and a probe was sent into its atmosphere. The probe transmitted data in the deep troposphere down to a pressure level of 22 bars. The orbiter monitored the planet's atmospheric and cloud structure as well as the Galilean satellites until 2003. In 2000, Jupiter was also observed by the Cassini spacecraft on its way to the Saturn system, and some combined measurements of the atmosphere and the magnetosphere by both spacecraft were successfully accomplished.

In August 2011, the JUNO spacecraft was launched by NASA with the main objective of probing Jupiter's interior and measuring its

gravity and magnetic fields, in order to better understand its formation scenario. The spacecraft reached Jupiter in 2016 and is performing polar orbits around the planet, thus bringing new information on the planet's atmosphere, internal structure, and magnetosphere.

For the future, a couple of missions are already foreseen by the space agencies, such as NASA's Europa Clipper which will investigate the moon after a launch between 2022 and 2025, but more importantly for Jupiter ESA selected in 2012 an even more ambitious mission, JUICE (JUPiter ICy moon Explorer), to be launched in 2022 for an arrival in 2030. The spacecraft will perform several maneuvers around Jupiter and its Galilean satellites, including two flybys of Europa, and will enter orbit around Ganymede in 2033. In the course of its 3-year nominal mission, JUICE will study the atmosphere, the magnetosphere and all the coupling processes in which Jupiter is involved within its system. In particular, JUICE will provide a global characterization of the Jovian atmosphere, from the clouds of its turbulent, convective troposphere, all the way through the middle atmosphere to the thermosphere. The results will bring us a better understanding of the dynamics, circulation, composition, chemistry, vertical structure, and coupling therein. This will be achieved by a combination of high inclination trajectories and broad coverage at different wavelengths (Fig. 1).

Dynamical Atmospheric Structure

The main cloud features of Jupiter – Great Red Spot, zones (whitish) and belts (brownish) – are known since the seventeenth century. The zone and belt structure can be interpreted, to first order, as a Hadley circulation with multiple cells generated by the fast rotation of Jupiter. Zones are regions of ascending motion and belts are regions of subsidence. Measurements by the Galileo probe, in 1995, confirmed this convective pattern, but they also showed that the present circulation is much more complex than this simple scheme.

The Coriolis forces induce zonal winds of opposite direction, north and south of each zone, generating multiple time-variable eddies. The biggest structure is the Great Red Spot in the southern



Jupiter, Fig. 1 The planet Jupiter as observed by the Cassini spacecraft in 2000. The Great Red Spot is clearly visible in the southern hemisphere, as well as the zone (whitish) and belt (brownish) structure all over the planet demonstrating the existence of a dynamical atmosphere. (Source: © NASA)

hemisphere. Its size is about 10,000–14,000 km in the north–south axis and 24,000–40,000 km in the east–west axis. The GRS is believed to be a giant anticyclonic structure; however, its stability over several centuries is not yet completely understood. The composition of the GRS, in particular its red color, is still an open question; it might be due to sulfur or phosphorus compounds, but their exact chemical composition remains unknown.

The Juno mission, in polar orbit around Jupiter since 2016, has revealed the unexpected complexity of atmospheric dynamics near the polar regions. The fast rotation of the planet and the strong Coriolis forces are responsible for the alternating zonal flows which have been observed for

long at low and mid-latitudes, but also to circumpolar cyclones near the poles. Surprisingly, the structures of these cyclones are not the same around the two poles, with eight circumpolar cyclones around the north pole and five around the south pole. These structures are also different from the persistent hexagonal features of Saturn's north pole. The reasons for the differences in these dynamical systems, as well as their stability, are still unknown. In addition, Juno instruments found that the atmospheric winds on Jupiter are long lasting and run deep into the atmosphere which has implications on our understanding of Jupiter's interior structure, core mass and, subsequently its origin. In June 2018, Juno made significant discoveries on lightning on Jupiter and the ways in which it is analogous to Earth's lightning, while the two types of lightning are somehow polar opposites. These findings significantly improved our understanding of the composition, circulation, and energy flows on Jupiter although the current distribution of lightning (mostly at the north pole) is not completely understood.

Atmospheric Composition and Structure

As all giant planets, the thermal vertical profile of Jupiter is characterized by a troposphere where the temperature decreases adiabatically with altitude and a tropopause where the temperature is minimum ($T = 110$ K at $P = 100$ Mbar). Above the tropopause, the temperature increases again with the altitude, due to the absorption of the solar infrared flux by methane and aerosols. At higher altitudes, other mechanisms contribute to a strong heating (planetary waves, high-energy particles).

As hydrogen is the main atmospheric component, most of the other species are in a reduced state. A first group consists in tropospheric compounds: CH_4 , NH_3 , PH_3 , GeH_4 , AsH_3 , CO , and H_2O . H_2S , not detected by spectroscopy, was identified by the mass spectrometer of the Galileo probe. Most of these species condense at the level of the tropopause, where the temperature is minimum, the two exceptions being CH_4 and CO . A second group contains the hydrocarbons produced by the photolysis of methane in the Jovian stratosphere (C_2H_2 , C_2H_4 , C_2H_6 , CH_3 , C_3H_8 , C_6H_6 ...). A third group includes oxides detected

in the Jovian stratosphere (H_2O , CO , CO_2) which have an external origin; indeed, if water came from the interior it would be trapped as ice at the tropopause. Following recent observations by the Herschel satellite, the origin of water seems to be the collision of comet Shoemaker-Levy 9 with Jupiter in 1994.

The cloud structure of Jupiter can be inferred from models of thermochemical equilibrium. At a pressure of about 0.5 bar, ammonia clouds are expected; they are believed to be responsible for the white color of the Jovian zones. At deeper tropospheric levels (about 2 bars), models predict clouds of nitrogen hyposulfide NH_4SH , and at a pressure of a few bars, water clouds should be present. The presence of water clouds has been demonstrated with the Near Infrared Mapping Spectrometer of Galileo; however, the spatial distribution of the Jovian cloud structure appears to be much more complex than expected from the models. There is an active convective circulation between zones and belts, as previously anticipated, with zones being upwelling regions, rich in clouds, and belts being regions of subsidence. However, the Galileo observations have shown that even within the belts, there are cloud-free, specific holes which are downwelling regions. In these regions, the radiation comes from deeper, warmer layers, hence their being called "hot spots." The Galileo probe entered one of these regions, free of clouds and very dry. The H_2O cloud was absent there, but the very low measured water content is not representative of the whole planet. Apart from oxygen, many other elements were successfully measured by the mass spectrometer of the Galileo probe.

Elemental and Abundance Ratios in Jupiter

The Galileo mass spectrometry measurements of the Jupiter atmosphere showed a general enrichment in all heavy elements with respect to hydrogen, as compared to the protosolar value. This enrichment factor, first estimated to 3 ± 1 , is now considered as being 4 ± 2 after revision of the solar abundances. This result provided a decisive support for the core accretion model for giant planet formation. According to this scenario, giant planets result of the accretion of a solid core

(mostly made of the rock and ice components) of about 10–12 terrestrial masses; then the gravity field of this accreted core was sufficient to induce the collapse of the surrounding nebula mainly composed of hydrogen and helium. After the collapse phase and the vaporization of the ices of the core, the relative abundances of heavy elements (C, N, O, S, and noble gases) must have been enriched with respect to their protosolar abundances. It can be shown that, if all elements were equally trapped in ices, an enrichment factor of 4 would be expected for Jupiter, which is in perfect agreement with the Galileo measurements. However, the general enrichment of Jupiter's planetesimals raises another question: some species, like N and Ar, cannot be trapped in ices unless their temperature is very low (<40 K). Their presence in Jupiter indicates that Jupiter's planetesimals accreted at a temperature much lower than that simply deduced from Sun–Jupiter distance. The origin of Jupiter's planetesimals still remains an open question.

The JUNO mission has been designed to help bring some new answers to this question. In particular, a determination of the O/H ratio in the deep interior of the planet was part of the objectives of the mission; this key measurement, as mentioned above, could not be performed by the Galileo probe. However, the first results of the JUNO Microwave Radiometry experiment, designed to probe the deep atmosphere of Jupiter down to a pressure of a few hundred bars, has shown that the dynamics of the deep atmosphere are by far more complex than anticipated. In particular, the ammonia mixing ratio below the H_2O and NH_4SH clouds is not constant until it reaches pressure levels higher than 60 bars; this unexpected result is likely to make more difficult the retrieval of the water content.

Internal Structure

We do not have direct measurements of Jupiter's internal structure. The only known parameters are its diameter, mass, density, and gravitational moments. The Voyager infrared spectrometer IRIS showed that Jupiter radiates more heat than it receives from the Sun (1.67 times the absorbed solar energy). The origin of this internal energy

would be the cooling of the planet, still in a slow contracting phase after the initial accreting phase. Helium condensation in Jupiter's interior, within the hydrogen metallic ocean, might also contribute to the internal energy.

Based on these constraints, theoretical models of Jupiter's internal structure have been proposed. It would consist in a rocky/icy core having a temperature of about 23,000 K, while the pressure would range from 50 to 100 Mbar or 5 to 10 TPa. This core would be surrounded by a convective ocean of metallic hydrogen and helium, above which, at about 0.8 Jovian radii, a layer of mostly molecular hydrogen and helium is expected to extend up to the observable layers of the atmosphere. However, the gravimetry measurements of the Juno mission have brought new information and also new questions about the internal structure of Jupiter. The measurement of Jupiter's gravitational harmonics has shown that Jupiter's gravity field is north–south asymmetric; the zonal flow observed at the cloud level actually persists down to a depth of about 3000 km below the cloud top. At this level, the electric conductivity would become sufficient for the differential rotation to be suppressed by magnetic drag, and closer to the center, the deep interior would rotate nearly as a rigid body. More results are expected to come as the JUNO mission continues its exploration around Jupiter.

The Jovian Magnetosphere

The large magnetosphere of Jupiter, first identified by the Jovian synchrotron radiation and later explored by spacecraft, can be explained by several factors: the great size of the planet, its fast rotation, and the presence of a liquid metallic interior. The Jovian magnetic field is generated by a dynamo effect within the ocean of metallic hydrogen and/or in electrically conductive sublayers of the molecular layer above. The dipole moment is tilted by 10° with respect to the rotation axis of the planet. This magnetic field is 14 times stronger than the Earth's.

As Jupiter is five times more distant to the Sun than the Earth and with a substantially stronger magnetic field, its magnetosphere is considerably more extended than the terrestrial one. Still, its structure shows strong analogies with the Earth's

magnetosphere. A shockwave, a magnetopause, and a magnetosheath are present in the sunward direction. The main difference is the interaction of the Jovian magnetosphere with Io (and to a lesser extent with Europa) whose orbit crosses the Jovian magnetosphere.

The magnetic field of Jupiter has also been explored by the JUNO mission. The first results of its magnetometer show that, near the cloud top, Jupiter's magnetic field is different from the expected models; this might imply that the region where the dynamo is generated could be located not very far beneath the surface, possibly (at least in part) in the molecular hydrogen layer, above the region where hydrogen is expected to be in metallic form.

The biggest planet of our solar system is the archetype of giant exoplanets. It is also where almost all the matter which is not in the sun has been stored. This makes it one of the most valuable objects to explore for understanding the origins and the bulk composition of our solar system but also of other planetary systems. Furthermore, it is our best example of connectivity between the different atmospheric layers, the atmosphere and interior, and the atmosphere and external environment. ESA's JUICE mission will considerably enhance our understanding of Jupiter in the 2030s.

Cross-References

- ▶ [Comet Shoemaker-Levy 9](#)
- ▶ [Europa](#)
- ▶ [Giant Planets](#)

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Jupiter Icy Moon Explorer Mission

Olivier Grasset¹, Dmitrij Titov² and Olivier Witasse²

¹University of Nantes, Nantes, Cedex 1, France

²European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Keywords

Habitability · Ganymede · Callisto · Europa · Jupiter · Moons

Acronyms

JUICE

Definition

The JUICE (JUPiter ICy moon Explorer) mission, selected in May 2012 to be the first large mission within the ESA's Cosmic Vision Program 2015–2025, will provide the most comprehensive exploration to date of the Jovian system in all its complexity, with particular emphasis on Ganymede as a planetary body and potential habitat. Investigations of the neighboring moons, Europa and Callisto, will complete a comparative picture of the environmental conditions on the Galilean moons and their potential habitability. The JUICE mission has been formulated with consultation and strong support from the international planetary science community, and it will have broad appeal across a range of different disciplines including geologists, astrobiologists, and magnetospheric and atmospheric scientists. Due to launch in April 2023, it will arrive at Jupiter in July 2031. The mission is planned to end in September 2035.

History

In 1995, the Galileo spacecraft arrived at Jupiter to conduct the first detailed orbital exploration of the

Jovian system in the footsteps of previous flyby missions (Pioneer 10–11, Voyager 1–2, and Ulysses). Despite its limitations, Galileo made a plethora of new discoveries in the Jovian system, especially as concerns the four Galilean satellites, each of which was revealed as a unique world and a fascinating destination for further in-depth exploration. Most importantly, Galileo discovered strong evidence for the existence of subsurface oceans hidden beneath the icy crusts of Europa, Ganymede, and Callisto, leading to the emergence of a new habitability paradigm that considers the icy satellites as potentially habitable. If extrasolar planetary systems share a common planetary architecture to our own solar system, then icy satellites of gas giants, having a subsurface liquid water ocean, could be the most common habitats in the Universe, probably much more abundant than earthlike environments, which require highly specialized conditions that permit surface oceans.

The detailed JUICE characterization of the wider Jovian system will extend the Juno mission's focused study of Jupiter's interior and inner magnetosphere that started in 2016 and will be the next logical step in our exploration of the outer solar system after Cassini's exploration of the Saturn system.

Overview

The overarching theme for JUICE is the emergence of habitable worlds around gas giants. Within our Solar System, we know of one body that has experienced the emergence of life: On Earth, living organisms have developed and proliferated even under the most extreme of environmental conditions. Is the origin of life unique to our planet or could it occur elsewhere in our Solar System or beyond? To answer this question, even though the mechanisms by which life originated on Earth are not yet clearly understood, one can assume that the necessary conditions involve the simultaneous presence of organic compounds, trace elements, water, energy sources, and a relative stability of the environment over time. JUICE will address the question: Are there current habitats elsewhere in the Solar System with the

necessary conditions (water, biological essential elements, energy, and stability) to sustain life? The spatial extent and evolution of habitable zones within the Solar System are critical elements in the development and sustainment of life as well as in addressing the question of whether life developed on Earth alone or whether it could have developed in other Solar System environments and was then imported to Earth. JUICE's objectives are listed in Table 1.

The focus of JUICE is to characterize the conditions that may have led to the emergence of habitable environments among the Jovian icy satellites, with special emphasis on the three ocean-bearing worlds, Ganymede, Europa, and Callisto. Ganymede is identified for detailed investigation not only since it provides a natural laboratory for analysis of the nature, evolution, and potential habitability of icy worlds in general, but also because of the role it plays within the system of Galilean satellites, and its unique magnetic and plasma interactions with the surrounding Jovian environment. JUICE will determine the characteristics of liquid water oceans below the icy surfaces of the moons, mainly with its magnetometer, laser altimeter, and radio-science experiments. This will lead to an understanding of the possible sources and cycling of chemical and thermal energy, allow investigation of the evolution and chemical composition of the surfaces and of the subsurface oceans, and enable an evaluation of the processes that have affected the satellites and their environments through time. The study of the diversity of the satellite system will be enhanced with additional information gathered remotely on Io and the smaller moons. The mission will also characterize the diversity of processes in the Jupiter system that may be required in order to provide a stable environment at Ganymede, Europa, and Callisto on geologic timescales, including gravitational coupling between the Galilean satellites and their long-term tidal influence on the system as a whole. The advanced instrumentation carried by JUICE (Table 2) will also permit extensive new studies of Jupiter's atmosphere (its structure, dynamics, and composition) and magnetosphere (three-dimensional properties of the

Jupiter Icy Moon Explorer Mission, Table 1 Science goals and objectives of JUICE

Exploration of the habitable zone: Ganymede, Europa, and Callisto	
Characterize Ganymede as a planetary object and possible habitat	Characterize the extent of the ocean and its relation to the deeper interior
	Characterize the ice shell
	Determine global composition, distribution, and evolution of surface materials
	Understand the formation of surface features and search for past and present activity
	Characterize the local environment and its interaction with the Jovian magnetosphere
Explore Europa’s recently active zones	Determine the composition of the nonice material, especially as related to habitability
	Look for liquid water under the most active sites
	Study the recently active processes
Study Callisto as a remnant of the early Jovian system	Characterize the outer shells, including the ocean
	Determine the composition of the nonice material
	Study the past activity
Explore the Jupiter system as an archetype for gas giants	
Characterize the Jovian atmosphere	Characterize the atmospheric dynamics and circulation
	Characterize the atmospheric composition and chemistry
	Characterize the atmospheric vertical structure
Explore the Jovian magneto sphere	Characterize the magnetosphere as a fast magnetic rotator
	Characterize the magnetosphere as a giant accelerator
	Understand the moons as sources and sinks of magnetospheric plasma
Study the Jovian satellite and ring systems	Study Io’s activity and surface composition
	Study the main characteristics of rings and small satellites

magnetodisc and coupling processes), and their interaction with the Galilean satellites will further enhance our understanding of the evolution and dynamics of the Jovian system. The long-term Jovian magnetospheric and atmospheric science will push significantly beyond the capabilities of previous missions like Galileo and directly complement the results of the short-lived Juno mission.

Basic Methodology

JUICE mission scenario and spacecraft. Following a launch with Ariane 5, JUICE will use an Earth/Moon-Earth-Venus-Earth-Earth gravity assist strategy to reach Jupiter. The cruise maneuvers are small, so that the mass reaching Jupiter is large. The nominal launch date is in April 2023, with an arrival at Jupiter in July 2031. The backup launch is in August/September 2023. After

insertion into Jupiter orbit, JUICE will use multiple gravity assists via flybys of the Galilean satellites to shape a comprehensive orbital tour over ~3.5 years. After reducing the orbit period with Ganymede flybys, this tour will implement two close Europa flybys, then a series of Callisto flybys so as to reach an inclination of 33° with respect to the equatorial plane of Jupiter. A dedicated series of Callisto then Ganymede gravity assists will make it possible to approach Ganymede at a low velocity. During the tour, Jupiter’s magnetosphere and atmosphere will be continuously monitored. At the end of the tour, JUICE will be set in a polar orbit around Ganymede, becoming the first spacecraft in history to enter orbit around an icy satellite in the outer solar system. This dedicated orbital phase will provide a comprehensive survey of the Solar System’s largest planetary satellite. The lowest orbit will be at 500 km in the baseline scenario and could reach 200 km depending on the propellant used



Jupiter Icy Moon Explorer Mission, Table 2 JUICE set of instruments with their main characteristics

Instrument acronym	Short description
JANUS	J ovis, A morum ac N atorum U ndique S crutator An optical camera to study moon geology, and to perform mapping of the clouds on Jupiter. JANUS will have 13 filters covering the range 350–1050 nm, a 1.3 degree field of view, and spatial resolution up to 2.4 m on Ganymede and about 15 km at Jupiter
MAJIS	M oons A nd J upiter I maging S pectrometer A hyperspectral imaging spectrometer for observing tropospheric cloud features and minor species on Jupiter and for the characterization of ices and minerals on the surfaces of icy moons. MAJIS will cover the 0.4 to 5.7 microns range, with spectral resolution of 3–7 nm. The spatial resolution will be up to 60 m on Ganymede and about 130 km on Jupiter
UVS	U V Imaging S pectrograph A UV spectrometer to characterize the composition and dynamics of the exospheres of the icy moons, to study the Jovian aurorae, and to investigate the composition and structure of the upper atmosphere. UVS will cover the wavelength range 55–210 nm with spectral resolution of <0.6 nm. Spatial resolution will reach 0.5 km at Ganymede and up to 500 km at Jupiter
SWI	S ubmillimeter W ave I nstrument A submillimeter wave instrument to investigate the temperature structure, composition, and dynamics of Jupiter's stratosphere and troposphere, and the exospheres and surfaces of the icy moons. SWI is a heterodyne spectrometer using a 30 cm antenna and working in two spectral ranges 1080–1275 GHz and 530–625 GHz with spectral resolving power of $\sim 10^7$
GALA	G anymede L aser A ltimeter A laser altimeter for studying the tidal deformation of Ganymede and the morphology and topography of the surfaces of the icy moons. GALA will have a 20 m spot size at 200 km and 0.1 m vertical resolution
RIME	R adar for I cy M oons E xploration An ice-penetrating radar to study the subsurface structure of the icy moons down to 9 km depth with vertical resolution of up to 50 m in ice. RIME will work at a central frequency of 9 MHz and will use a 16 m dipole antenna
J-MAG	J UICE M AGnetometer A magnetometer to characterize the Jovian magnetic field, its interaction with the internal magnetic field of Ganymede, and to study subsurface oceans of the icy moons. J-MAG will use fluxgates sensors and a scalar magnetometer for absolute calibration mounted on a boom
PEP	P article E nvironment P ackage A package of sensors to characterize the plasma environment in the Jovian system. PEP will measure density and fluxes of positive and negative ions, electrons, exospheric neutral gas, thermal plasma, and energetic neutral atoms in the energy range from <0.001 eV to >1 MeV with full angular coverage. The composition of the moons' exospheres will be measured with a resolving power of more than 1000
RPWI	R adio & P lasma W ave I nvestigation A radio and plasma wave instrument to characterize the radio emission and plasma environment of Jupiter and its icy moons. It will use Langmuir probes to measure DC electric field vectors up to a frequency of 1.6 MHz and to characterize thermal plasma and medium- and high-frequency receivers, and dipole antennas and magnetometers to measure electric and magnetic fields in radio emission in the frequency range 80 kHz–45 MHz
3GM	G ravity & G eophysics of J upiter and G alilean M oons GM is a radio science package comprising a Ka transponder and an ultrastable oscillator to study the gravity field and the extent of internal oceans on the icy moons, and to investigate the structure of the neutral atmospheres and ionospheres of Jupiter (0.1–800 mbar) and its moons
PRIDE	P lanetary R adio interfere & D oppler E xperiment PRIDE will use the telecommunication system of the spacecraft and ground based very long baseline interferometry to perform precise measurements of the s/c position and velocity

during the mission and on spacecraft health. The current end of mission scenario involves spacecraft disposition on Ganymede.

The spacecraft uses a conventional bipropellant propulsion system. The basic design for the spacecraft is very similar to that of previous large flight systems such as Cassini, Mars Reconnaissance Orbiter, and Rosetta. JUICE will be the second Jovian mission using solar arrays as the power source, following Juno. JUICE's trajectory will remain outside of Jupiter's inner radiation belts to provide a long-lived, stable, and versatile platform to accomplish the broad range of science objectives.

JUICE Payload (Table 2). The JUICE spacecraft will carry a highly capable suite of ten state-of-the-art scientific instruments. The remote sensing package includes spectro-imaging capabilities from the ultraviolet to the near-infrared, an imaging system, and a submillimeter wave instrument. The geophysical package includes laser altimetry and radar sounding for exploring the surface and subsurface of the moons. The radio science instrument complements the remote sensing package (to enable probing of the Jovian/satellite atmospheres) and the geophysics package (enabling estimation of gravity fields). The in situ package includes a magnetometer, a radio, and plasma wave instrument as well as a particle package. This payload suit will be supported by an experiment using ground-based very-long-baseline interferometry (VLBI). Since the selection of the payload in 2013, a thorough effort has been made to ensure that the numerous scientific objectives related to the study of the emergence of habitable worlds in the Jovian system (internal structure, geology, composition, and tenuous exospheres of the icy moons and composition and dynamics of the giant atmosphere, magnetospheres, and plasma environment) can be achieved with the selected payload, with important benefits of synergies between individual measurements.

Future Directions

The European Space Agency has selected in June 2021 the scientific themes for its science program

for the timeframe 2035–2050. One of the top priorities will be the investigation of the habitability potential of worlds in our Solar System, in particular the moons of Jupiter or Saturn. Building on the legacy of the international Cassini-Huygens mission to Saturn and ESA's upcoming Jupiter Icy Moons Explorer, a future outer Solar System mission with advanced instrumentation would focus on the study of the connection of ocean-bearing moon interiors with their near-surface environments, also attempting to search for possible biosignatures.

Cross-References

- [Callisto](#)
- [Europa](#)
- [Ganymede](#)
- [Jupiter](#)

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Jupiter's Biggest Moons

► Galilean Satellites

JWST

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Galaxies · Exoplanets · Kuiper Belt Object ·
Space Telescope · Redshift

Synonyms

James Webb Space Telescope; Next-generation
space telescope; NGST

Definition

The James Webb Space Telescope (JWST) is an infrared space telescope project led by ► [NASA](#) with major contributions of the European Space Agency (ESA), the Canadian Space Agency (CSA) and space agencies from other nations. The development lasted two decades. The 6250 kg spacecraft has been launched on December 25, 2021, to be placed around the Sun-Earth L2 Lagrange point. The telescope is composed of a segmented primary mirror with a diameter of about 6.5 m. The focal point is equipped with four major instruments which are working in the Near and Mid Infrared wavelengths. They combine various functions of taking picture (cameras), analyzing the light (spectrometer), and blocking the starlight (coronagraph).

History

In 1989, while the Hubble space telescope was awaiting to be launched, scientists and engineers

gathered at the Space Telescope Science Institute to shape the Next Generation Space telescope. This workshop outlined that the typical lead time to develop such a major project is 25 years. The basic trade-off was between a 10 m telescope in high Earth orbit or a 16 m telescope on the moon (Bely 1989). Finally in 1996 a group of scientists, HST and beyond Committee, gathered by the Association of Universities for Research in Astronomy has delivered the report defining the main requirements of the Next Generation Space telescope. The committee used widely the material which was provided by three independent study teams. The telescope must have a mirror larger than 4 m, and the orbit could be either at L2 or a 1 to 3 AU ellipse, to reach in any case a low temperature (70 K or less) allowing infrared observations in the 1–5 μm wavelength. In this report it was assumed that the construction could be achieved for 2005 and for a cost less than \$700 million (US cost). Finally in 2002 the industrial teams and the science teams for the building of the telescope have been selected while the international cooperation has been organized. Scientists, engineers, and professionals from up to 14 countries contributed throughout the two decades of development. The European and Canadian contributions to the instruments and the launch have been finalized.

Overview

The James Webb Space Telescope was launched from Kourou (French Guyana) December 25, 2021, with an Ariane5 rocket. The secondary mirror and the primary segmented mirror have been successfully deployed as well as the large five layer sunshield which unfurled smoothly (Fig. 1). From its working position, at the L2 Lagrange point, the telescope will always face the night side of the Earth and the Moon. JWST can only point at roughly half of the sky at a given moment. While orbiting the sun at the same pace than the Earth, it will point at any point in the sky on the course of one year. Each 18 segments of the primary mirror can be adjusted with 6 degrees of

JWST, Fig. 1 An overall view of the telescope while the integration teams carefully guide Webb's suspended telescope sections into place just prior to integration. (Image credit: NASA/Chris Gunn)



freedom to achieve a “perfect alignment.” This is performed with the NIRC*am* instrument through a process known as a wavefront sensing and control. While traveling to the L2 Lagrange point and orbiting there, the entire spacecraft cools down to its working temperature of 40 K. This temperature is required to be able to perform Infra-Red observations between the wavelength of 0.6 μm up to 28.6 μm .

Near Infra-Red Camera (NIRC*am*) is the primary imager of JWST, working in the wavelength range of 0.6 to 5 μm . It is also a spectrometer. It is equipped with coronagraphs, to mask a centered bright object enabling to take pictures and measurements of faint sources nearby. The instrument is operating at 37 K (Burriesci 2005) and aims to detect light of the earliest stars and galaxies during their formation, to study the population of stars of nearby galaxies and in the Milky Way and also objects of the Kuiper Belt. The instrument, also used for metrology to align the elements of the segmented mirror, is provided by Arizona State University and Lockheed Martin's Advance Technology Center.

Near Infra-Red Spectrograph (NIRSpec) operates between 0.6 and 5.3 μm (Birkmann et al. 2016) and can perform analysis of a single object but is able also to observe simultaneously 100 sources using the microshutter array capabilities. The instrument is working around 42.8 K. It will study thousands of galaxies during the 5-year nominal mission. The instrument is a contribution

of ESA, built by Airbus Defence and Space while the microshutter arrays are provided by the Goddard Spaceflight Center.

Near Infra-Red Slitless Spectrograph/Fine Guidance Sensor (NIRISS/FGS) is both a camera and a spectrograph designed to capture images of bright objects. It is operating at around 40 K and between 0.6 μm and 5 μm but some observations for the observation of exoplanets is optimized between 0.6–2.5 μm (Maszkiewicz 2012). NIRISS will contribute to various science objectives like the detection of the first light and to the science of the exoplanets. The FGS is a camera system used to determine the right pointing direction by identifying selected stars and ensuring the exact and stable pointing of the entire telescope. The instrument is a contribution of the Canadian Space Agency.

Mid Infra-Red Instrument (MIRI) is equipped with cameras, spectrographs, coronagraphs, and an integral field unit allowing to work as a kind of Spectro-imager (giving an image of a field of view for each single wavelength) (Wright et al. 2008). It is working over a range of 4.6 to 28.6 μm . It operates at a lower temperature than the other instruments. The detector stage is precooled at 18 K and the nominal working temperature is 7 K. MIRI is fulfilling several objectives of JWST, observing the redshifted light of ancient and distant galaxies, and also young stars while forming. It will detect faint light of comets and study Kuiper Belt bodies. The instrument is a

wide international cooperation between the USA and European countries coordinated by ESA.

These instruments and the overall spacecraft are designed to fulfil the four large science objectives enlightened in the decadal survey 2001 (National Research Council 2001): “NGST is the top priority for this decade because it will reveal the first epoch of star formation and trace the evolution of galaxies from their birth to the present. It will also provide a unique window onto the birth of stars and planets in our own galaxy. Having NGST’s sensitivity extend to 27 μm would substantially improve its ability to study Kuiper Belt objects (KBOs) in our solar system, the formation of stars and planets in our galaxy, and the dust emission from galaxies out to redshifts of 3.” Note that NGST was named, in 2002, after James Webb, former administrator of NASA during the Apollo Era. The design of the instruments and the global shaping of the current program lead also to major contribution to the study and characterization of some of the closest exoplanets.

Cross-References

- [European Space Agency](#)
- [HST](#)
- [Lagrange Points](#)
- [NASA](#)

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K

K, REE, and P-Rich Lunar Material

► [Kreep](#)

K/T Boundary

► [KT Boundary](#)

Kaapvaal Craton, South Africa

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The Kaapvaal ► [craton](#) in South Africa is, along with the ► [Pilbara craton](#) of Western Australia, the only areas where mid-Archean (3.6–2.5 Ga) volcanic and sedimentary rocks are relatively well preserved. The craton covers an area of about $1.2 \times 10^6 \text{ km}^2$ and is made up of several strongly deformed early Archean (3.0–3.5 Ga) greenstone belts intrusive into tonalitic gneisses (ca. 3.6–3.7 Ga) and cut by a variety of granitic plutons (3.3–3.0 Ga). The craton formed and

stabilized between about 3.7 and 2.6 Ga when major granitoid batholiths intruded, and deformation thickened the crust. At the same time, a thick, stable harzburgitic (► [olivine](#)-orthopyroxene peridotite) keel formed the lower part of the lithosphere. Subsequent evolution from 3.0 to 2.7 Ga involved collision with surrounding cratons and the development of basins filled with thick sequences of both volcanic and sedimentary rocks. Similarities of rock records of the Kaapvaal and Pilbara cratons suggest that they were once part of a single continent called Valbara. Barberton, the largest greenstone belt in the craton, is well known for its ► [komatiites](#) (ultramafic volcanic rocks) and traces of early life preserved in ► [cherts](#) and other sedimentary rocks. Also present in the Kaapvaal craton is the Bushveld complex, an enormous mafic-ultramafic layered intrusion, and the 2.0 Ga Vredefort meteorite impact crater, the largest on Earth (300 km in diameter).

Cross-References

- [Archean Eon](#)
- [Barberton Greenstone Belt](#)
- [Barberton Greenstone Belt, Sedimentology](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Crater, Impact](#)
- [Craton](#)

- [Granite](#)
- [Greenstone Belt](#)
- [Pilbara Craton](#)

Kant-Laplace Nebular Hypothesis

Stéphane Le Gars

Centre François Viète, Université de Nantes,
Nantes, BP, France

Keywords

Astronomy · Cosmogony · Galaxies · History ·
Kant · Laplace · Nebula · Origins · Physics ·
Solar system

History

In 1755, the philosopher Immanuel Kant (1724–1804) brought out a work of his early youth, *Allgemeine Naturgeschichte und Theorie des Himmels* (Universal natural history and theory of the heavens) in which he expressed his ideas concerning the solar system's origin (Kant 1755). His cosmogony was entirely guided by Newton's mechanics: Kant assumed that the origin matter was diffused all over space, where it formed a kind of chaos. The constituent particles of this chaos, initially at rest, came to attract each other under the effect of gravitation and developed rotational motion. This motion, accelerating, created a circular ring in which breaking up produced in its turn planets and their satellites. Kant, in his cosmogonic hypothesis, was prompted by an analogical principle and the search of a systematic organization. He proposed that every system has a center and is reproduced in a hierarchical way, passing analogically from the Earth-Moon system, to the solar system, then to the distribution of stars in the Milky Way, and lastly from the galaxies (still called at that time nebulae) around the center of the universe: Kant's cosmogony aimed at stating a cosmic order.

If Kant said his hypothesis was scientific, in reality it was impossible to be confirmed by

observations at that time: it was only speculative. Moreover, it did not abide by certain laws of mechanics, such as the angular momentum conservation: How could particles shielded from all external effects begin a rotational motion? The French mathematician Pierre Simon Laplace (1749–1827) proposed in 1796 a cosmogonic hypothesis close to Kant's, without knowing the latter's work (Laplace 1824). His cosmogony appeared immediately more scientific, especially because Laplace limited himself to consider the solar system's structure, but not the universe's organization. Furthermore, he avoided the problem of setting the primitive nebula in motion, considering it already in a uniform rotation. His approach was different from Kant's because it was based more on a reasoning of probability (planets and satellite's revolution and rotation direction, known at that time) than on an evolutionary viewpoint. Aspects of the cosmogonic hypothesis quickly called the “Kant-Laplace's hypothesis” and discussed throughout the nineteenth century are still globally accepted today (Merleau-Ponty 1983; Michel 1975; Poincaré 1911; Wolf 1886).

Cross-References

- [Planet Formation](#)
- [Solar Nebula](#)

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Kaolin

► [Kaolinite](#)

Kaolinite

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Kaolin](#)

Definition

Kaolinite is an extremely common layered silicate clay mineral with the chemical composition $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$. It consists of one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of alumina octahedra. The name is derived from Chinese *Gaoling* meaning “high hill,” a mountain located in Jingdezhen, Jiangxi province, China. Kaolinite has a low cation exchange capacity. It is a soft, usually white mineral produced by the chemical weathering of aluminum silicate minerals such as feldspar. It is often colored reddish-orange by the presence of traces of iron oxides but may range from white, yellow, or light orange when lesser amounts of iron are present. Kaolinite occurs abundantly in soils formed from chemical weathering of rocks in hot, humid climates.

Cross-References

► [Clay](#)

Kelvin-Helmholtz Timescale

Daniele Galli
INAF Osservatorio Astrofisico di Arcetri, Largo
E. Fermi 5, Italy

Definition

The Kelvin-Helmholtz timescale is the time required for a star to radiate its own gravitational energy. It is defined as the ratio of the star's gravitational energy GM^2/R (where M and R are the stellar mass and radius, respectively, and G is the gravitational constant), and the star's luminosity L (energy radiated per unit time):

$$t_{\text{KH}} = GM^2/RL$$

For the present-day Sun, $t_{\text{KH}} = 30$ Myr. A star with no internal energy sources (e.g., a pre-Main Sequence star before turning on nuclear reactions) slowly contracts on a Kelvin-Helmholtz timescale, radiating away all its gravitational energy. Suggested reading: Stahler and Palla (2004).

History

This concept was elaborated by the physicists William Thomson, Lord Kelvin (1824–1907) and Hermann von Helmholtz (1821–1894) from their investigations on the age of the Sun and the Earth and definitely formulated by the pioneer astrophysicist August Ritter (1826–1908). See Shaviv (2008).

Cross-References

► [Pre-Main-Sequence Star](#)

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Kepler

Emeline Bolmont

Department of Astronomy, Université de Genève,
Versoix, Switzerland

Keywords

Asteroseismology · Exoplanets · Photometry ·
Spectroscopy · Transiting planets

Definition

Kepler was a NASA mission to discover and characterize transiting planets around other stars (exoplanets), with a special emphasis on rocky planets where water could be liquid on the surface and life as we know it might be comfortable. Kepler also supported programs for asteroseismology and general astrophysics. It discovered more than 2000 planets making it the most prolific exoplanet discovery instrument so far.

History

Serious thinking about the feasibility of using very precise photometry to detect small changes in brightness when planets transit in front of their stars dates back more than 35 years (e.g., Borucki and Summers 1984). Subsequent proposals for space missions to search for small transiting planets, such as FRESIP (Borucki et al. 1996) in the 1990s, were viewed as technologically premature. However, this objection was answered by careful experiments with ► [CCDs](#), which demonstrated that the photometric precision required to detect a planet like the ► [Earth](#) passing in front of a star like the Sun could be achieved in a laboratory simulation of the mission. Scientific interest in the mission was piqued by the discovery of the first transiting planet, HD 209458 (e.g., Charbonneau et al. 2000), and *Kepler* was selected as NASA's tenth *Discovery* class mission. *Kepler* was launched successfully on a Delta II from Cape Canaveral in March 2009 and had

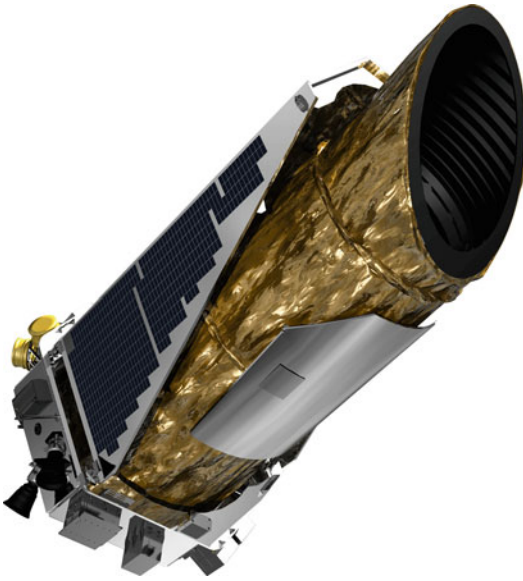
sufficient consumables to operate for a decade. It ended its operations in October 2018.

Overview

Kepler is a NASA satellite which discovered more than 2000 exoplanets over the span of 4 years. In 2012, a problem with reactions wheels prevented *Kepler* from continuing its nominal mission. However, an extended mission was approved in 2014, named K2, and it discovered a few hundred more planets until its end in 2018. *Kepler* has revolutionized our understanding of planetary systems, offering exquisite statistics. In particular, it showed that one of the most common observed exoplanet populations are the super-Earths and mini-Neptune populations.

Basic Methodology

The design of *Kepler* was driven by the goal of discovering an Earth-like planet transiting a Sun-like star in an orbit that would allow water to be liquid on the surface of the planet. The goal of detecting planets with orbital periods as long as a year set the requirement that the mission duration should be at least 4 years, so that at least three transits could be detected. The probability that the inclination of a 1-year orbit is properly aligned for transits to occur is less than 1%, and this set the requirement that at least 100,000 solar-type stars should be monitored continuously in order to yield enough planet detections to provide a statistically meaningful result for the case where Earth analogs are rare. This led to the requirement for a telescope with a wide field of view, on the order of 100 square degrees. To achieve the photometric precision needed to detect reliably a dimming as small as an Earth transit, 84 parts per million, a meter-class telescope was required. The *Kepler* photometer uses a Schmidt telescope with an array of 42 CCDs in a curved focal plane. The spacecraft is in an Earth-trailing orbit, which provides a much more stable environment than a low Earth orbit. The spacecraft is rotated to a new orientation four times a year in order to maintain



Kepler, Fig. 1 The *Kepler* flight unit (<https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>)

illumination of the solar panels. The target area is more than 55° north of the ecliptic, and the focal plane is well protected from solar illumination by a sun shield. Figure 1 shows an illustration of the *Kepler* flight unit.

To aid selection of an optimized list of targets similar to the Sun, the Kepler Input Catalog (KIC) was prepared before launch. The KIC contains all the known stellar objects in the *Kepler* field of view, based on existing catalogs. This information was supplemented by stellar classifications of more than two million stars bright enough to be good targets, based on more than 50 million measurements of accurate positions and magnitudes in a set of filter-defined wavelength bands in the Sloan Digital Sky Survey plus a custom gravity-sensitive filter (e.g., Athay and Canfield 1969). These observations were obtained with KeplerCam on the 1.2-m telescope at the F. L. Whipple Observatory on Mount Hopkins in Arizona.

Because of telemetry limitations, full images were transmitted to the ground only after spacecraft maneuvers, nominally once per month, in order to confirm proper reacquisition of the target field. In normal operation, a limited number of pixels are saved around each target for later

transmission to the ground for processing. This allowed the development of the data reduction pipeline to continue during the mission, thus resulting in improved photometric performance as various subtle instrumental effects were understood and modeled. For most targets, the images were accumulated and stored on the spacecraft for an integration time of 30 min, but a limited number of targets could be sampled with a cadence of 1 min, thus providing better time resolution for the light curves of transient events, such as the ingress and egress of transits. After the first year of operation on orbit, the photometric performance of all the data obtained by *Kepler* was close to the specification of 20 parts per million for a $V = 12$ magnitude solar-type star over an integration time of 6.5 h.

Key Research Findings

In the first year of operation, *Kepler* already had identified several hundred candidate-transiting planets. Many of the transit light curves implied planets smaller than Neptune. A key part of the *Kepler* mission is still an ongoing effort to confirm and characterize the candidates as true transiting planets, using a variety of ground-based and space-based observations. This includes reconnaissance spectroscopy aimed at the elimination of systems involving eclipsing binaries that masquerade as transiting planets, and to provide more precise classification of the stellar characteristics. The second aspect is quite important, because the accuracy with which planetary parameters such as radius and mass can be determined is often set by uncertainties in those parameters for the host star. Another important step in the follow-up of *Kepler* candidates is deep imaging with very high spatial resolution, with techniques such as adaptive optics, speckle imaging, and even HST (Hubble Space Telescope) imaging. This can reveal nearby companions that are hidden in the blur of the *Kepler* images, due to the large pixels, which are 4 arcsec^2 on the sky. The *Kepler* data also allows very precise astrometry, despite the large pixels, because of the extraordinarily large number of collected photons and continuous duty cycle.

Motion of the image centroids during transit events can often be measured to better than 0.0001 pixels. When combined with the high-resolution images, this is a powerful tool for detecting background eclipsing binaries, on the one hand, or for confirming that the target star is the source of the transits, on the other hand. In some cases, observations in the infrared with the now retired Warm Spitzer Space Telescope could be used to test whether the depth of the dimmings were achromatic, as expected for transits. The gold standard for confirming and characterizing a transiting planet is a spectroscopic orbit for the host star that yields a mass for the unseen companion that is consistent with a planetary interpretation. This final step usually requires substantial time on precious resources such as the HIRES spectrometer on the Keck I telescope, the HARPS spectrometer on the ESO La Silla 3.6 m telescope, or now ESPRESSO at the VLT. Limited access to such facilities dictates that not every candidate can be fully confirmed. Besides, the orbital amplitude of less than 10 cm^{-1} that the Earth induces in the Sun is just starting to be in reach of a few existing radial-velocity instruments (e.g., ESPRESSO), and it is clear that it will be challenging to disentangle planetary signals from the activity of the stars themselves (see ► [Activity, Magnetic](#), Cretignier et al. 2020) to allow velocity measurements at this level. For the smallest planets, the strategy is to eliminate as many as possible of the astrophysical false positives that might mimic Earth-like transits.

As of November 2021, *Kepler* and follow-up observations such as radial velocity measurements had confirmed about 2400 exoplanets in more than 1700 systems. An additional more than 2300 candidate exoplanets still await confirmation (see https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html). Orbiting stars which were in the Kepler field of view, 361 candidates, and planets were found in the ► [habitable zone](#), for instance, Kepler-62 e and f (Borucki et al. 2013) or Kepler-186 f (Quintana et al. 2014). Amusingly, a habitable zone planet was recently rescued from its false positive status

(i.e., this planet was initially classified as a false positive by the Kepler pipeline). Its name is Kepler-1649 c and as most of its fellow Kepler habitable zone planets, it orbits a star significantly less massive than the Sun (Vanderburg et al. 2020).

Several dramatic breakthroughs in asteroseismology using *Kepler* data were reported in the same time frame (Gilliland et al. 2010; Davies et al. 2016; Yu et al. 2018).

A first problem with a reaction wheel which stabilizes the spacecraft was discovered on July 16, 2012. After several tests, the science data collection resumed. A second reaction wheel failed on May 11, 2013. The spacecraft was no longer fully operational.

However, on May 16, 2014, NASA announced the approval of extending the *Kepler* mission to the so-called K2 mission, which lasted until 2018. Although the photometric precision of the K2 mission was an order of magnitude poorer than that of the original mission, a much larger area of the sky has been observed. The K2 missions confirmed 476 planets, and 850 candidates remain to be confirmed.

Future Directions

The main legacy of *Kepler* is the frequency and characteristics of the population of extrasolar planets, from those with periods shorter than a few months to planets belonging to the family of Super-Earths and Mini-Neptunes. This information is critical for the design of future, much more expensive missions for astrometric and direct detection of exoplanets, such as the European PLATO mission.

Cross-References

- [Activity, Magnetic](#)
- [Astrometric Planets](#)
- [CCD](#)
- [CoRoT Satellite](#)

- [Direct-Imaging, Planets](#)
- [ESPRESSO](#)
- [Exoplanets, Discovery](#)
- [PLATO 2.0 Satellite](#)
- [Radial-Velocity Planets](#)
- [Spectroscopic Orbit](#)
- [Spitzer Space Telescope](#)
- [TPF/Darwin](#)
- [Transiting Exoplanet Survey Satellite](#)
- [Transiting Planets](#)

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Kepler 11: Multiple Transiting Planet System

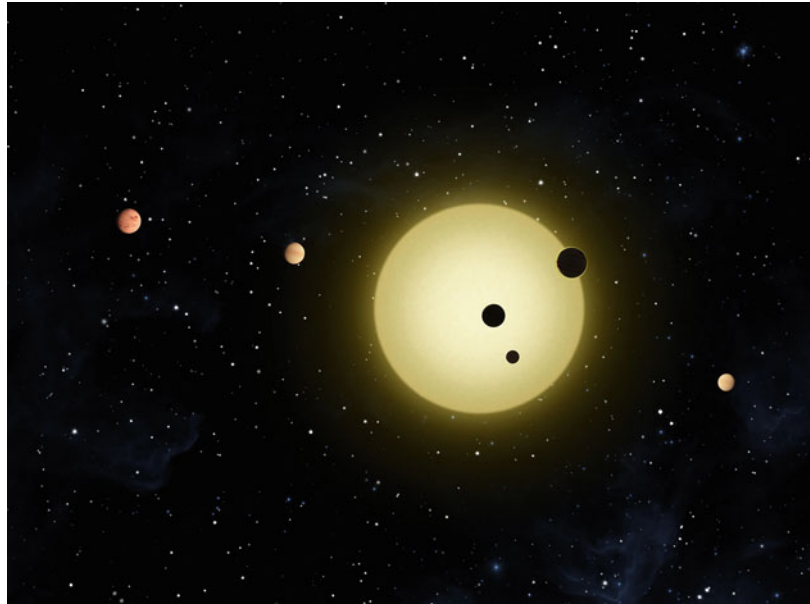
Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

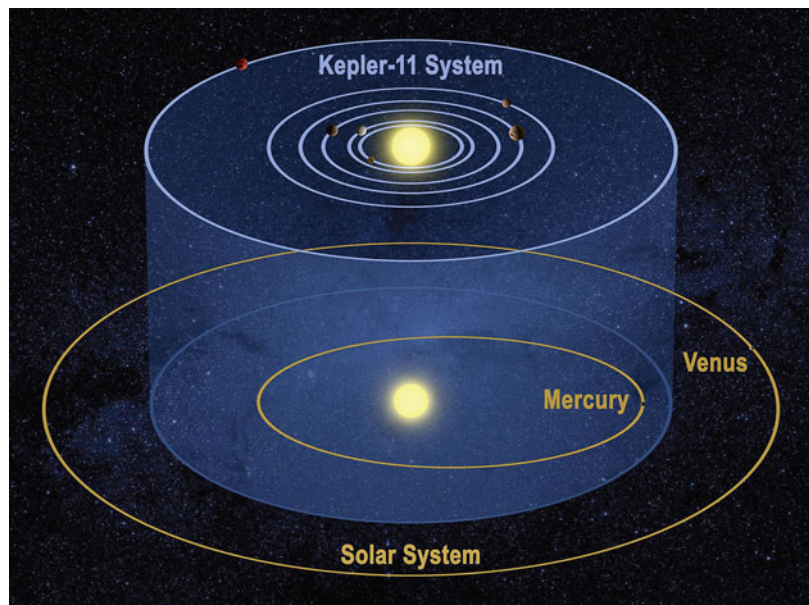
Definition

Kepler 11 system is the 11th planetary system detected by the *Kepler* space telescope (Lissauer et al. 2011). The central star of this system is Sun-like and hosts six planets, five with orbital periods between 10 and 47 days and one with a longer period. The Kepler 11 planetary system is the first discovered case of a star system with six transiting planets. Figure 1 shows an artist's rendering of this system. All discovered planets are larger than Earth. Their masses were estimated thanks to the observed transit timing variations, which were large enough due to the compactness of the system. These radii and masses measurements show that the six planets have low densities (Lissauer et al. 2013). The orbits of planets b–f would easily

Kepler 11: Multiple Transiting Planet System, Fig. 1 Artist's rendering of the Kepler 11 planetary system



Kepler 11: Multiple Transiting Planet System, Fig. 2 Schematic presentation of the orbits of Kepler 11 planets



fit inside the orbit of Mercury, with planet g only slightly outside of it (Fig. 2). Despite this close packing of the orbits, dynamical integrations indicate the system has the potential to be stable on a time scale of billions of years.

Cross-References

- [Kepler](#)
- [Planet Detection: Transit Timing Variation](#)
- [Transit](#)

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Kepler 16b: First Circumbinary Planet

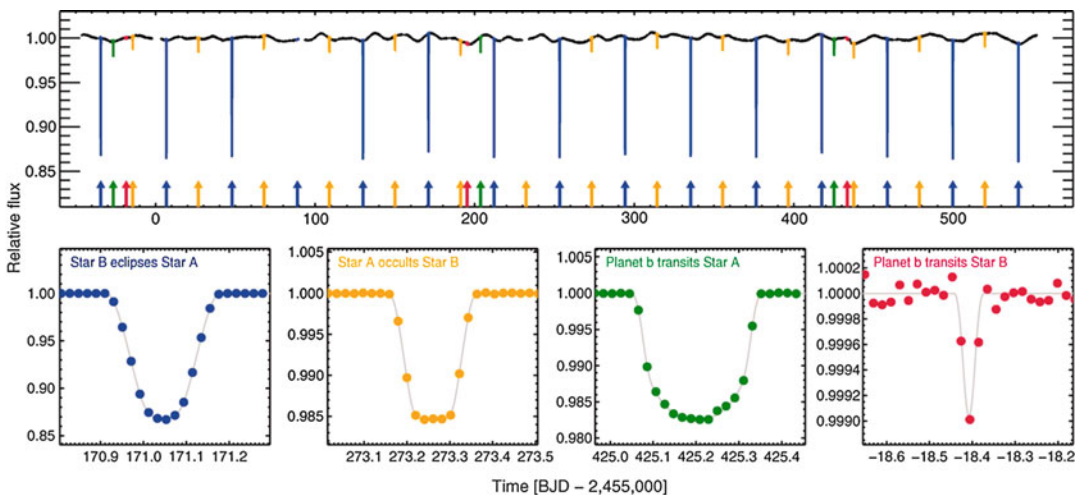
Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Definition

Kepler-16b is the first circumbinary planet discovered around a pair of low-mass and main-sequence stars using the Kepler space telescope (Doyle et al. 2011). Data from the Kepler spacecraft revealed transits of the planet across both stars, in addition to the mutual eclipses of the binary (Fig. 1). The planet has a mass of 0.33 Jupiter masses, comparable to Saturn in mass and size, and is in a nearly circular orbit with a period of ~229 days. The host binary consists of two eclipsing stars, 0.69 and 0.20 times as massive as the Sun, and has an eccentric (0.16) orbit with a period of 41 days. The motions of all three bodies are confined to within 0.5° of a single plane, suggesting

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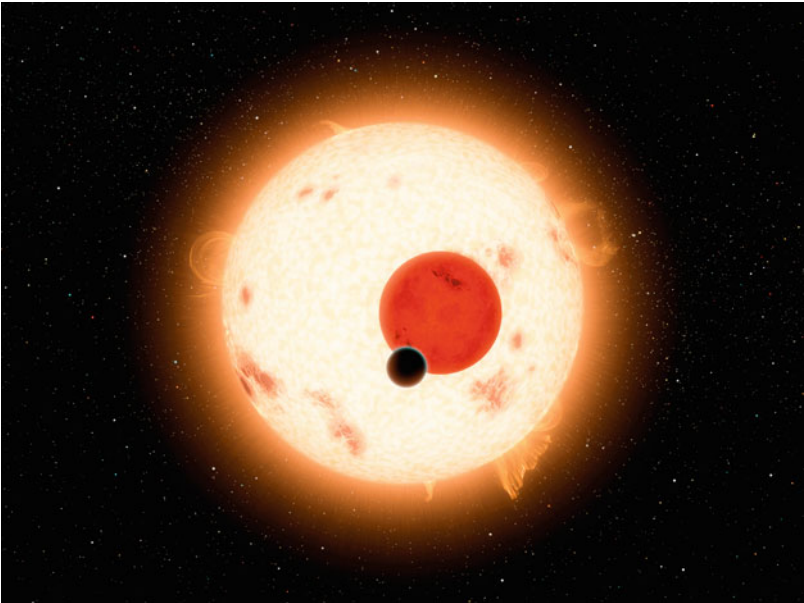


Kepler 16b: First Circumbinary Planet, Fig. 1 The light curve of Kepler 16. As shown here, the light curve, in addition to the eclipses of the two stars, shows the eclipse of each star by the planet as well (Doyle et al. 2011)

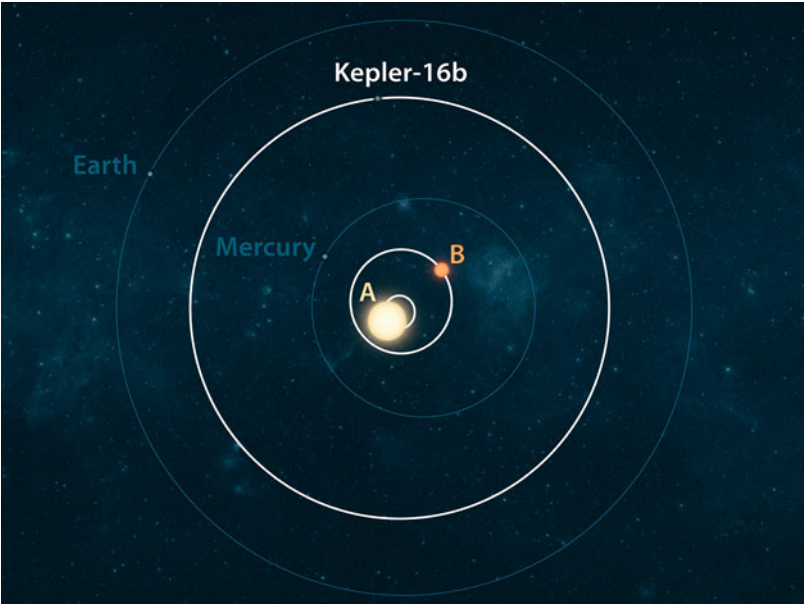
that the planet formed within a circumbinary disk. Kepler-16b is also the first circumbinary planet to have been detected in the habitable zone of its host binary (Haghighipour and Kaltenegger 2013). Although this planet is too large to be habitable, at least by terrestrial life forms, it may have natural

satellites that might be habitable. Figure 2 shows an artist’s rendering of the Kepler-16 circumbinary system. Figure 3 shows the size of this system compared with the solar system. A movie of the habitable zone of Kepler-16 can be found at <http://astro.twam.info/hz-ptype/>.

Kepler 16b: First Circumbinary Planet, Fig. 2 Artist’s rendering of Kepler 16 circumbinary system



Kepler 16b: First Circumbinary Planet, Fig. 3 A comparison between the planetary system of Kepler 16 and the solar system



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Kepler 186f: First Earth-Sized Planet in Habitable Zone

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

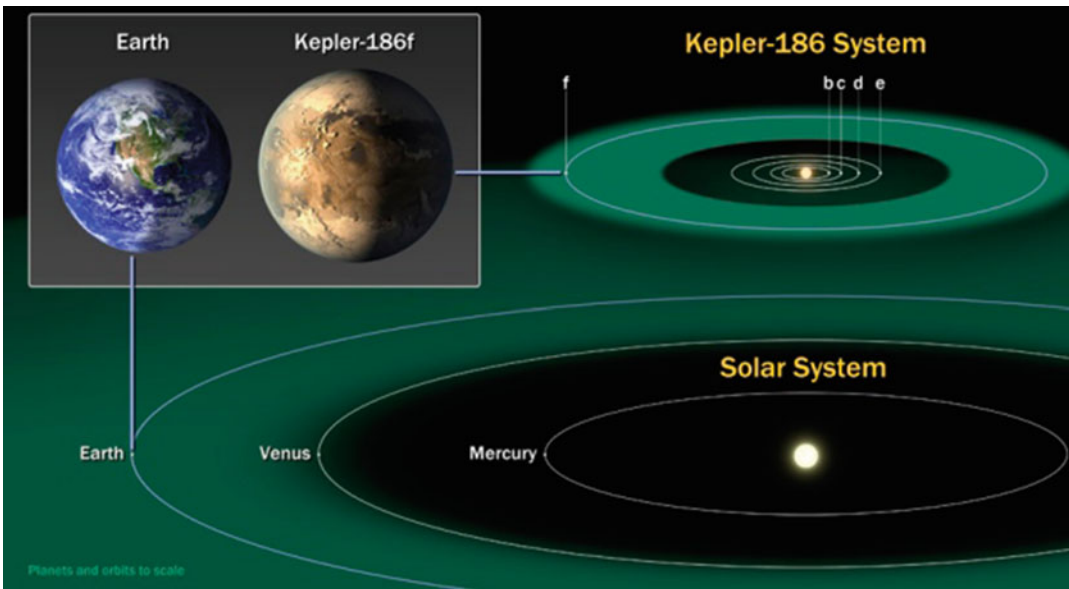
Definition

Kepler-186f is the first Earth-sized planet in the ► [habitable zone](#) detected by the Kepler space telescope. This planet is the outermost of the five

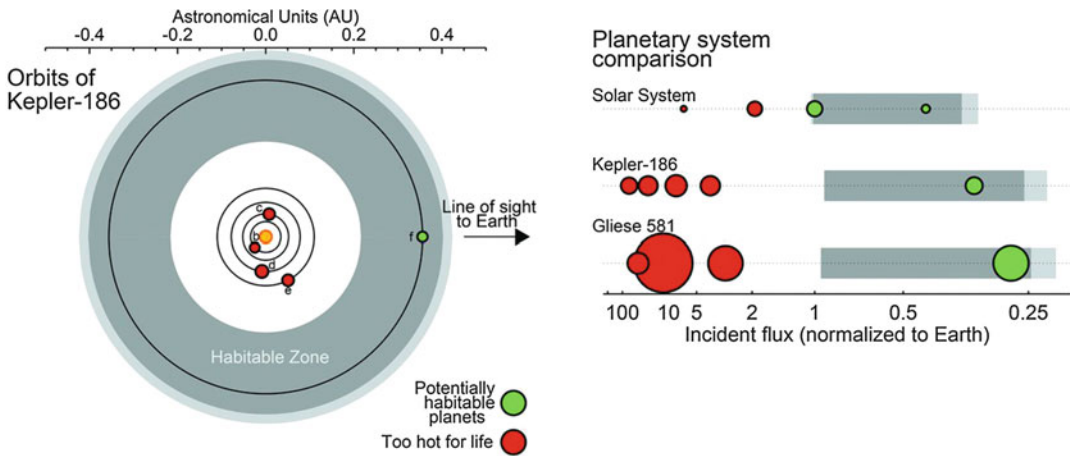
planets transiting Kepler 186, a 0.47 solar radius, main sequence M1 star with a surface temperature of 3788 K. The inner four planets of this system were detected using the *Kepler* data from the first 2 years (Rowe et al. 2014; Lissauer et al. 2014). These planets are all smaller than 1.5 Earth radii and have orbital periods between 3.9 and 22.4 days. Kepler-186f was detected with an additional year of data (Quintana et al. 2014). Figure 1 shows an artist's rendering of this planetary system.

Conservative estimates suggest that the habitable zone of Kepler186 extends from 0.22 to 0.40 AU around this star (Kopparapu et al. 2013a, b). With an orbital period of ~130 days and a semimajor axis of ~0.35 AU, Kepler-186f is right in the star's habitable zone. Figure 2 shows a comparison between the flux received by this planet and those of other known potentially habitable exoplanetary systems. Bolmont et al. (2014) discuss the planetary system evolution and habitability in more detail than in Quintana et al. (2014). They found that the planet can sustain surface temperatures above the freezing point of water with 0.5–5 bars of carbon dioxide, depending on its nitrogen content.

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Kepler 186f: First Earth-Sized Planet in Habitable Zone, Fig. 1 An artist's rendering of Kepler 186f comparing to the inner Solar System. (Courtesy of NASA)



Kepler 186f: First Earth-Sized Planet in Habitable Zone, Fig. 2 A schematic view of the habitable zone of Kepler 186 compared to that of Gliese 581 and the Solar System (Quintana et al. 2014)

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► Kepler

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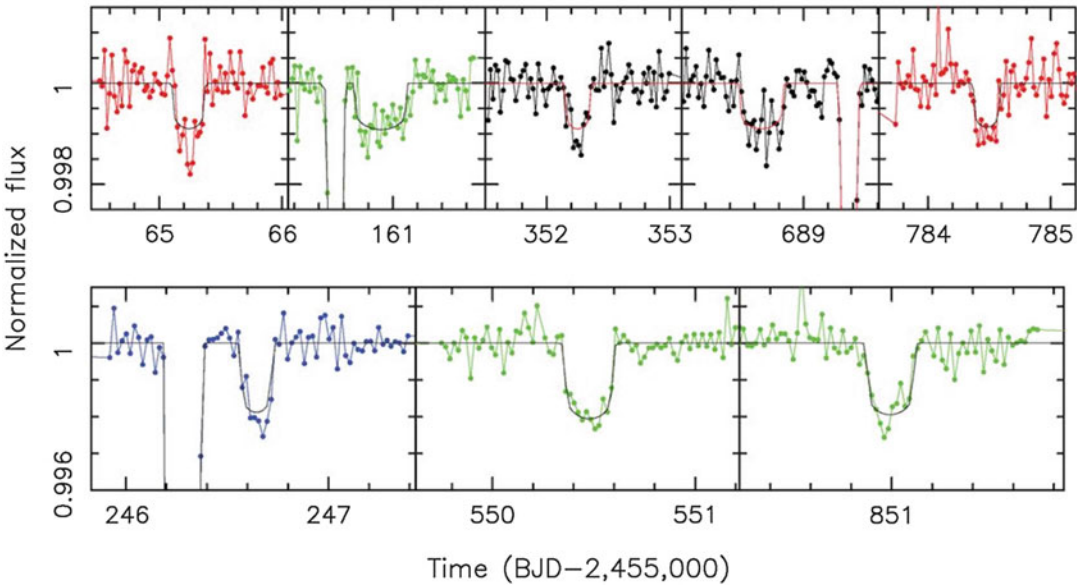
Kepler 47: First Multi-circumbinary Planet System

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Definition

The eclipsing binary Kepler-47 is the first system detected to have multiple ► [circumbinary planets](#) (Orosz et al. 2012). The binary consists of a Sun-like star and a companion roughly one-third its size, orbiting each other every 7.45 days. The planets were detected using transit photometry when each planet transits the stars of the binary. Figure 1 shows some of the planetary transits of this system. The inner and outer planets of Kepler-47 system have radii 3.0 and 4.6 times that of Earth, respectively. The inner planet, Kepler-47b,

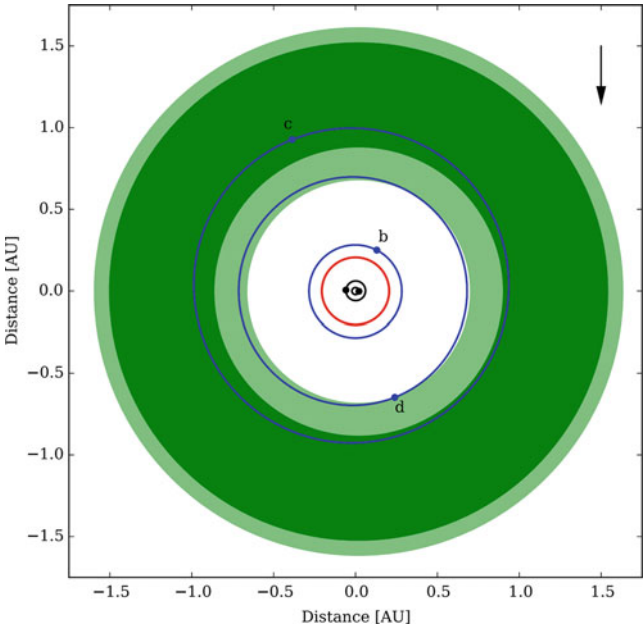


Kepler 47: First Multi-circumbinary Planet System, Fig. 1 The normalized flux near five representative transits of the inner planet (*upper*) and all three transits of the

outer planet (*lower*) are shown (Orosz et al. 2012). The deepest minima correspond to the eclipse of the planet-hosting star by the other star of the binary system

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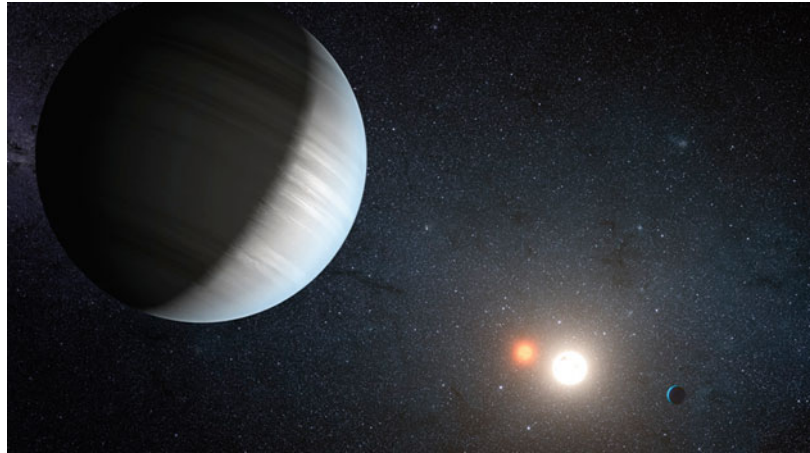
Kepler 47: First Multi-circumbinary Planet System, Fig. 2 Graph of the narrow (*dark green*) and empirical (*light green*) HZs of Kepler 47 binary system. Calculations show that the effect of the secondary star is minute indicating that the HZ of the system is in most part determined by the primary star. The figure also shows the orbits of the three planets of this system in *blue*, with the two stars indicated by *dots* (Orosz et al. 2019)



has an orbital period of 49.5 days. The outer planet’s orbital period is 303.2 days.
Calculation of the ► [habitable zone](#) (HZ) of the Kepler-47 binary by Haghighipour and

Kaltenegger (2013) has shown that the outer planet, Kepler-47c has been found to spend some time in the binary habitable zone (Fig. 2). Since this planet is larger than Earth, it cannot be

Kepler 47: First Multi-circumbinary Planet System, Fig. 3 Artist's rendering of the Kepler 47 circumbinary planetary system. (Figure courtesy of NASA)



habitable. However, it can have natural moons that could be habitable. A movie of the evolution of *the* habitable zone of this system can be found at <http://astro.twam.info/hz-ptype/>. Recently, a third planet was detected in the system between planet b and c (Orosz et al. 2019).

The detection of the Kepler-47 planetary system as the first with multiple planets in circumbinary orbits establishes that close binary stars can host complete (and even habitable) planetary systems. Figure 3 shows an artist's rendering of this system.

Cross-References

- [Habitable Zone in Binary Stars Systems](#)
- [Kepler](#)

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Kepler 9: First Transiting System Confirmed by TTV

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

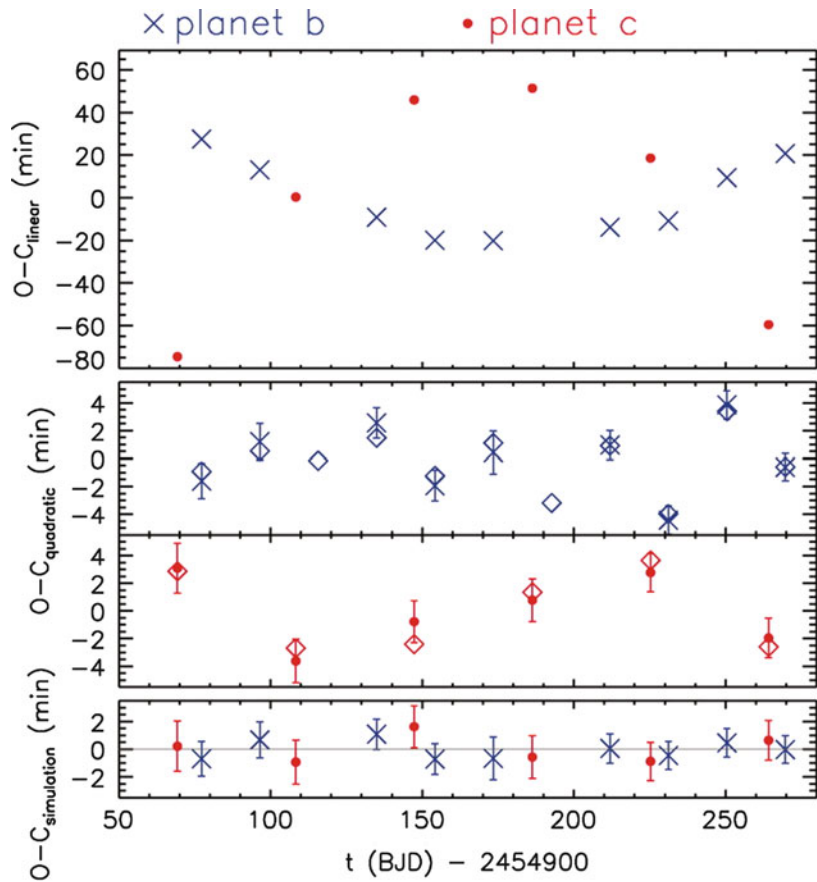
Definition

The planetary system of the star Kepler 9 is the first system confirmed by the Transit Timing Variation Method (TTV). The central star of this system, a solar-like star, hosts two Saturn-sized planets in 19.2- and 38.9-day periods, in a near 2:1 [mean motion resonance](#) (Holman et al. 2010). The analysis of the observational data indicated that the periods of these two planets are increasing and decreasing at average rates of 4 and 39 min per orbit, respectively. It was also shown that the transit times of the inner body display an alternating variation of smaller amplitude. Figure 1 shows these variations for both planets. The observed TTVs are characteristic of gravitational interaction of two planets near a 2:1 orbital resonance.

Further analysis of the Kepler 9 data pointed to the existence of a third planet, Kepler 9d, in a 1.59-day orbit. Kepler 9d is a [Super-Earth](#) with a radius 1.64 times that of Earth's (Torres et al. 2011).

Kepler 9: First Transiting System Confirmed

by TTV, Fig. 1 Variations in observed transit times “O” of planets Kepler 9b (blue crosses) and Kepler 9c (red dots) (Holman et al. 2010) compared to calculated transit times “C.” The three panels show three different ways of estimating the calculated transit times “C.” Top panel: The calculated transit times “C” were estimated with linear ephemerides (where $C = A + P \cdot t$, where A and P are constants, and t is the epoch of transit). Middle panel: The calculated transit times “C” were estimated using quadratic ephemerides. Bottom panel: The calculated transit times “C” were estimated using the outcome of a numerical simulation of the orbital evolution of the two planets with fitted planetary masses and orbits



Cross-References

- [Kepler](#)
- [Saturn](#)

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Kepler, Johannes

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

History

Johannes Kepler (1571–1630), born in December 27, 1571 in Weil der Stadt (Germany), is one of the fathers of the modern physical astronomy. He revolutionized astronomy, by breaking with the dominant notion of circular motion of the planets, discovering the three laws of planetary motion that bear his name (published in 1609 and 1619): (1) planets move in elliptical orbits with the Sun at

a focus; (2) the line connecting a planet with the Sun will sweep over equal areas in equal periods of time; (3) the square of a planet's period is proportional to the cube of its mean distance from the Sun.

In March 7, 2009 NASA launched the Kepler Mission specifically designed to survey the region of our Milky Way galaxy in order to discover Earth-size planets in or near the habitable zone of other stars.

Kepler-10

Nader Haghighipour

Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

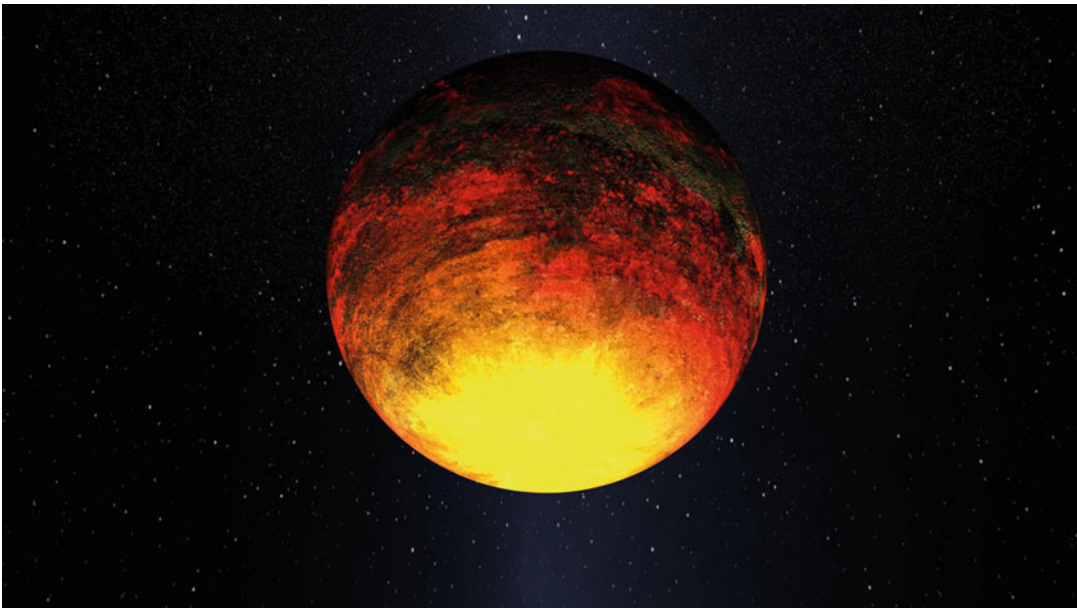
Definition

Kepler-10, an old (11.9 ± 4.5 Gyr) sunlike main-sequence star, is the central star of the

tenth planetary system discovered by the *Kepler* space telescope (Batalha et al. 2011). This star has a temperature of 5627 ± 44 K, mass of 0.895 ± 0.060 solar masses, and radius of 1.056 ± 0.021 solar radii. Kepler-10 is host to two planets, Kepler-10b (Batalha et al. 2011) and Kepler-10c (Fressin et al. 2011). The latter planet has a period of 45 days. ► [Radial velocity](#) measurements from HARPS-North and Keck-HIRES do not seem to agree on its mass, only that it should be below 20 Earth masses.

Overview

Kepler-10b was the first rocky planet detected by the Kepler telescope and was confirmed with radial velocity follow-up observations from Keck-► [HIRES](#). The mass of the planet was measured with a precision of around 30%, which was insufficient to constrain models of its internal structure and composition in detail.



Kepler-10, Fig. 1 Artist's rendering of the surface of Kepler-10b

In 2014, Dumusque et al. used the data from ► [HARPS](#) and obtained the mass and radius of planet *b* to be 3.33 ± 0.49 Earth masses and 1.47 ± 0.03 Earth radii, respectively. With these values, the density of the planet is $5.8 \pm 0.8 \text{ g cm}^{-3}$, which is very close to the value predicted by models with the same internal structure and composition as the Earth. More recently, Weiss et al. (2016) used additional precise radial velocity measurements from Keck-HIRES to revisit the properties of the planets. In particular, they found a higher mass for Kepler-10c than in Dumusque et al.; however, the data from HARPS and Keck-HIRES do not agree which could be due to a source of noise not well accounted for. They also hypothesize the presence of an additional third planet due to the presence of transit timing variations on Kepler-10c.

The orbital period of planet Kepler-10b is slightly larger than 20 h making this planet one of the closest planets to their host stars. The close proximity of this planet to star Kepler-10 causes the surface of the planet to have a very high temperature. Figure 1 shows an artist's rendering of the surface of Kepler-10b.

Cross-References

- [HARPS](#)
- [HIRES](#)
- [Planet Detection: Transit Timing Variation](#)
- [Radial Velocity](#)

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Kepler-37b: A Moon-Sized Planet

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

Definition

Kepler-37b, with a radius of ~ 0.296 Earth radii (Stassun et al. 2017), slightly larger than the radius of the Moon, is the smallest extrasolar planet discovered as of February 28, 2013 (Barclay et al. 2013). Figure 1 shows the sizes of three planets of the system. Kepler-37 is a main-sequence star, slightly cooler and smaller than the Sun. It has an effective temperature of $\sim 5417 \text{ K}$, and its mass and radius are 0.87 and 0.79 times the mass and radius of the Sun, respectively. This star is host to four planets, Kepler-37b, c, d, and e. Kepler-37e was discovered using transit timing variations by Hadden and Lithwick (2014). The radii (in Earth radius) and orbital periods (in days) of planets b, c, and d are (0.296, 0.75, and 1.94) and (13.37, 21.30, and 39.79), respectively. Observational data cannot be used to constrain the mass of Kepler-37b. However, models of the interior of planetary systems suggest that a mass a few times larger than that of the Moon would result in an unreasonably high bulk density for the planet.

Cross-References

- [Kepler](#)
- [Planet Detection: Transit Timing Variation](#)
- [Transit](#)



Kepler-37b: A Moon-Sized Planet, Fig. 1 An artist's rendering of the three planets around Kepler 37 compared to the planets in the solar system. (Figure courtesy of JPL)

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Kepler-444

Tiago L. Campante
 Instituto de Astrofísica e Ciências do Espaço,
 Universidade do Porto, Porto, Portugal
 Departamento de Física e Astronomia, Faculdade
 de Ciências da Universidade do Porto, Porto,
 Portugal

Keywords

Asteroseismology · Galaxy: disk · Planets and
 satellites: terrestrial planets · Planet–star
 interactions · Stars: fundamental parameters ·
 Stars: late-type · Techniques: photometric

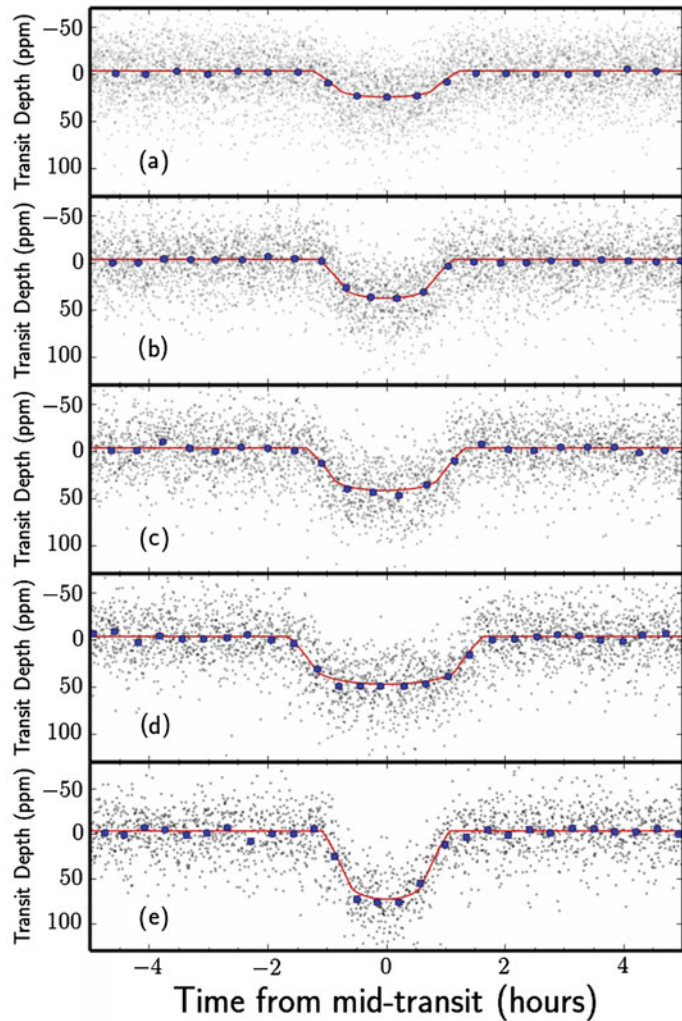
Definition

The Kepler-444 planetary system is the oldest known system of terrestrial-size planets. The host star, Kepler-444, is an ancient (11.2 ± 1.0 Gyr) Sun-like star from the stellar population of the Milky Way's thick disk. Based on photometry from the *Kepler* spacecraft, a system of five transiting planets was discovered orbiting Kepler-444, their sizes ranging between those of Mercury and Venus. The system is highly compact, with all planets orbiting the parent star in less than 10 days.

History

Transit-like signals, indicative of five planets orbiting *Kepler* Object of Interest 3158 (KOI-3158; named Kepler-444 after it had been confirmed), were detected in nearly continuous, 4-year-long *Kepler* photometry (Tenenbaum et al. 2013). The five planets were subsequently identified as planet candidates based on the examination of *Kepler* pixel-level and light curve data.

Kepler-444, Fig. 1 Phase-folded transit light curves of the five planets orbiting Kepler-444 (Campante et al. 2015). From panels (a) to (e): transits of planets Kepler-444b, Kepler-444c, Kepler-444d, Kepler-444e, and Kepler-444f, respectively. Observed data are shown as gray dots. Blue dots correspond to a binning of the observed data. The best-fitting transit model is shown as a red line. (© AAS. Reproduced with permission)



K

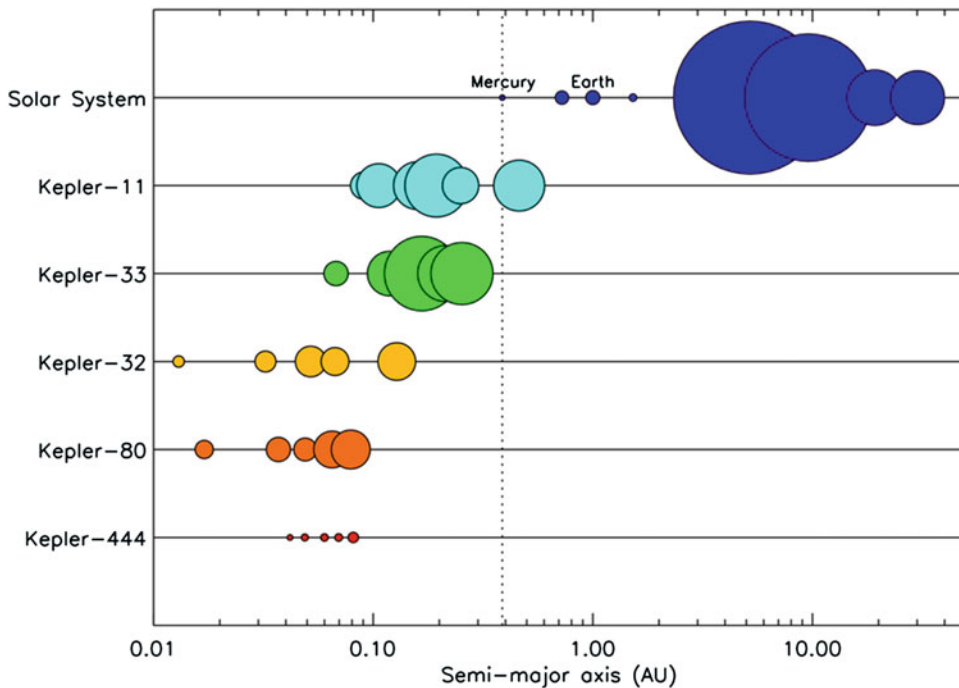
Campante et al. (2015) validated the system as a true five-planet system orbiting the target star and provided a detailed characterization of its planetary and orbital parameters based on an analysis of the transit photometry (see Fig. 1).

Overview

Kepler-444 (also known as HIP 94931, KIC 6278762, KOI-3158, and LHS 3450) is a cool main-sequence star of spectral type K. With an apparent magnitude $V = 8.86$ and lying at a distance of 35.7 ± 1.1 pc in the constellation Lyra, it is both

among the brightest and nearest *Kepler* planetary hosts. Kepler-444 is iron-poor ($[\text{Fe}/\text{H}] = -0.55 \pm 0.07$ dex) and moderately enhanced in terms of α -process elements ($[\alpha/\text{Fe}] = 0.26 \pm 0.07$ dex), indicating membership of the old stellar population of the Galactic thick disk (the star's kinematics corroborate this; Campante et al. 2015).

A precise ($\sim 9\%$) age of 11.2 ± 1.0 Gyr has been measured for Kepler-444 from detailed asteroseismology based on *Kepler* photometry (Campante et al. 2015). The old age of Kepler-444 suggests that thick-disk stars were among the hosts to the first planets in the Galaxy. The same



Kepler-444, Fig. 2 Semi-major axes of planets in the highly compact multiple-planet systems Kepler-444, Kepler-11, Kepler-32, Kepler-33, and Kepler-80 (Campante et al. 2015). Semi-major axes of Solar System

planets are shown as reference. The vertical dotted line marks the semi-major axis of Mercury. Symbol size is proportional to planetary radius. (©AAS. Reproduced with permission)

study quotes values for the stellar mass and radius of 0.758 ± 0.043 solar masses and 0.752 ± 0.014 solar radii, respectively. A thorough reappraisal of the fundamental stellar properties of Kepler-444 (Buldrin et al. 2019), based on revised spectroscopic parameters and the added constraint from its *Gaia* parallax, led to fully consistent values. The latter study further suggests that Kepler-444 bore a convective core during a significant fraction of its life on the main sequence, which could potentially affect the internal transport of angular momentum in later stages of stellar evolution.

Kepler-444b, the innermost and smallest planet (within 2σ of the size of Mercury), had its radius measured with a precision of ~ 100 km (Campante et al. 2015). All five planets are sub-Earth-sized with monotonically increasing radii as a function of orbital distance: 0.403 (Kepler-

444b), 0.497 (Kepler-444c), 0.530 (Kepler-444d), 0.546 (Kepler-444e), and 0.741 (Kepler-444f) Earth radii. Kepler-444c, d, and e are similar in size to Mars. Kepler-444f has a size intermediate to Mars and Venus. The system is highly compact, both in terms of its architecture and dynamically (see Fig. 2). All planets orbit the parent star in less than 10 days, or within 0.08 au. Moreover, adjacent planet pairs are close to being in strong 5:4, 4:3, 5:4, and 5:4 first-order, mean-motion resonances (as one moves away from the star).

Kepler-444 is in fact the primary (Kepler-444A) in a triple system (Campante et al. 2015; Dupuy et al. 2016), which also harbors a spatially unresolved pair of M dwarfs (Kepler-444B and C) at a projected distance of 1.8 arcsec (~ 66 au). Such configuration poses a challenge regarding the early evolution of the system (Dupuy et al. 2016; Papaloizou 2016), as planetary formation and

migration in a (likely) truncated protoplanetary disk are not yet fully understood.

Based on a transit-timing analysis, Mills and Fabrycky (2017) were able to determine the masses and densities of planets d and e (both with a composition consistent with that of the Solar System terrestrial planets or even of a pure water planet), placing upper limits on the properties of the remaining planets. Determining the planetary masses from radial velocities would be extremely challenging, the predicted semi-amplitude being ~ 0.3 m/s even with all five planets contributing. They infer from the mass ratio of planets d and e that the system experienced significant orbital period changes after a formation scenario involving migration, or else formed in situ.

Finally, observations in H γ Lyman- α made with the *Hubble* Space Telescope led to the detection of significant flux variations during the transits of Kepler-444e and f, as well as at times when no planets were transiting (Bourrier et al. 2017). If planetary in origin, this signal could be due to absorption by hydrogen exospheres trailing the two outermost planets. Both planets would then have to contain substantial amounts of water to replenish their atmospheres, making them bona fide waterworlds.

Cross-References

- [Abundances of Elements](#)
- [Astroseismology](#)
- [Dwarf Star](#)
- [Gaia Mission](#)
- [HST](#)
- [Kepler](#)
- [Kepler 11: Multiple Transiting Planet System](#)
- [Mean Motion Resonance](#)
- [Milky Way](#)
- [Ocean Planet](#)
- [Planet Detection: Transit Timing Variation](#)
- [Planetary Migration](#)
- [Terrestrial Planet](#)
- [Transiting Planets](#)

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Keplerian Orbits

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Definition

Johannes Kepler is famous for his three laws of orbital motion for the planets in the solar system. The first two were presented in his *Astronomia nova*. In essence, they state that planets move in elliptical orbits, sweeping out equal areas in equal times. The powerful third law surfaces in his *Harmonice Mundi*, where Kepler shows that the square of the planet's orbital period is proportional to the cube of the orbit's semimajor axis. Newton reformulated the problem in terms of masses and showed how the masses of the orbiting bodies enter into the third law. When objects follow Newton's formulation and move

in orbits that follow Kepler's laws, they are said to have Keplerian orbits.

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Kerogen

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Definition

The kerogen is the macromolecular organic matter that is insoluble in organic solvents (soluble portion is known as ► [bitumen](#)). Kerogen is present in ancient sedimentary rocks and meteorites. It is composed of smaller molecules that have covalently bound together during synthesis (including biosynthesis), diagenesis, and thermal alteration processes. In sediments, kerogen is the fossil organic matter source of oil and natural gas. The degree of hydrogen loss and aromatization is often used as an indicator of thermal maturity. The degree of structural order versus disorder for aromatic sheets is a defining characteristic of different kerogens identifiable by Raman spectroscopy. Organic-walled fossils resistant to acid maceration (such as acritarchs, spores) are observed in some kerogens.

Cross-References

- [Acid Maceration](#)
- [Bitumen](#)
- [Microfossils](#)
- [Microfossils, Analytical Techniques](#)

Kerogen-Like Matter

- [Insoluble Organic Matter](#)

Ketenyl Radical (HCCO)

Marcelino Agúndez
Instituto de Física Fundamental,
CSIC, Madrid, Spain

Synonyms

[Ethynyloxy](#)

Chemical Formula

HCCO

Definition

The ketenyl radical is a short-lived chemical species on Earth and an important intermediate in combustion chemistry and astrochemistry. Its rotational spectrum has been characterized in the laboratory, showing that it closely approximates a prolate symmetric top (Endo and Hirota [1987](#)). On Earth, the HCCO radical is produced during the oxidation of acetylene by the reaction between C_2H_2 and O (Peeters et al. [1994](#)), while in the interstellar medium, where it has been recently detected (Agúndez et al. [2015](#)), it is thought to be formed in the gas phase through the reaction between OH and C_2H (Wakelam et al. [2015](#)).

Cross-References

- [Acetylene \(\$C_2H_2\$ \)](#)
- [Combustion](#)
- [Earth](#)

- [Hydroxyl Radical \(OH\)](#)
- [Interstellar Medium](#)
- [Oxygen, Atomic](#)
- [Radical](#)
- [Spectroscopy, Rotational](#)

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Ketose

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A ketose is a monosaccharide ► [carbohydrate](#) containing a ketone group. The simplest ketose is dihydroxyacetone (DHA), which usually participates in biochemical processes as its phosphate ester. 2-Ketoses can isomerize into ► [aldoses](#) in water. Some biological ketoses of note besides DHA are sedoheptulose-7- phosphate, xylulose-5-phosphate, and ribulose-5-phosphate, which are important intermediates in the pentose phosphate cycle. DHA has been detected in extracts from Murchison meteorite.

Cross-References

- [Aldose](#)
- [Carbohydrate](#)
- [Dihydroxyacetone](#)

Kinetic Isotope Effect

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[Isotope effect](#); [Isotopic effect](#)

Definition

A kinetic isotope effect (*KIE*) is an effect observed due to differences in the chemical reaction rates of a molecule with a heavier isotope (k_H) relative to one containing a lighter isotope (k_L):

$$KIE = k_L/k_H.$$

Molecules with different isotopic compositions generally react with other molecules in the same manner, but their reaction rates show differences due to their mass differences and sometimes also due to the lower natural abundance of certain isotopes. For example, $^{13}C^{16}O_2$ is heavier than $^{12}C^{16}O_2$ by about 2.3%, and the abundance ratio of $^{13}C^{16}O_2/^{12}C^{16}O_2$ is about 1.1%. In photosynthesis by plants, the fixation rate of $^{13}C^{16}O_2$ is slower than that of $^{12}C^{16}O_2$, which causes a decrease of the $^{13}C/^{12}C$ ratio in biosynthesized glucose. Thus, the isotopic composition of natural samples is an important parameter in studying their origins. For example, the isotopic composition of organic carbon can be used to distinguish whether it is of abiological or biological origin, and even by which carbon fixation pathway it is derived.

Cross-References

- [Delta, Isotopic](#)
- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)
- [Isotope](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)

Klenow Fragment

- [DNA Polymerase](#)

Komatiite

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Keywords

Archean volcanic rock · Mantle temperature

Definition

Komatiite is a volcanic rock of ultramafic composition. It is distinguished from the more common basaltic magma by a higher content of MgO (>18%) and correlated low contents of most other elements.

Overview

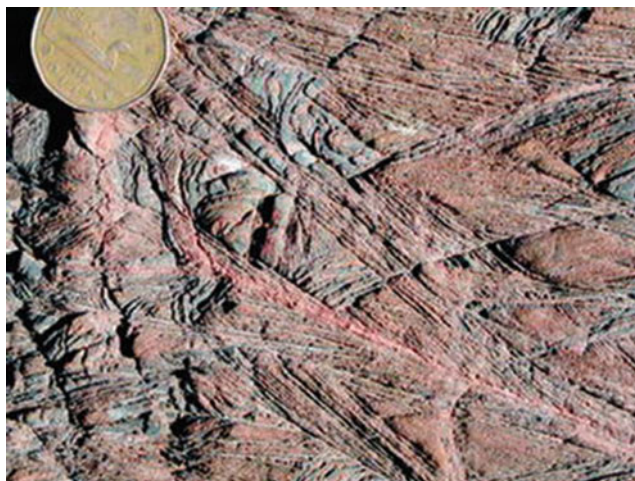
Komatiite is relatively common in Archean greenstone belts, rare in Proterozoic belts, and virtually absent in younger regions. The type area is the 3.5-Ga Barberton greenstone belt of South Africa where the rock type was first discovered; their name comes from this type locality: the Komati River in Kaapvaal Craton. Examples are now

known in most Archean ► [greenstone belts](#), and komatiitic ► [basalt](#), the fractionation product of komatiite, occurs in Proterozoic belts of northern Canada. The komatiites of Gorgona Island off the coast of Colombia are the sole well-documented examples of Phanerozoic komatiite. So far, the older komatiitic magma would be the 3.8 Ga-old parental magma of the Nuvvuagittuq sills (O'Neil et al. 2011). The komatiites, older than 3.4 Ga, have different chemical compositions from younger komatiites, being characterized by high CaO/Al₂O₃ and low Al₂O₃/TiO₂ (Sossi et al. 2016). Important ore deposits of Ni-Cu sulfides are found in komatiites in Australia and Canada. Komatiite normally erupts in subaqueous lava flows, differentiating into an upper layer with spinifex texture and a lower ► [olivine](#) cumulate layer. Spinifex texture, emblematic of komatiite, consists of large and elongated, up to several centimeters long, bladed, skeletal olivine crystals in a matrix of fine clinopyroxene and glass (Fig. 1). The texture forms during crystallization of hot lava in the steep thermal gradient within the upper part of the flow. The eruption temperature of komatiite can be estimated from the MgO content of the parent liquid (Campbell and Griffiths 2014): The maximum MgO content, inferred from examples in South Africa and Australia, is greater than 30%, which corresponds to a temperature higher than 1,670 °C (Wilson 2019), some 400 °C hotter than that of typical basalt.

Komatiite results from partial melting in unusually hot parts of mantle, most probably in mantle plumes. The abundance of komatiite in the Archean is a manifestation of high temperatures in the mantle at that time. On the other hand, the presence of diamond in Archean komatiites indicates that they derived from a high-pressure source (Capdevila et al. 1999; Cartigny 2010). The release of Ni from hydrothermally altered komatiite in the oceanic crust may have been important during the early evolution of ► [life](#). The decrease in the abundance of komatiite may have provoked a decline in the activity of methanogenic Archaea, which was linked to the rise of oxygen in the early Proterozoic.

Komatiite,

Fig. 1 Spinifex Texture in a komatiite sample from Munro, Canada. (Photo Nicholas Arndt). The characteristic bladed-shaped spinifex structure is made of olivine grains in a matrix of fine clinopyroxene and glass

**Cross-References**

- [Archean Environmental Conditions](#)
- [Archean Mantle](#)
- [Archean Tectonics](#)
- [Barberton Greenstone Belt](#)
- [Earth, Formation, and Early Evolution](#)
- [Mantle Plume, Planetary](#)

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Korarchaeota

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid,
Madrid, Spain

K

Definition

Korarchaeota has been incorporated into the TACK superphylum of Archaea. So far the members of this phylum have only been detected in hydrothermal environments. Korarchaeota were originally discovered by microbial community analysis of ribosomal RNA genes from environmental samples of a hot spring in Yellowstone, but recently they have been identified in other hydrothermal environments, like Kamchatka, Russia. No pure cultures from this phylum have been isolated yet. Methane metabolism genes have been identified in the genome of a stable enrichment mixed culture of Korarchaeota. The detection of methanogenesis in one of the most deeply rooted archaeal phyla supports the hypothesis that this metabolism was an early energy conservation system.

Cross-References

- [Archaea](#)
- [Hydrothermal Reaction](#)
- [Hyperthermophile](#)
- [Methanogenesis](#)
- [TACK, Archaea](#)
- [Yellowstone National Park, Natural Analogue Site](#)

Kozai Mechanism

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planetary dynamics, the Kozai mechanism is a coupling between ► [orbital](#) inclination and eccentricity that can drive large oscillations in both quantities. For low eccentricity and inclination, motion in the plane and out of the plane are independent, but if either value is large (especially if both are), angular momentum can be readily exchanged, and the two parameters could change significantly more than expected in the decoupled case. For example, one mechanism for exciting the eccentricity of a planet orbiting a star is perturbations from a binary stellar companion whose orbit is highly inclined with respect to the planet's orbital plane.

Cross-References

- [Orbit](#)

Krebs Cycle

- [Citric Acid Cycle](#)

Kreep

Daniele L. Pinti
Research Centre for the Dynamics of the Earth
System, Université du Québec à Montréal,
Montréal, QC, Canada

Keywords

Lunar basalts · Lunar highlands · Anorthosite ·
Lunar magma ocean · Potassium · Phosphate ·
REE · Thorium

Acronyms

KREEP K (potassium), rare-earth elements
(REE), and P (phosphorous)

Synonyms

[K, REE, and P-rich lunar material](#)

Definition

KREEP is a lunar rock having very high concentrations of incompatible elements. Its name is an acronym for the incompatible elements K (potassium), rare-earth elements (REE), and P (phosphorous).

Overview

Numerous samples of KREEP material were collected during Apollo 12, 14, 15, 16, and 17 missions, yet a few of them were pristine endogenous igneous rocks (the so-called KREEP basalts), the majority being polymictic breccia (Warren and Wasson 1979). Typical mineralogical modal composition of KREEP basalts is 86–98% of pyroxene and plagioclase, the remaining being often cristobalite (a high-temperature phase of quartz, SiO₂), ilmenite (FeTiO₃), minor phosphate, iron and sulfide, and groundmass (data from sample 14,276, Apollo 14; samples 15,382 and 153,866, Apollo 15). Typical concentrations of K₂O and

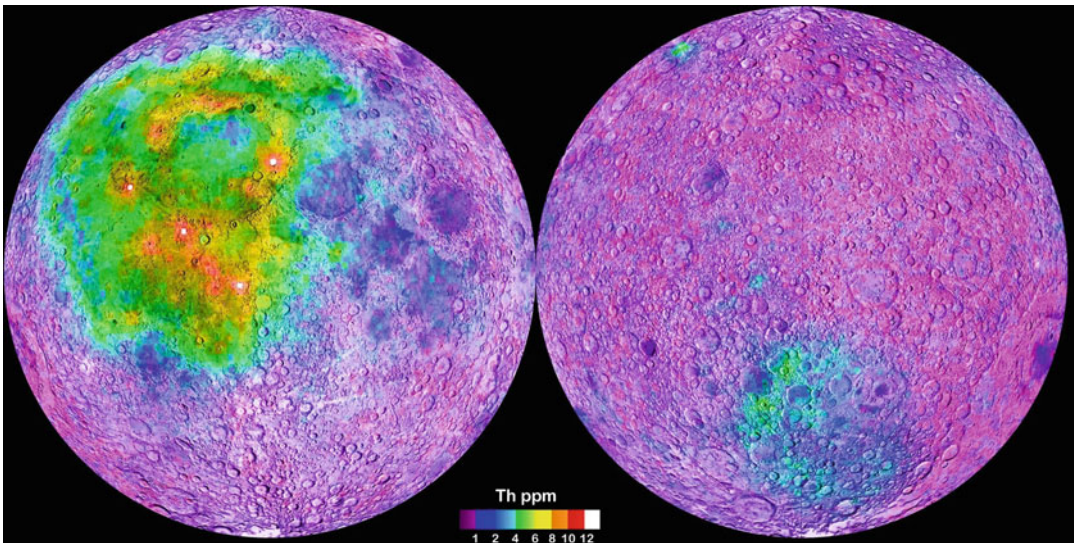
P_2O_5 are 0.5–1 wt%, while Rb has abundances of 12–25 ppm and Lanthanum up to 300 times the chondritic abundance, well above the abundances found in the anorthosites and gabbros of the lunar highlands and the mare basalts. Ages of the KREEP basalts are usually around 3.95 Ga, but Rb-Sr and Sm-Nd chronology of an Apollo 17 KREEP basalt gave even older 4.08–4.13 Ga ages (Shih et al. 1992) with model age for the source of the KREEP basalt at 4389 ± 45 Ma (Borg et al. 2015).

The origin of KREEP basalts is intrinsically related to the origin of the Moon itself. When the Mars-size protoplanet Theia hit the Earth and impact debris formed the Moon, the large amount of potential energy liberated was transformed into thermal energy which brought to the formation of a magma ocean (the Lunar Magma Ocean or LMO; e.g., Elkins-Tanton et al. 2011). As crystallization of the LMO proceeded, olivine and pyroxene precipitated and sank to form the lunar mantle. Less dense anorthositic plagioclase floated, forming an anorthositic crust. Residual melt was progressively enriched by incompatible elements (i.e., those that partition preferentially into the liquid phase) forming the “KREEP”-rich

layer ultimately trapped at the base of the anorthositic crust. Subsequent melting of this layer has produced KREEP-rich basalts.

The ubiquitous presence of KREEP samples in the diverse landing sites of the Apollo missions suggested that this KREEP material had been formed by melting of a widespread layer beneath the Moon’s crust. However, this assumption was denied by the results of the thorium mapping by the Lunar Prospector mission’s Gamma-Ray Spectrometer (GRS) (Fig. 1). Thorium is a high incompatible element and thus a good tracer of the incompatible element-rich material, such as KREEP. Results of the thorium distribution on the Moon showed that most of it is concentrated, for unknown reasons, underneath the *Oceanus Procellarum* and the *Mare Imbrium*. This is a unique lunar geological province that is now known as the *Procellarum KREEP Terrane* (Jolliff et al. 2000). These results casted doubts on the representativity of Moon petrology of the Apollo mission samples. To reconcile the ubiquitous presence of KREEP samples among the Apollo sites and the apparent localized magmatic source, it must be considered the fact that most of KREEP samples are polymictic breccia and thus

K



Kreep, Fig. 1 Thorium (Th) concentrations on the surface of the Moon as measured by the Gamma-Ray Spectrometer (GRS) embarked on the Lunar Prospector mission. Thorium correlates with the location of KREEP. (Credit NASA)

derived from large impacts that could have dispersed KREEP material very far, well beyond the original magmatic source region.

Cross-References

- [Anorthosite](#)
- [Breccia](#)
- [Moon, Origin of](#)
- [Moon, The](#)

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KT Boundary

Philippe Claeys
Earth System Science, Vrije Universiteit Brussel,
Brussels, Belgium

Synonyms

[Cretaceous/Paleogene \(KPg\)](#); [Cretaceous/Tertiary boundary \(KT\)](#); [K/T boundary](#)

Definition

The Cretaceous/Tertiary boundary (KT), also often called the Cretaceous/Paleogene (K/Pg) boundary, is a stratigraphic interval marking the

contact between the Mesozoic and Cenozoic eras, 66 Ma ago. The KT boundary is characterized by the last major mass extinction in the Earth history that saw the demise of the nonavian dinosaurs along with 50–60% of the Earth fauna and flora.

Overview

Over most of the Earth surface, this stratigraphic interval is composed of a mm- to cm-thick clay layer containing evidence of a large-scale asteroid or comet impact on Earth. The KT clays contain a significant enrichment in platinum group elements (Pt, Ir, Os, Rh, Ru, and Pd), better known as the KT iridium peak, amounting to several tens of ppb (parts per billion). This enrichment is clearly indicative of a meteoritic or extraterrestrial contribution to the sedimentation, being iridium rare on the Earth surface (about 1–2 ppb). Recently, the Ir positive anomaly was found also within the peak-ring sequence of the Chicxulub crater, drilled by IODP-ICDP in 2016 (Goderis et al. 2021). Other impact markers such as shocked quartz and zircon, indicative of the high pressures generated by the impact (> 5 GPa) as well as highly oxidized Ni-rich magnesioferrite spinels (often called cosmic spinels, which likely formed in the atmosphere, e.g., Toppani and Libourel 2003), also concentrate in the KT clay layer. This clay unit forms the distal ejecta material spread all over the Earth after the Chicxulub impact in the Yucatan Peninsula, Mexico. Closer to the impact site, around the Gulf of Mexico region, the KT boundary thickens to several meters of high-energy sediments. This proximal succession is composed at the base of glass spherules similar in composition to the Chicxulub impactites. This ejecta unit is followed by thick coarse sandstone units, most likely deposited by high-energy tsunami waves triggered by the cratering event. The Ir anomaly occurs just above the coarse sandstone, diluted by the high sediment input generated all over the Gulf region. In marine settings, the abruptness of the mass extinction is clearly visible in the microplankton that disappears precisely at the moment of deposition of the KT clay layer. The extinction of the

calcareous primary producers is widespread and affected the whole marine food chain. The decrease in microplankton was short lived and oceanic biologic productivity recovered after the KT boundary. The layer directly above the KT boundary is characterized by opportunistic organisms, before the recovery phase indicated by the appearance of new Paleogene species. On the continent, the extinction of diverse vegetation and the destruction of forest also coincide with the ejecta deposition. A fern-spore spike occurs at the boundary, illustrating the demise of the vegetation.

Cross-References

- [Chicxulub Crater](#)
- [Crater, Impact](#)
- [Ejecta](#)
- [Evolution, Biological](#)
- [Impactite](#)
- [Iridium](#)
- [Mass Extinctions](#)
- [Shocked Quartz](#)

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Kuiper Belt

Maria Antonietta Barucci¹ and Sonia Fornasier^{1,2}
¹LESIA, Observatoire de Paris, Université PSL, CNRS, Université de Paris, Meudon, France
²Institut Universitaire de France (IUF), Paris, Cedex 05, France

Keywords

Centaurs · Composition · Ices · Organics · Origin · Planetesimals · Transneptunian objects · Volatiles

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Definition

The Kuiper Belt is the region in the solar system beyond the orbit of Neptune that contains bodies rich in volatiles orbiting the Sun, also known as transneptunians.

Overview

In the last decades, the outer solar system has been found to be densely populated by a multitude of icy bodies called Kuiper Belt objects, Edgeworth-Kuiper objects, or transneptunian objects. The discovery of these bodies revolutionized our understanding of the solar system and most ideas relative to the evolution of the protoplanetary nebula. The general interest in the outer solar system grew rapidly in the scientific community. In fact, these bodies located so far from the Sun are considered as the fossils of the protoplanetary disk, which, consequently, can provide important information on the processes that dominated the evolution of the early solar nebula as well as of other planetary systems around young stars.

Transneptunian objects (TNOs) as well as asteroids and comets can be considered as the building blocks (planetesimals) of the solar system, offering clues to the composition of the matter from which planets formed some 4.6 billion years ago. The investigation of the physical properties of these icy bodies, as remnants of the outermost planetesimal swarms, is essential to understanding the formation and the evolution of the whole population of solar system bodies.

TNO science has rapidly evolved in recent years, linking together different research areas. The attempt to know this population's properties and history is one of the most active research fields in planetary science.

The first transneptunian object to be discovered was Pluto by Clyde Tombaugh in 1930 (later numbered 134,340; see numbering convention described below). This discovery confirmed early ideas concerning the existence of solar system objects beyond the orbit of Neptune. In fact just a few months after Pluto's discovery, Frederick Leonard (1930) wrote in a popular article:

Now that a body of the evident dimensions and mass of Pluto has been revealed, is there any reason to suppose that there are not other, probably similarly constituted, members revolving around the Sun outside the orbit of Neptune?... As a matter of fact, astronomers have recognized for more than a century that this system is composed successively of the families of the terrestrial planets, the minor planets, and the giant planets. Is it not likely that in Pluto there has come to light the first of a series of ultra-Neptunian bodies, the remaining members of which still await discovery but which are destined eventually to be detected?

Later on, in the years 1943 and 1950, Kenneth Edgeworth and Gerard Kuiper hypothesized the existence of small bodies beyond Neptune and Pluto. A more conclusive study by Fernández and Ip in 1982 argued for the existence of a source of short-period comets close to the ecliptic plane and beyond the known planetary orbits.

Even if many researchers hypothesized the existence of such a population, only after more than 60 years, in 1992, did Jewitt and Luu discovered a second transneptunian object 1992 QB₁ (now numbered 15,760; Jewitt and Luu 1993), if we do not take into consideration the discovery of

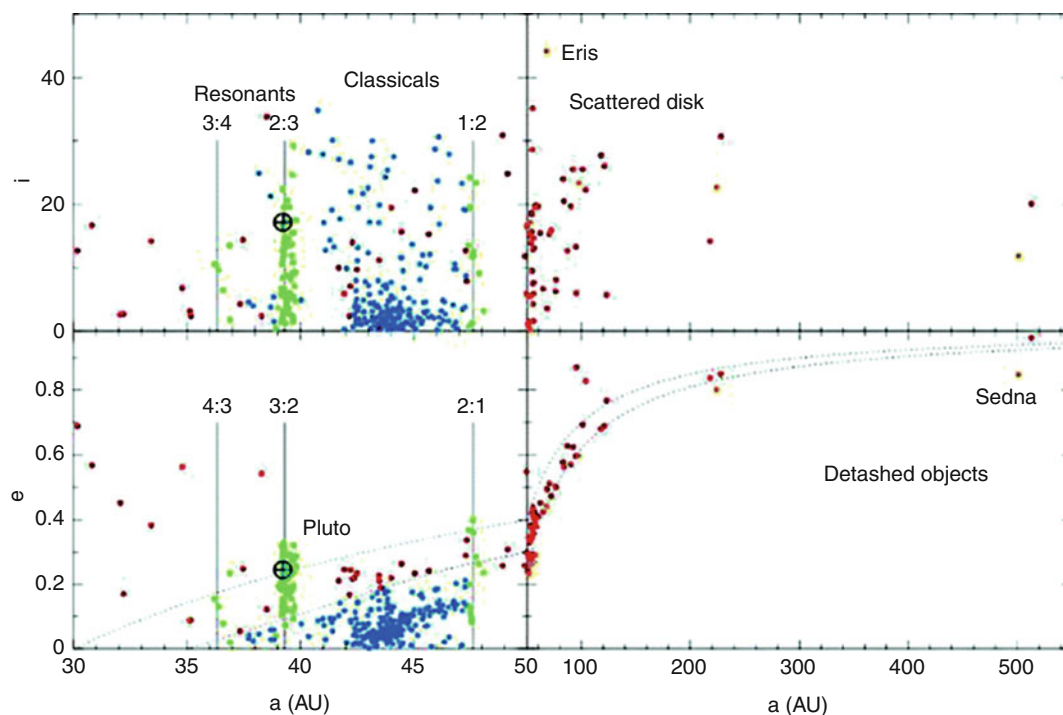
Pluto's moon Charon in 1978 (because at that time, it was considered a satellite of the ninth planet). This was an epochal astronomical discovery and within 2–3 years more than 100 distant objects were discovered. Determining their orbits was in general difficult because of their faintness and the necessity to observe them for several months. After discovery, these objects receive a provisional designation as asteroids (year of discovery followed by letters and number for the order of discovery). Only when the orbit is well known, do they receive a number and a name. As activity is not visible during the discovery and observations, their number follows the order number of asteroids rather than comets.

More than 3000 transneptunian objects with well-constrained orbits are known up to date, showing a variety of sizes, orbits, and surface characteristics. Because of their distance and their faintness, some transneptunians were lost after discovery. Satellites have been detected for a large fraction of these objects using optical methods of high-resolution imaging. Most of these satellites have been found with the Hubble Space Telescope (Noll et al. 2008; Grundy et al. 2011). Recently, stellar occultations by Centaurs and TNOs permit the discovery of the first ring systems not circling a giant planet: a double ring around the Centaur Chariklo (Braga-Ribas et al. 2014), a single ring around the dwarf planet Haumea (Ortiz et al. 2017), and rings are suspected on other bodies (Ortiz et al. 2015).

The largest TNOs, Pluto, Eris, Makemake and Haumea, have been classified as dwarf planets by the International Astronomical Union in 2006.

Dynamical Classification

The population has been classified (Gladman et al. 2008) into several groups, following their distance from the Sun and their orbital characteristics: (1) classical objects, (2) resonant objects, (3) scattered disk, and (4) detached objects (Fig. 1). The first two groups are also known as the Kuiper Belt, containing objects with an average distance from the Sun between 30 and 55 AU with almost circular orbits and small inclinations.



Kuiper Belt, Fig. 1 The diagram illustrates the distribution of transneptunian objects (resonant, classical, scattered disk, and detached objects) at different semimajor axes (a), eccentricities (e), and inclinations (i). (Provided by A. Morbidelli)

Resonant objects are trapped in mean-motion resonances with Neptune and that dynamical configuration provides them a dynamical stability. Although more than 20 resonances exist, the 3:2 mean-motion resonance with Neptune ($a = 39.4$ AU), which hosts Pluto, is the most densely populated, and objects trapped into this resonance are called plutinos. The origin of these resonant objects is closely related to Neptune's migration: indeed, while Neptune was migrating outward, objects that followed the outward migration of Neptune were swept and captured in a mean-motion resonance.

Classical objects are those having a low eccentricity and moderate inclination. Several authors refer to two distinct populations in the classical belt based on orbital inclination: dynamically "hot" (high inclination, $>5^\circ$) objects and dynamically "cold" (low inclination, $<5^\circ$) objects. Numerical simulation by Gomez (2003) showed that the hot population could find its origin in the migration of Neptune, which scattered the

planetesimals originally formed inside about 30 AU. The current classical belt would hence be the superposition of these bodies with the local population (cold objects), believed to have formed in situ beyond 30 AU. The so-called Kuiper Belt has a characteristic edge at about 48 AU, near the location of the 2:1 mean-motion resonance. It is not clear how this edge formed and if it is real (or due to an observational bias effect). The position of this edge might depend on Neptune's migration (Levinson and Morbidelli 2003) or a close stellar passage as suggested by Ida et al. (2000).

Scattered disk objects (SDOs) or scattered objects are considered those that have orbits with large eccentricities and perihelion distances near Neptune's location. Several objects previously classified as SDOs are in fact resonant. The majority of SDOs have unstable orbits and are perturbed by the close encounters with Neptune, but some might have survived since the origin of the solar system (Duncan and Levison 1997). Part of them

might have been injected in their present orbits from other regions by perturbation produced by stars passing nearby our solar system (Levinson and Morbidelli 2003) or by sweeping resonances during the planetary migration phases (Malhotra 1995).

Detached objects are those with orbits having large eccentricities ($e > 0.24$) and with large perihelion distances out of Neptune's influence. They have very long lifetimes under the influence of other planetary perturbations. Their origin is not well understood and several scenarios exist to explain their formation. The best example of this category is (90377) Sedna, which has a semimajor axis of 501 AU, with perihelion and aphelion distances at 76 and 927 AU, respectively. The most distant TNO known today is 2017 MB₇ with perihelion at 4.46 AU and aphelion at 2906 AU. It is probable that many more distant objects are waiting to be discovered. A large population in the distant region is predicted, but no surveys for fainter objects have yet succeeded in detecting such distant objects.

During the planetary migration in our solar system, most of the mass of the Kuiper belt was lost, and part of the bodies ejected outside feeding the Oort cloud. Later, the migration of bodies in the opposite direction, that is, from the Oort cloud to the Kuiper belt region, could have taken place because of the gravitational perturbations produced by supernovae explosion, galactic tide, or nearby passing stars.

Another group of objects with similar physical characteristics is called *Centaurs*, which orbit in the region between Jupiter and Neptune and interact strongly with all the giant planets. Planetary perturbations and mutual collisions in the Kuiper Belt are probably responsible for the ejection of objects onto Centaur orbits. Because Centaurs cross the orbits of the outer planets, they are dynamically unstable with a short lifetime (10^6 – 10^7 years), after which they can be ejected from the solar system, impact the giant planets, or evolve into Jupiter-family ► [comets](#) (JFCs) or near-Earth objects (NEOs). Centaurs are widely believed to come from the transneptunian region and to be scattered into their present orbits by gravitational instabilities and

collisions. Hence, like the transneptunian objects, Centaurs accreted at low temperature and large solar distances and must still contain a relatively pristine material.

Basic Methodology

The availability of very large telescopes, both ground based (≥ 8 m) and orbiting the Earth (Hubble, Spitzer, and Herschel), has enabled observational studies of the physical properties of a significant number of objects, but the physical properties of smaller transneptunian objects remain still poorly known. Obtaining this information for the whole population is still a big challenge. In situ observations by the NASA New-Horizon mission permitted a detailed investigation of the dwarf planet Pluto and of its satellite system, and the first study of a relatively small sized TNO, Arrokoth.

The diameter of the TNOs can be estimated from their absolute magnitude, but only if their albedo is known, which can be determined when both the reflected light and the thermal radiation at long wavelengths are measured (the so-called radiometric technique). These objects are very cold (30–50 K); their thermal radiation is very weak because of their distance from the Sun, and their blackbody peak is near 70–100 μm , that is in a wavelength region not easily accessible from ground-based observatories because of the telluric atmosphere's low transmission. Therefore, observations from space telescopes are required to study the size of this population at a statistically significant level. In the past 15 years, the Spitzer, WISE, and Herschel infrared space telescopes permitted a big step forward in the determination of the transneptunian population size, albedo, and thermal properties. The Spitzer Space Telescope has been used to observe approximately 50 Centaurs and transneptunian objects (Stansberry et al. 2008), and using both thermal emission and ground-based measurements of the visible radiation, their dimensions have been determined with a precision of 10–20%. Wise observed about 50 Centaurs and SDO. Finally Herschel, whose instruments cover the peak of the TNOs thermal

emission, investigated 170 TNOs and Centaurs (Müller et al. 2020).

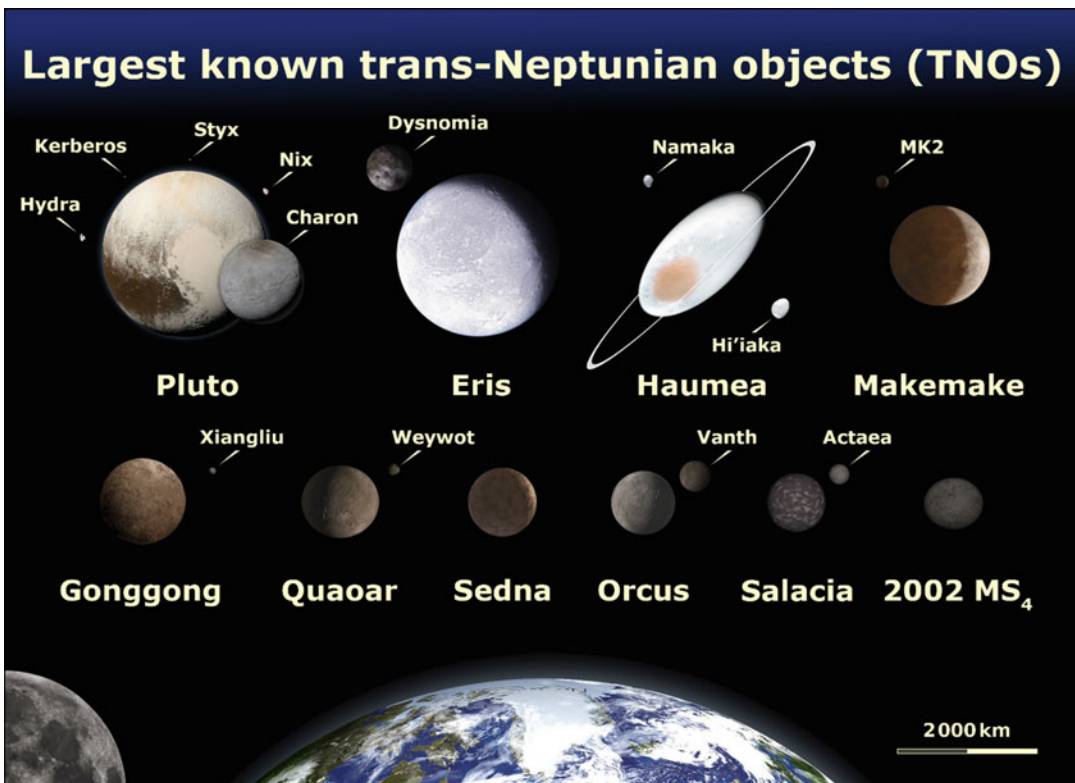
The most striking observation is the huge variation of the albedo value across the TNO population, which includes both extremely dark surfaces with geometric albedo of 2–3% and high reflective bodies reaching an albedo of 96% in the case of Eris. Very high albedo are however unusual and associated to few TNOs, including the volatile-rich dwarf planets and the members of Haumea family, all showing at their surfaces exposures of water ice. Excluding these peculiar bodies, the TNOs surfaces are quite dark with an average albedo of $9.9 \pm 0.5\%$.

The size of known TNOs ranges from a few tenths of km to 2376 km for the dwarf planet Pluto. An observational bias affects the smaller TNOs, because their detection and precise characterization is extremely challenging. The smallest TNOs measured is Arrokoth, flew-by in

2019 by the New-Horizon mission, a contact binary object having an equivalent diameter of 18 km (Stern et al. 2018). The largest TNOs is Pluto, followed by Eris which is very similar in size (2326 km), Haumea (elongated body with equivalent diameter of 1595 km), Makemake (1440 km), GongGong (1230 km) and ~1000 km bodies like Quaoar, Orcus, Sedna, and Salacia (see Fig. 2, and Barucci et al. 2021).

Besides radiometry, diameters can be measured very precisely by the stellar occultation technique, measuring the duration of a star flux occultation when a TNO or a Centaur pass in front of it. This technique allowed the precise size estimation for about 15 TNOs and Centaurs, and the discovery of ring systems around Haumea and Chariklo. This technique is powerful but limited by the fact that it requires high accuracy both in the TNOs ephemeris and in the stellar catalogs.

K



Kuiper Belt, Fig. 2 Picture of the biggest transneptunian objects that are reported in scale with their estimated sizes, satellites, and rings. (© NASA Courtesy)

The TNOs’ density can be estimated only when satellites are detected, and consequently, the mass of the primary is available. When the orbital period and distance of the satellites can be determined, the mass of the primary body can be calculated from Kepler’s third law, and the mass of the satellite can also be estimated from the magnitude of the systems’ components. The mean density reflects the internal composition, particularly the relative fraction of ices, silicates, and metals, as well as the internal structure. Density has been computed for 25 binary systems, and it spans a wide range, from ~ 0.3 to nearly 2.5 g/cm^3 .

Most of the TNOs smaller than 400 km have density less than 1 g cm^{-3} , implying a small rock to ice ratio and a high porosity to varying degrees. The lowest measured density ($\sim 0.3 \text{ g cm}^{-3}$) is for Altjira and Typhon, implying that about 50–70% of the interior of these bodies consists of void space. TNOs larger than ~ 750 km in diameter have density greater than 1 g/cm^3 indicating a larger rock to ice ratio and/or less porosity. The highest density has been measured for the dwarf planet Eris (2.5 g/cm^3 , Sicardy et al. 2011), followed by Pluto, Haumea, and Makemake (density of $1.7\text{--}1.85 \text{ g/cm}^3$), suggesting a large rock to ice ratio for the dwarf planets. Table 1 shows some physical characteristics of these objects.

The current uncertainty in the size distribution of the TNOs does not allow us to define the total mass of the population. Current estimation ranges from 0.01 to a few times $0.1 M_{\text{solar}}$.

A TNO’s rotational period can be determined by measuring its light curve. The few dozen known rotational periods span from a few hours to several days with a peak around 7.7 h, which appears to be significantly slower than the main-belt asteroids of similar size. From the rotational properties, it is also possible to extract information on the collisional history, since the current spin properties are supposed to have been strongly affected by the mutual collisions experienced by these bodies. On the basis of considerations of the rotational stability, the density can be also constrained. Assuming that the amplitudes of the observed light curve are due to the body’s shape, with negligible albedo variations on the surface, an estimation of a lower limit to the axis ratio a/b on the hypothesis of an ellipsoid shape can be also deduced. Smaller objects appear to be more elongated.

The statistics on binary TNOs can provide models of their formation. Angular moment and relative sizes of most binaries are consistent with formation by dynamical capture. The small satellites of the largest objects, in contrast, more likely result from collisions. More than 70 trans-neptunian binaries are known, but triple or multiple systems have also been detected.

Kuiper Belt, Table 1 Properties of the largest TNOs

	Pluto	Eris	Makemake	Haumea	Sedna	Quaoar	Orcus
Diameter (km)	2376 ± 2	2326 ± 12	1440 ± 9	1595 ± 11	995 ± 80	1110 ± 5	958 ± 23
a (AU)	39.4	67.9	45.4	43.1	491	43.7	39.1
e	0.25	0.43	0.16	0.19	0.84	0.04	0.23
i (deg)	17.1	44.0	29.0	28.2	11.9	8.00	20.6
H	−0.45	−1.1	−0.13	0.25	1.57	2.5	2.3
Surface ices	CH ₄ + N ₂ + CO	CH ₄ +?	CH ₄ + C ₂ H ₆	H ₂ O	CH ₄ + N ₂ +?	H ₂ O + C ₂ H ₆ +?	H ₂ O +?
Albedo (%)	52^{+14}_{-3}	96 ± 4	77 ± 2	51 ± 2	32 ± 6	11 ± 1	23 ± 2
Mass (10^{20} kg)	130.3 ± 0.3	167 ± 2	26 ± 5	40.0 ± 0.4	—	14 ± 2	6.4 ± 0.1
Density g cm^{-3}	1.85 ± 0.01	2.5 ± 0.7	1.7 ± 0.4	1.76 ± 0.08	—	1.99 ± 0.46	1.53 ± 0.12

Composition

While spectroscopy provides more details for surface composition investigation, photometry has been the most extensively used technique to explore the surface properties of these remote objects, since most TNOs are extremely faint. Many different photometric observational campaigns have been performed, particularly in the visible region, which provided data for a large number of objects.

About 200 objects have been observed with photometric surveys, revealing surprising color diversity; the TNOs exhibit a large range of surface optical colors. A large number of transneptunian objects have surface colors much redder than any other solar system bodies. Statistical analyses have been used in researching a wide range of possible correlations between optical colors and orbital parameters. The visible and near-infrared color correlation indicates that a single coloring agent is responsible for the wavelength dependence. In particular, there is a well-confirmed correlation (Doressoundiram et al. 2008) between color and orbit inclination. Highly inclined classical objects have diverse colors ranging from gray to red and have large sizes, while low-inclination classical objects are generally smaller and mostly very red. This cluster of “cold” (low-eccentricity, low-inclination) classical objects composed of smaller sizes is supposed to be primordial.

Results on the photometry of binary TNOs observed with the Hubble Space Telescope demonstrate a very strong correlation between primary and satellite colors, concluding that the colors of binaries as a group are indistinguishable from that of the larger population of apparently single transneptunian objects. The color of binaries or single objects is one characteristic signature of surface compositional differences set in the solar nebula.

Multicolor broadband photometry can provide only limited constraints on the surface composition of the population. In fact, colors can be influenced not only by composition, but also by scattering effects in particulate regolith and by viewing geometry. Colors cannot, in general, be used to determine composition, but they can be

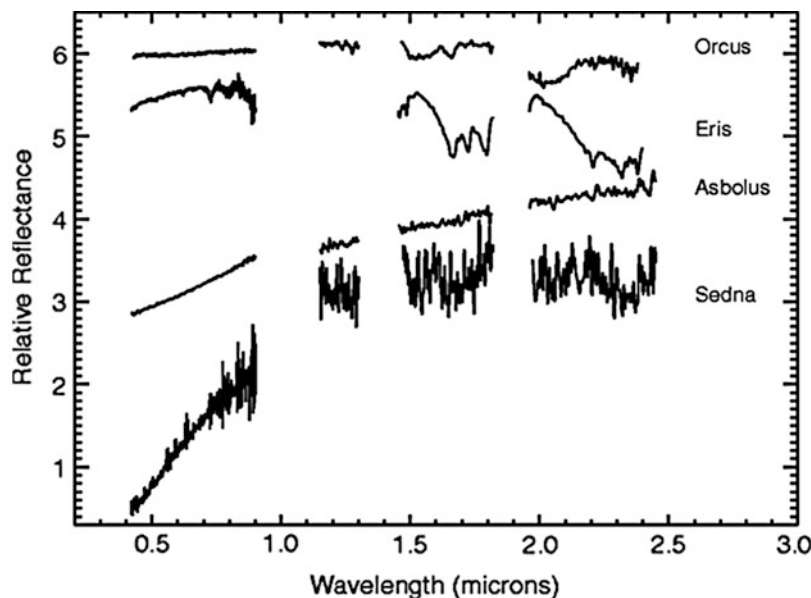
used to classify objects into groups. A taxonomy based on color indices (B-V, V-R, V-I, V-J, V-H, and V-K) has been obtained (Barucci et al. 2005) identifying four groups of objects with homogeneous color content: BB, BR, IR, and RR. The group BB contains objects with neutral colors and RR those with very red colors (the reddest among the solar system objects), while the two others have an intermediate behavior. The physical significance of color diversity is still unclear, though it is reasonable to assume that the different colors reflect intrinsically different compositions or compositions that differ due to different evolutionary histories. The trend from neutral (BB) to very red (RR) groups indicates the possible sequence of alteration processes (collisions, resurfacing, craters, UV and/or energetic particle bombardment, etc.), and each group could represent an evolutionary stage of the population, and its number density gives an indication of the duration of each phase representing the effects of different alteration processes. Cosmic-ray bombardment will be the cause for an exposed surface to become redder, and impacts excavating “fresh material” will cause differently colored surfaces. These as well as other evolutionary processes (e.g., outgassing, surface gardening, atmospheric interaction, etc.) can also account for the observed differences.

The Centaurs seem to have a different distribution of colors. The available data suggest that the Centaurs’ colors may have a bimodal distribution, while the TNOs do not. This has been explained by past or present sublimation activity. In fact, when these objects pass closer to the Sun, they can develop an active coma.

The most detailed information on composition can be acquired only from spectroscopic observations, especially covering the wavelength range between 0.4 and 2.4 μm . This wavelength range provides the most sensitive technique to characterize from the ground the major mineral phases and ices present on transneptunian objects (Fig. 3). Silicate minerals like feldspar, carbonaceous assemblages, organics, and water-bearing minerals have diagnostic spectral features in the visible and near-infrared spectral regions. In the near-infrared region, there are also signatures

Kuiper Belt,

Fig. 3 Visible and near-infrared spectra of some TNOs (Sedna, Eris, and Orcus) and a Centaur Asbolus. The four objects have spectra with different behaviors (from flat to very red spectra), different absorption bands, and different signal-to-noise ratios



from ices and hydrocarbons. Weakly active Centaurs or TNOs could also show fluorescent gaseous emission bands.

Most of the known transneptunian objects are too faint for spectroscopic observations, even with the world's largest telescopes, and so far, only the brightest bodies have been observed by spectroscopy. The exposure time required is generally long, and as the objects rotate around their principal axis, the resulting spectra often contain information coming from both sides of the object.

Visible spectra are mostly featureless, showing large variations of the spectral slope, thus confirming the wide range of colors from neutral to very red. The visible wavelength is important to constrain models and to infer information on the composition, particularly for the ultrared objects. The ultrared slope is assumed to indicate the presence of organic material on the surface, as in the case of the Centaurs Nessus and Pholus (the reddest objects known up to now). A few objects show signatures which are very similar to those due to water-altered minerals found in some main-belt asteroids and meteorites (Barucci et al. 2008a). How an aqueous alteration process could have occurred at such low temperatures far from the Sun is not yet well understood, but it

cannot be excluded that hydrated minerals could have been formed directly in the early solar nebula; in fact, hydrous silicates have been detected in interplanetary dust particles (IDPs) and in [micrometeorites](#).

The near infrared (1–2.4 μm wavelength) is the most diagnostic region to determine the presence of ices. Signatures of water ice, methane, and methanol can be easily detected if the spectra are of good quality. In a few cases, some data at longer wavelengths have been obtained with the far-IR space telescope Spitzer. To investigate the composition, radiative transfer models have been used to interpret the features and the spectral behavior using intimate or geographical mixtures of organics, silicate minerals, carbonaceous assemblages, ices, and/or hydrocarbons. The red slopes are in general well reproduced supposing the presence of organic compounds on the surface like kerogen (complex dark organic compound) and tholins (synthetic macromolecules produced by irradiation of gaseous mixtures).

The results given by the spectral modeling have to be considered as only indicative. In fact, much of the information obtained from spectral modeling is nonunique, especially if the necessary constraints are not well established ([albedo](#), signatures with high-sensitivity detections of

fainter components, etc.). The details on fractional coverage of different materials and even the presence of these materials are easily influenced by choices of model parameters. Nevertheless, the modeling can be used to pick out broad variations in TNO spectra.

Key Research Findings

In recent years, about 80 objects including Centaurs have been spectroscopically observed and analyzed. Following their spectral characterization, four principal groups can be identified.

Water Ice Group

Water ice should be the main component of transneptunian objects, and many have spectra showing moderate to deep absorptions due to water ice. Most spectra with high signal-to-noise (S/N) show the presence of a feature at 1.65 μm characteristics of crystalline water ice. It is still a matter of debate whether water ice was amorphous or crystalline in the protosolar nebula. While crystalline water ice is neither expected at these low temperatures nor should be stable against cosmic-ray and UV bombardment, crystalline water ice appears to be ubiquitous in the outer solar system, from the icy satellites of the giant planets to TNOs. The presence of crystalline water ice implies that ice has been heated to temperatures above 100/110 K. This heating could have occurred by impacts or generated in the deep interiors and the ice then been emplaced onto the surface. The quality of most spectra is too poor to distinguish between amorphous or crystalline water ice. Nonetheless, when trying to model the spectra, the best fit model is usually obtained when using a combination of the two water ice states.

Methane Group

The largest TNOs – Eris, Pluto, Sedna, and Makemake – display spectra dominated by methane absorption, some objects showing spectra of methane dissolved in nitrogen. Pluto and probably Sedna and Eris share these properties, together with Neptune's satellite Triton (supposed to be a

transneptunian object captured by Neptune). Methane is present in these large objects because their gravity is high enough to retain such a volatile component, but in smaller quantity, methane may be present also on smaller objects. A small amount of ethane (by-product of methane ice irradiation) has also been detected on Quaoar.

Methanol Group

Some objects – Pholus (55638) 2002 VE₉₅ and possibly Bienor – show spectra with methanol. Many objects have a low signal-to-noise ratio, especially in the near-infrared region around 2.2 μm , but many objects show a decreasing slope after 2.2 μm implying a possible presence of methanol or similar organic molecules.

Featureless Spectra Group

Many objects have featureless spectra in the near infrared, with a wide range of colors. Obviously, many spectra are featureless when observed at low S/N, but many have sufficient S/N spectra to rule out the signature due to water ice. These objects could be mantled by a surface rich in organics or carbon. As all these objects are supposed to be composed of ices, irradiation processes have to be responsible for these properties. Laboratory experiments have showed that irradiated ices become redder with increasing irradiation. Molecules progressively lose their hydrogen atoms, which results in a polymerization of the surface layer and the formation of a crust.

Ammonia or ammonia hydrate has been detected in the spectra of a few objects (Charon, Orcus). A firm detection of ammonia would have important implications on the composition of the primitive solar nebula in the region at low density, far from the Sun.

The Largest Objects

The dynamical and physical characteristics of the largest transneptunian objects are summarized in Table 1.

Pluto

Pluto is the largest transneptunian extensively investigated from ground-based telescope and

in situ thanks to New-Horizon mission. In fact, its high albedo and its position at perihelion make it the brightest object of the transneptunian population, and for this reason, it was the first discovered and has been heavily observed. Its surface shows both compositional heterogeneity and geological diversity (Stern et al. 2018), including smooth volatile-rich planitia, craters, troughs, and scarps produced by extensional tectonics, polygonal networks associated to convection cells, and mountains as high as 6 km supported by a water ice bedrock. Pluto retains an atmosphere mainly composed of N_2 , with lesser amounts of CH_4 and CO , and showing seasonal variations.

Pluto composition is dominated by methane, nitrogen, and lesser amounts of CO ice and minor hydrocarbon species. The methane is present in both pure and diluted states, and ethane is also present in its surface together with relatively dark and spectrally red regions with featureless spectra. These last reddish units may be the product of the irradiation of ices native to Pluto's surface, or generated from cryovolcanic activity, or result from the deposition of the atmospheric haze over geological timescales. The New-Horizon mission revealed that Pluto has been and still is geologically active, and its internal structure should be differentiated including a rocky core, an icy mantle, and a crust dominated by volatile material, which may survive as ice due to the low temperature, ranging between 30 and 60 K.

Pluto is surrounded by five known satellites (Charon, Styx, Nix, Kerberos, and Hydra). The formation of these satellites could be as a consequence of a grazing collision between the proto-Pluto and Charon. Charon is the biggest with a diameter of 1212 km and its mass is about a tenth of that of Pluto. It is not massive enough to retain an atmosphere. Its surface shows compositional variations and, conversely to the methane-rich Pluto, it is dominated by water ice. The lack of craters on its surface suggests that it may have been geologically active. The other satellites of Pluto are relatively small, with size ranging from 10 to 12 km for Styx and Kerberos, to about 36 km for Nix and Hydra (Stern et al. 2018).

Eris

Eris has a highly eccentric orbit, with a perihelion at 38.4 AU, typical for scattered objects, and an aphelion at 97.5 AU. Its orbital period is about 560 years. It is the most massive object $((1.67 \pm 0.02) \times 10^{22} \text{ kg})$ of the TNO population and it has one known satellite, Dysnomia, that is 500 times fainter than Eris. The spectrum is very similar to that of Pluto even if the visible part is less red than that of Pluto. No variation has been seen on Eris to an upper limit of 0.05 mag. The visible and near-infrared spectra are dominated by absorption from methane. As shown by Merlin et al. (2009), the near-infrared spectrum shows no evidence for shifts of the methane absorption wavelength, while the visible part of the spectrum shows small shifts, implying that methane is dissolved in nitrogen. These observations suggest a stratification, with a layer of diluted methane ice between two layers of pure methane ice. The possibility to have depleted nitrogen in the deepest layers after sublimation processes that enrich adjacent layers during condensation processes can be also suggested. Eris seems to be covered by more pure methane ice than Pluto and Triton. The amount of nitrogen on Eris' surface is probably smaller and less important than on the surfaces of the latter objects. The high albedo and the lack of rotation are consistent with a surface dominated by seasonal atmospheric cycling.

Makemake

Makemake belongs to the classical population. It has an orbital period of nearly 306 years, more than Pluto's 248 years and Haumea's 283 years. It is the brightest TNO after Pluto and has a surface dominated by methane. The methane absorption features on its surface spectrum are deeper and broader than those on the other objects. A signature of ethane is also present. Ethane is one of the expected products from dissociation of both gaseous and solid-state methane. For its known characteristics, Makemake can be a transition between the larger-surface-volatile-rich objects and the smaller-surface-volatile-depleted objects.

A relatively large satellite of about 260 km in size was discovered orbiting around Makemake, permitting to reconcile discrepancy in the thermal fluxes recorded by Spitzer and Herschel space observations.

Haumea

(136108) Haumea is a unique dwarf planet boasting a system of satellites, rings, and a family of objects all with almost pure water ice surfaces. Haumea has a typical orbit for the classical dynamical group, with an orbital period of 283 years and a perihelion at 35 AU. It has an unusual light curve, with large amplitude and small rotational period (3.92 h) implying an ellipsoid shape. Star occultation by Haumea permits to determine its size and its very elongated shape and to discover a ring of about 70 km width located 2300 km from the center of the dwarf planet (Ortiz et al., 2017). Haumea is very elongated, its shape corresponds to a $2320 \text{ km} \times 1705 \text{ km} \times 1025 \text{ km}$ ellipsoid. Its equivalent diameter, that is that of a sphere having the same volume, is 1595 km. The near-infrared spectroscopy reveals the deepest water ice absorption found in these objects, with surface composition similar to the surface of Pluto's moon Charon. Its characteristics and those of its two satellites (Namaka and Hi'iake) all point to a collisional origin for the system (Brown et al. 2007). A large near-infrared survey showed that a number of TNOs having deep water ice absorption are all dynamically clustered near the dynamical position of Haumea, representing a dynamical family. It is probable that the objects of this family, the first family detected in the TNO population, are the collisional fragments of a giant impact on the proto-Haumea.

Sedna

Sedna is one of the most remote objects with a perihelion distance at 76 AU, an aphelion distance at 927 AU, and an orbital period of about 11,000 years. It is also one of the reddest trans-neptunian objects known. Methane and possibly nitrogen seem to be present on the surface of this object, and a similarity with Triton has been proposed, which could indicate that these two objects

originated in the same zone. This would better account for the origin of Sedna and would support a capture hypothesis for Triton. During its perihelion passage, Sedna may have a temporary N_2 atmosphere whose properties depend upon the rotational period.

Quaoar

Quaoar is a 1000 km size body belonging to the classical dynamical group. The rotational period is approximately 8.84 h, and it has one known satellite (Weywot, about 80 km in size). The best compositional model obtained so far (Barucci et al. 2015) reported a surface made of crystalline water ice, methane, as well as ethane, nitrogen, organic materials, and possibly ammonia water. The presence of high volatile material such as ammonia water and nitrogen suggests that the surface of Quaoar may be relatively young and shaped by an efficient renewal mechanism.

Orcus

Orcus is in the 3:2 resonance with Neptune with an orbit similarly to that of Pluto. It is a 1000 km size body. A relatively big satellite (diameter of $276 \pm 17 \text{ km}$) has been discovered and named Vanth. The derived density is $1.53 \pm 0.15 \text{ g cm}^{-3}$ (Fornasier et al. 2013), the lowest known value among the large TNOs listed above. A possible rotational period of about 10 h has been estimated. Crystalline water ice and possibly ammonia (Barucci et al. 2008b) have been found on its surface from spectroscopic observations. The existence of such ices may indicate a renewal mechanism on the surface such as geological activity.

Physical Processes

The TNO population is considered to contain the most pristine objects in the solar system, but over the 4.5 Gy of the solar system life, they have experienced various modifying processes.

The structure and the chemistry of the surface of these objects are affected by bombardment by cosmic ray and solar wind ions and/or micrometeorites, with the result that the molecular complexes are structurally changed and the molecular

compositions of ice and minerals are altered over time. Laboratory experiments on a variety of appropriate materials irradiated by energetic particles, simulating the space environment, show molecular transformation that leads to the production of different components. Energetic particles dissipate their energy in a complicated cascade of interactions that results in the production of molecules that were not present in the initial composition. Laboratory experiment shows the formation of an irradiation mantle, breaking bonds in the ice molecules to allow the formation of radicals, leading to the escape of hydrogen and the formation of a carbon-rich layer with low albedo. This can easily mask the presence of volatiles. The depth to which material can be damaged is a function of the particle energy.

Hudson et al. (2008) reported the estimation of the irradiation at different distances from the Sun. TNOs orbiting in the classical belt (40–50 AU) received lower irradiation than those orbiting beyond the terminator shock (beyond about 85 AU); the latter have upper layers more deeply affected by irradiation-induced chemistry, forming a crust rich in carbon. The formed crust hides the real composition of these objects, and complex organic materials called “tholins” (produced by spark discharge in low-pressure gases) or “kerogen” (found in terrestrial oil shales) are often used as analogues for interpreting the spectra of the surface.

It is clear that collisions have played an important role in the evolution of this population. The consequence of collisions is not only the alteration of the surface properties but also the modification of the internal structure of the targets. Collisions are relevant to both small and large objects. One example is Charon, a moon of Pluto, but completely different in composition from Pluto; it has been modeled to have formed from a disk of debris ejected during the collision of Pluto with a body of almost equal size, in a process similar to that of the formation of Earth’s Moon. It has been suggested that the collisional family associated with Haumea originated from a parent body having a high-density rocky core and a low-density icy mantle that suffered a giant collision, ejecting a large fraction of its mantle into space. In fact, some objects with similar spectral characteristics

(deep H₂O ice band and neutral color) have been identified to be clustered around Haumea.

The internal structure of TNOs can also display a great diversity. The detection of crystalline H₂O ice or ammonia ice on the surfaces raises the question of internal activity. Laboratory experiments on water ice irradiation at the same conditions as TNOs indicate that crystalline water ice on the surface should be completely amorphized by irradiation in about 10⁷ years; in fact, crystalline water ice is neither expected at these very low temperatures nor should be stable against cosmic-ray and UV bombardment. Both internal (cryovolcanism) and external (micrometeoritic or larger impacts) surface renewal mechanisms have been considered to account for the presence of crystalline water on the surface of these objects, even if the understanding of the physics of the crystalline/amorphous phase transition is not clear. Laboratory experiments show the same behavior for the ammonia hydrates, which are easily destroyed by energetic radiation.

Studies of the early evolution of transneptunian objects concluded that some bodies (depending on the orbit and size) should have lost all volatile ices, such as water ice crystallized because of the heat generated by accretion, short-lived radiogenic elements, and differentiation (McKinnon et al. 2008). The presence of some ices on the large TNOs indicates that other mechanisms (not only space weathering and collisions) could be the cause of the surface properties. Some internal geological activities, for example, have been proposed as explanation for the surface characteristics of Orcus and Quaoar.

Models of the interiors of TNOs show that cryovolcanism, which is considered the most probable mechanism to explain geological activity on some satellites of the outer planets, may be possible on the bigger transneptunian objects (diameter >1000 km). Outgassing from the interior is another important evolution process not only because of the high volatile content but also due to the possible high porosity of these objects. In fact, the porosity can increase the conductivity of volatiles to the surface and the size of the reservoir that supports the escaping atmosphere or coma. The high albedos and the detection of

volatiles on the surfaces on some transneptunians suggest a possible presence of an atmosphere, even as a transient phenomenon. Pluto has a seasonal atmosphere. The requirement for atmospheric formation on these low-gravity objects requires the presence of gases or sublimating/evaporating materials on the surface, and this implies a resupply mechanism such as internal activity or impactors. The detection of surface volatiles and high albedos on some TNOs thus indicates the possible existence of at least transient (e.g., seasonal) atmospheres on some of these objects. The definitive evidence for atmospheres can only come from occultations or direct spectroscopic detection with spacecraft.

Future Directions

Many ongoing and future surveys [the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST)] are and will cover the transneptunian region, allowing the discovery of many more objects, with orbital and physical characterization. The population of small and very faint objects can be discovered only through occultations of background objects; in fact, this method could investigate down to the sub kilometer-sized population of the TNO size distribution, as well as the outer region of the Kuiper Belt. This technique can be applied to many new objects thanks to the high precision stellar catalogues produced by GAIA mission. Stellar occultations observed from the ground will be also the most powerful tool available to determine the shape, size, and the presence of an atmosphere for the larger objects with well-known precise orbits. In the future, 30–40 m size telescopes like the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the Extremely Large Telescope (ELT) will allow a better characterization of many of these objects, extending the investigation also toward fainter TNOs. Finally, the James Webb Space Telescope, expected to be launched in 2021, will permit a big step forward in the characterization of the surface properties of these distant solar system objects.

Cross-References

- ▶ [Centaurs \(Asteroids\)](#)
- ▶ [Cryovolcanism](#)
- ▶ [Lightcurve](#)
- ▶ [Mean Motion Resonance](#)
- ▶ [Near-Earth Objects](#)
- ▶ [Planetary Migration](#)
- ▶ [Planetesimals](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Solar Nebula](#)
- ▶ [Tholins](#)
- ▶ [Trans-Neptunian Object](#)

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Kuiper Belt Object

► [Trans-Neptunian Object](#)

L

L-Amino Acids

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

L-amino acids are the only enantiomer of the amino acids with a chiral carbon atom encoded by genetic molecules into the proteins of terrestrial organisms. There are some D-amino acids found in the proteins of living organisms, but these are added by post-translational modification reactions or incorporated through nonribosomal synthesis.

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Enantiomers](#)
- [Homochirality](#)
- [Isomer](#)
- [Ribosome](#)

L1544

Charlotte Vastel
Institut pour la Recherche en Astrophysique et
Planétologie, Toulouse, France

Keywords

Chemistry · Molecules · Interstellar medium ·
Complex organic species · IRAM telescopes ·
Herschel Space Observatory

Definition

L1544 is a prototypical prestellar core which represents the earliest phase in the process of star and planet formation. This core is relatively isolated in the Taurus molecular complex (distance ~ 140 parsecs, coordinates: $\text{ra}(2000) = 05^{\text{h}} 04^{\text{m}} 17.21^{\text{s}}$, $\text{dec}(2000) = +25^{\circ} 10' 42.8''$) and has been extensively observed by single-dish and interferometer spectroscopy. L1544 is characterized by a low temperature ($T \sim 7$ K) and high density ($n(\text{H}_2) > 10^6 \text{ cm}^{-3}$) in its center. The temperature increases and the density decreases as a function of radius. L1544 is contracting making it the perfect example of the evolution of a starless core towards the protostar phase.

Overview

Soon after the discovery of radio emission from interstellar molecules, L1544 was recognized as a strong source of line emission and absorption (Dieter 1973; Minn and Greenberg 1973; Cheung et al. 1973), and since then, it has been a target for the search for rare molecular species. Beichman et al. (1986) did not find any infrared IRAS point source associated with L1544 that fulfils their ► [protostar](#) selection criteria and categorized this core as “starless.” L1544 has then been classified as a prestellar core, which is a subset of starless cores that are gravitationally bound and hence expected to participate in the star-formation process (Ward-Thompson et al. 1994). Detailed studies of the L1544 prototypical prestellar core have found central temperatures of only 7 K (Crapsi et al. 2007). An extreme molecular deuteration is a major characteristic of pre-stellar cores where ► [Carbon Monoxide](#) (CO) is depleted from the gas phase which leads to the preferential reactions between the H_3^+ ion with HD, feeding the ► [deuterium](#) of the latter ion, and distributing deuterium in the gas-phase and on the grain surfaces. A high deuterium fractionation has been detected in L1544 (e.g., Caselli et al. 1999; Crapsi et al. 2005; Bizzocchi et al. 2014) in which H_2D^+ has been detected (Caselli et al. 2003). The central 7000 au is called the deuteration zone, where the freeze-out of abundant neutrals such as CO and O, the main destruction partners of the H_3^+ isotopologues, favor the formation of deuterated molecules. The outer ring (7000–30,000 au) is called the dark-cloud zone (Caselli and Ceccarelli 2012), where carbon is mostly locked in CO, gas-phase chemistry is regulated by ion-molecule reactions and deuterium fractionation is reduced.

The ► [Herschel-HIFI](#) instrument detected for the first time ► [water](#) in a prestellar core (Caselli et al. 2012) with an inverse P-Cygni profile, characteristic of gravitational contraction in the inner regions.

Maps at the IRAM-30m telescope revealed a chemical differentiation in this core. For example ► [methanol](#) (CH_3OH) shows an asymmetric

structure (Bizzocchi et al. 2014) in the northern part of the core, consistent with central depletion (CH_3OH is produced on the surface of ► [dust grains](#) by successive hydrogenation of CO). On the contrary, the $\text{c-C}_3\text{H}_2$ distribution peaks in the southern part of the core, where photochemistry maintains more C atoms in the gas phase (Spezzano et al. 2016). Several ► [complex organic molecules](#) (COMs) (e.g., acetaldehyde, dimethyl ether, formic acid, and methyl formate, propyne) have been detected at the dust peak (Vastel et al. 2014) and methanol peak (Jiménez-Serra et al. 2016), likely related to methanol, as well as CH_3O , a possible product of methanol photodissociation (Bertin et al. 2016). A nonthermal desorption mechanism is possibly responsible for the observed emission of methanol and COMs from the external layer of the core. Many species (CH_2CN , HCNH^+ and HC_3NH^+) have recently been detected for the first time in a prestellar core (Vastel et al. 2015; Quénard et al. 2017) and an extensive study has been performed (Vastel et al. 2018) on the sulfur chemistry. Sulfur is likely depleted in the cold and dense phases of the interstellar medium, although there is no strong evidence of sulfur in the observations of the ice mantles so far.

The large-scale properties of the L1544 cloud have been studied in CO (Tafalla et al. 1998) and shows that L1544 is part of an elongated filament. More recently, the large-scale Herschel dust continuum map shows the interaction between two almost perpendicular ► [Interstellar Filaments](#), with the L1544 methanol peak found at the intersection (Punanova et al. 2018).

Cross-References

- [Carbon Monoxide](#)
- [Complex Organic Molecules](#)
- [Deuterium](#)
- [Dust Grain](#)
- [Gas-Grain Chemistry](#)
- [Herschel Mission](#)
- [Interstellar Filaments](#)
- [Methanol](#)

- [Molecular Depletion](#)
- [Molecules in Space](#)
- [Protostars](#)
- [Radiative Transfer](#)
- [Radio Astronomy](#)
- [Water](#)

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Lab on a Chip

- [Biosensor](#)

Laboratoire Interuniversitaire des Systèmes Atmosphériques

- [LISA](#)

Laboratory Astrophysics, General Definition of

Ludovic Biennier¹ and Karine Demyk²

¹Institut de Physique de Rennes, UMR CNRS 6251, Université de Rennes 1, Rennes Cedex, France

²Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, Toulouse Cedex 4, France

Keywords

Laboratory experiments · Theoretical calculations · Astronomical observations · Space missions

Definition

Laboratory astrophysics is a multidisciplinary field that explores astrophysical phenomena and supports the interpretation of astronomical observations, solar-system in situ measurements, and extraterrestrial sample analysis through the use of laboratory experiments, theoretical calculations, and numerical simulations. Laboratory astrophysics provides fundamental data for the modeling of astrophysical and planetary environments and processes.

Overview

Primarily driven by ground-based observations, space missions, and meteoritic material studies, the research areas covered include atomic and

molecular astrophysics, physics and chemistry of condensed matter, plasma astrophysics, fluid dynamics, and nuclear and particle astrophysics. The tools range from quantum chemical calculations, to large-scale facilities such as synchrotrons, ion accelerators, and ultrahigh-intensity lasers. Laboratory astrophysics relies on the collaboration of experts from many fields: astronomers, physicists, chemists, geophysicists... (Savin et al. 2012).

In the context of astrobiology, one of the first aims of laboratory astrophysics is to understand the nature, origin, evolution, and fate of cosmic matter – dust, ice, and molecules – observed in space, in environments often characterized by harsh physical conditions and submitted to strong UV irradiation, cosmic rays, impact of electrons, or shock waves (Sandford et al. 2020). Despite these extreme conditions, a very rich chemistry is observed in interstellar clouds leading to a high molecular complexity. Emission or absorption spectroscopic studies of solids and molecules (from the X-ray to the millimeter domain) play a key role in the identification of the various components. They are complemented by in-depth investigation of gas-phase mechanisms, solid-state chemistry, and gas/solid interactions at the molecular level. The understanding of the physical and chemical processes at play requires the development of state-of-the-art laboratory experiments (dedicated ultrahigh vacuum chambers, low-temperature flow reactors, excitation sources...) to identify precise reaction pathways, determine branching into various reaction exit channels, measure quantitative reaction kinetics, or photo-processing cross sections. Some of these devices are installed on large infrastructures such as heavy ion accelerators or synchrotrons.

One of the major issues is to understand how the molecular complexity reached in the ISM is transmitted along the lifecycle of astronomical objects from interstellar clouds to new stars, protoplanetary disks and possibly inherited by planetary bodies and comets (Ceccarelli et al. 2017; Öberg et al. 2021). In that endeavor, the analysis of primitive meteoritic and cometary materials, as well as of samples from return-

missions, is pivotal. Dedicated analytical platforms (spectroscopy, microscopy, nanoscale secondary ion mass spectrometry, mass spectrometry, chromatography...) are crucial to characterize the soluble and insoluble organic matter and the mineral phase, to investigate the chirality of the molecular components, or to study isotopic fractionation, shedding some light on the interstellar chemical cycle and on the formation of the Solar System (Nittler and Ciesla 2016). These studies are also supported by comparison with laboratory analogues of dust grains and ices. The analysis of planetary samples benefits also from laboratory simulation reaction chambers, in particular for planetary or satellite atmospheres.

With the discovery of thousands of exoplanets, the question of the emergence of life and of the conditions of its apparition has come back to the frontline. Progress in this quest requires spectroscopic characterization of the atmosphere of the exoplanets (gas composition, vertical structure, presence of clouds/haze) as well as their host stars (stellar opacities) and relies heavily on laboratory data, theoretical calculations, and atmospheric photochemical modeling (Madhusudhan 2019). The determination of the internal structure of the exoplanet is also important to shed light onto the interaction between the atmosphere and the surface.

Concomitantly, a better understanding of the primitive Earth is essential to establish the physicochemical conditions for the emergence of life – element availability, water temperature, pH, ionic strength, energy, irradiation, gradients, and molecular diffusion – and identify the more adapted natural settings ranging from submarine hydrothermal vents to volcanic pools (Westall et al. 2018). Experiments also explore the role of exogenous matter in the emergence of life and allow us to better define the range of conditions in which this process could take place. The advent of biochemical systems likely does not solely result from more complex or diverse chemistry but from a specific organization that is self-sustaining and able to replicate itself; this remains to be demonstrated in the laboratory.

Laboratory astrophysics is a vibrant field of research shaped to open perspectives in related disciplines.

Cross-References

- [Absorption Spectroscopy](#)
- [Chromatography](#)
- [Flow Reactor](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Microbiology](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Interstellar Medium](#)
- [Mass Spectrometry](#)
- [Synchrotron Accelerator](#)

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Laboratory Characterization of Meteorites

Hassan Sabbah

Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse (UPS), CNRS, CNES, Toulouse Cedex 4, France

Definition

Laboratory characterization of meteorites refers to the in-depth investigation of their physical and chemical features using analytical techniques. Based on their petrological characteristics, bulk chemical composition, and oxygen-isotope composition, meteorites are classified into recognized groups. Investigations of primitive meteorite and their components (chondrules, refractory inclusions, and matrix) have increased our understanding of the early solar system and its evolution. Characterization of presolar grains found in meteorites helped scientists in constraining models of nucleosynthesis in red giant stars and supernova. Investigating organic compounds in meteorites aims to understand the role of meteorites in delivering to Earth the components necessary for life.

Cross-References

- [Earth](#)
- [Meteorites](#)
- [Red Giant](#)
- [Solar System](#)

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Laboratory Dust Analogs

Karine Demyk

Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, 9 Av. du Colonel Roche, 31028 Toulouse Cedex 4, France

Definition

Laboratory dust analogs are materials aiming at imitating cosmic materials to interpret astronomical observations. They may be natural samples but are in most cases synthesized by various techniques aiming at reproducing the main physical and chemical properties of cosmic matter inferred from observations: composition, structure, and size. Cosmic materials collected from Space or on Earth being very rare, analogs of silicate, oxide, carbon-based dust and ices are used in experiments simulating the evolution of cosmic dust in astronomical environments (e.g., photons and cosmic rays irradiations, shocks, gas-grain interaction).

Cross-References

- [Circumstellar Disk](#)
- [Dust Grain](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Star Dust](#)

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Laboratory Ice Spectroscopy

- [Interstellar Ice Spectroscopy Experiments](#)

Labyrinthus, Labyrinthi

Ernst Hauber

Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Definition

A complex of intersecting valleys or ridges (definition by the International Astronomical Union; <http://planetarynames.wr.usgs.gov/jsp/append5.jsp>). It is used as a descriptor term for naming surface features on ► [Venus](#) and ► [Mars](#).

Cross-References

- [Mars](#)
- [Venus](#)

Lactic Acid

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

Lactic acid is an organic chemical compound that plays a role in several biochemical processes. It was first isolated in 1780 by the Swedish chemist Scheele. It is a carboxylic acid with the chemical

formula $\text{CH}_3\text{CH}(\text{OH COOH})$. It has a hydroxyl group adjacent to the carboxyl group, making it an α -hydroxy acid. Lactic acid is chiral and has two optical isomers. One is known as L-(+) or (S)-lactic acid, and the other, its mirror image, is D-(-) or (R)- lactic acid. L-(+)-Lactic acid is the biologically important isomer. In biochemistry, L-lactate is produced via reduction of pyruvate in a process of fermentation or anaerobic respiration. Lactic acid can also be derived from the deamination of alanine.

Cross-References

- [Chirality](#)
- [Hydroxy Acid](#)

Lacus

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Synonyms

[Lake](#)

Definition

The term lacus (lake) refers to a number of small low-► [albedo](#) plains on the ► [Moon](#) and ► [Titan](#) and also to one on ► [Mars](#). Lacus features usually exhibit a well-pronounced and sharp boundary and have a size of 100–200 km in diameter. While on the Moon lacus are associated with Mare features and caused by basaltic flood volcanism, lacus on Titan refers to small dark areas possibly associated with liquid ► [hydrocarbons](#).

Cross-References

- [Albedo](#)
- [Hydrocarbons](#)

- [Mare, Maria](#)
- [Mars](#)
- [Moon, the](#)
- [Oceanus, Oceani](#)
- [Palus, Paludes](#)
- [Titan](#)

Ladder of Nature

- [Great Chain of Being](#)

Lagrange Points

- [Lagrangian Points](#)

Lagrangian Point Objects

- [Trojans \(Asteroids\)](#)

Lagrangian Points

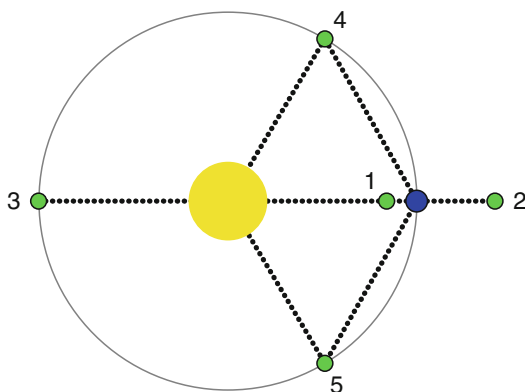
Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Synonyms

[Lagrange points](#)

Definition

The Lagrangian points are five points in the orbital plane of two gravitationally bound bodies, where a small mass stays in equilibrium with respect to the other two, that is, remains at constant distances relative to them, despite the orbital movement. They are named after the Italian-French mathematician Joseph-Louis Lagrange who discovered



Lagrangian Points, Fig. 1 This cartoon locates the five Lagrange points in a two-massive body system

those five specific points while he reformulated the Newtonian mechanics. Three of the points, called L1, L2, and L3, are located on the line joining the two massive bodies, one is inside the segment joining the two bodies and the other two are outside. The two last Lagrangian points, L4 and L5, lie symmetrically on each side of this segment, each at the top of an equilateral triangle built on the two main bodies (see Fig. 1); these two locations are stable, that is, if the small mass at L4 or L5 is slightly displaced, it will be pulled back. In astronautics, Lagrange points L1 and L2 of the Sun-Earth system are of peculiar importance because they are locations where a spacecraft can be sent and maintained, far from the disturbing environment of Earth, but staying close enough for communication. Several space observatories have already been put at L2. Celestial objects are also found at Lagrange points, that is, the case of the Trojan asteroids at L4 and L5 of the Sun-Jupiter system.

Cross-References

- [Gravitation](#)
- [Trojans \(Asteroids\)](#)

Lake

- [Lacus](#)

Lamarck's Conception of Origins of Life

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes,
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Nantes, France

History

The French naturalist Jean-Baptiste de Monet, Chevalier de Lamarck (1744–1829) suggested an evolutionary theory in 1802, which was later called transformism. In this theory, he claimed that species changed and produced series. Transformations appeared when the environment and the habits acted on organisms for a long time.

In his theory, Lamarck gave a very important place to spontaneous generations. Indeed, for him, they were at the beginning of the series, and furthermore, describing them, I gave a short model of his theory.

Lamarck claimed that gelatinous matter could receive the “vital orgasm,” a sort of agitation of molecules opposed to universal attraction. “Uncontainable” fluids, caloric and electricity, could provoke this “vital orgasm.” Later, the containable fluids, gases and liquids, especially water, crossed this matter and deposited particles. This process was the beginning of nutrition. Lamarck considered that this steep of transformation corresponded to the structure of the simplest “polyp,” a monad just capable of elasticity. The continuous flow of water, always passing the same way, produced a little tunnel, the first digestive tube.

Two points have to be underlined. Firstly, in his description of the spontaneous generation process, Lamarck summarized how all the principal causes of transformism act on matter and produce changes in species. Secondly, Lamarck's theory on spontaneous generations currently exists in nature, and therefore vegetal and animal series are continuously beginning.

However, if Lamarck spoke of permanent spontaneous generation, he did not really deal with the primordial origin of life, which was difficult to conceive in the context of his theory and

especially regarding his own chemical conceptions, according to which all the matter on Earth was combined by living beings.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [Spontaneous Generation, History of](#)

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Laminated Microbial Ecosystems

- [Microbial Mats](#)

Landing Site

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

A landing site is the planned, designated, or reached location on a ► [planet](#), ► [moon \(satellite\)](#), ► [asteroid](#), or ► [comet](#) to host a landing probe, be it a hard landing (impact probe) or a soft landing.

Cross-References

- [Asteroid](#)
- [Comet](#)
- [Planet](#)
- [Satellite or Moon](#)

Landmass Accretion

- [Accretion](#)

Landslide (Mars)

Alessandro Airo
Institut für Geologische Wissenschaften Tektonik
und Sedimentäre Geologie, Freie Universität
Berlin, Fachbereich Geowissenschaften, Berlin,
Germany

Definition

The main occurrence of landslide deposits on Mars are found within the Valles Marineris canyon system, where about 50 prominent landslides have been identified that originated from the canyon walls leaving behind curved scars cut into the canyon rim. The ages of landslide deposits in the Valles Marineris canyon system range from 3.5 Ga to as little as 50 Ma, implying that the triggering mechanism is ongoing and that the process of mass wasting is based on a non-changing flow rheology (Quantin et al. [2004a](#)).

If the mass wasting processes at Valles Marineris were supported by gas, fluids, or a basal lubrication remains debated. The geometric relation between run-out distance and landslide volume suggest predominantly dry mass wasting conditions (Soukhovitskaya and Manga [2006](#)), while the geometric relation between run-out distance and vertical drop imply a high mobility of the landslides and therefore indicate a fluidization process facilitated by the presence of a gas or a liquid (Quantin et al. [2004b](#)). The later mechanism is supported by dynamic model simulations showing that the landslide geometry matches best if a small fraction of liquid or gas is present (Harrison and Grimm [2003](#)). Others have argued that the great mobility of the landslides has been due to basal lubrication by subsurface ice or evaporites (De Blasio [2011a](#)).

The aureole deposits at the lower flanks of Olympus Mons may also represent landslide

deposits, however slower processes such as gravity spreading may have caused their formation. With a run-out distance of up to 700 km and a volume of almost one million cubic kilometers these are likely the largest landslide remnants in the solar system. Numerical studies suggest their extremely long run-out distance only to be possible through lubrication by water or ice, which might indicate the former presence of a northern ocean (De Blasio 2011b).

Cross-References

- [Dark Streaks \(Mars\)](#)
- [Slope Lineae, Recurrent](#)
- [Slope Streaks \(Mars\)](#)

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Langevin Rate Coefficient

Steven B. Charnley
Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Langevin value](#)

Definition

The Langevin rate coefficient is the theoretical ► [reaction rate coefficient](#) for an ion-molecule process, calculated classically (i.e., neglecting quantum-mechanical effects), assuming that reaction occurs upon every collision. The basic principle is that the ion induces a dipole in the (nonpolar) molecule; the theory does not work well for the interaction of an ion and a ► [polar molecule](#).

Cross-References

- [Interstellar Chemical Processes](#)
- [Ion-Neutral Reaction](#)
- [Reaction Rate Coefficient](#)

Langevin Value

- [Langevin Rate Coefficient](#)

Langmuir-Hinshelwood Mechanism

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Definition

This is a theoretical model of bimolecular chemical reactions on solid surfaces in which two atoms or molecules are adsorbed on the surface and at least one diffuses on the surface until both are close enough to interact. In the interstellar medium, the formation of molecular hydrogen is thought to occur primarily through reactions on the surfaces of dust grains (See Wakelam et al. 2017).

Cross-References

- [Adsorption](#)
- [Eley-Rideal Mechanism](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)

References

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Lanthanides

- [Rare Earth Elements](#)

Laplace Resonance

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

The Laplace resonance among orbiting bodies is a series of two consecutive 2:1 ► [mean motion resonances](#), making a 4:2:1 period ratio among the three bodies. Among Jupiter’s Galilean satellites, Io, Europa, and Ganymede are in the Laplace resonance. This commensurability was first pointed out by Pierre-Simon Laplace and now bears his name. This interaction prevents the orbits of the satellites from becoming perfectly circular due to tidal interactions with Jupiter and therefore permits tidal heating of Io and Europa. Three of the extrasolar planets orbiting the star Gliese 876 are also in a Laplace resonance.

Cross-References

- [Mean Motion Resonance](#)
- [Orbit](#)

Large Ice-Cap Instability

- [Snowball Earth](#)

Large Millimeter Telescope

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[LMT](#)

Definition

The Large Millimeter Telescope/Gran Telescopio Milimétrico “Alfonso Serrano” (LMT) is a 50 m diameter single-dish radio telescope optimized for astronomical observations at millimeter wavelengths ($0.85 \text{ mm} < \lambda < 4 \text{ mm}$). The project is a binational collaboration between Mexico and the USA, led in Mexico by the Instituto Nacional de Astrofísica, Óptica y Electrónica and in the USA by the University of Massachusetts, Amherst. The LMT is an open-air telescope at an altitude of 4600 m on a mountain in the Mexican state of Puebla (latitude about +19°). The LMT began scientific observations with the inner 32 m of the dish in 2013; the full 50-m diameter surface was completed in 2018, making the LMT the most sensitive single-dish radio telescope in the world operating at millimeter wavelengths. It has already shown that it is an important link in millimeter-wavelength ► [VLBI](#) experiments.

Cross-References

► [Radio Astronomy](#)

Larson's Law

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

Larson's law is an empirical relationship, discovered by Richard Larson in 1981, between the size of a ► [molecular cloud](#) and its internal velocity dispersion. Larson found that the average velocity dispersion within a cloud is proportional to its size raised to a power n . This relation holds for clouds ranging in size from about 0.1 to 100 parsecs. Subsequent studies have confirmed the law, with n currently measured as 0.5. The theoretical basis of Larson's law is still not understood. The existence of this relationship may signify that the diffuse gas spawning molecular clouds is dominated by turbulent motion. Dense cores, the clouds that form individual stars, have sizes in the order 0.1 parsec and have internal velocities that do not obey the law.

Cross-References

► [Fragmentation of Interstellar Clouds](#)
► [Molecular Cloud](#)

Last Common Ancestor

► [Last Universal Common Ancestor](#)

Last Universal Ancestor

► [Last Universal Common Ancestor](#)

Last Universal Common Ancestor

Luis Delaye
Departamento de Ingeniería Genética,
CINVESTAV-Irapuato, Irapuato, Mexico

Keywords

Comparative genomics · Early cellular evolution · Lateral gene transfer · Secondary gene losses · Tree of life

Synonyms

[Cenancestor](#); [Last common ancestor](#); [Last universal ancestor](#); [LCA](#); [LUCA](#)

Definition

The last universal common ancestor (LUCA) or cenancestor is the most recent ancestor from which all currently living species have evolved.

Overview

The idea that all life is related by common ancestry can be traced back to the publication of *The Origin of Species* by Charles Darwin (1872), where he wrote in the last chapter of his book, "...I should infer from analogy that probably all the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed." However, it was not until the second half of the twentieth century, with the analysis of molecular sequences, that the modern discussion of the nature of the last universal common ancestor (LUCA or cenancestor) began.

Initially, Woese and Fox (1977a) suggested that the ancestor of ► [Bacteria](#) and ► [Eukarya](#) (the main lines of descent known at that time) was a *progenote*, i.e., a primitive entity with an imprecise relationship between ► [genotype](#) and

► [phenotype](#). Later on, the use of a small subunit of the rRNA molecule as a phylogenetic marker led to the discovery of ► [Archaea](#) as a third line of descent. Accordingly, the definition of the progenote was extended to include the three cellular domains (Bacteria, Archaea, and Eukarya), and by 1977, Woese and Fox suggested that the three domains evolved independently from the progenote.

This picture of the last universal ancestor began to change when Gogarten et al. (1989) and Iwabe et al. (1989) used ► [paralogous genes](#) to find the root of the universal tree of life. Both analyses showed that the root of the universal tree was placed in the branch leading to Bacteria, suggesting a bacterial-like universal ancestor. This picture was reinforced by a compilation of shared traits among the three cellular domains that indicated that the last ► [common ancestor](#) was already a complex organism more similar to present-day bacteria than to progenotes (Lazcano et al. 1992).

Then, the first comparative genome analysis led to a controversy that continues to be unsolved today. In an attempt to identify the minimum gene set required for cellular life, Mushegian and Koonin (1996) compared the ► [genomes](#) of *Haemophilus influenzae* and *Mycoplasma genitalium*. The inferred minimum gene set contained 256 genes, most of them showing eukaryotic and archaeal homologues. Among the exceptions were seven key proteins involved in DNA replication, including the replicative DNA polymerase. Bacteria uses one kind of DNA polymerase while Archaea and Eukarya use another. This observation led to the proposal that the last universal common ancestor had an RNA genome (Mushegian and Koonin 1996) and that DNA evolved independently, twice (Leipe et al. 1999). Clearly, this proposal differs from previous suggestions of a more bacterial-like LUCA (Lazcano et al. 1992). The proposal that the cenancestor had an RNA genome was contested by Becerra et al. (1997), arguing that caution should be taken in backtracking characteristics of the cenancestor when only complete ► [genomes](#) from parasitic organisms are taken into account, because those genomes are prone to secondary gene loss.

However, the lack of homology between the Bacterial and Archaeal/Eukaryal replicative DNA polymerases continues to fuel the debate.

A new twist on the reconstruction of the coding capacities of LUCA came from the analysis of complete genome sequences. A pattern emerged as more genomes became fully sequenced from different lineages of the tree of life. A large number of phylogenies derived from universally conserved genes didn't reflect the canonical division of Archaea, Bacteria, and Eukarya. This led to the suggestion that in the long run, the process of ► [lateral gene transfer](#) dominates the history of life (Doolittle 1999). If this is indeed the case, then it would be impossible to reconstruct the gene complement of LUCA (Zhaxybayeva and Gogarten 2004). These observations led to the proposals of a universal common ancestor dominated by rampant horizontal or lateral gene transfer (Woese 1998). However, ► [phylogenetic trees](#) derived from gene content reinforced the separation between Archaea, Bacteria, and Eukarya, suggesting that the history of life has not been completely dominated by lateral gene transfer (Tekaia et al. 1999). The level of lateral gene transfer throughout the history of life continues to be a matter of debate today (Williams et al. 2011; Kutschera 2011; O'Malley and Koonin 2011).

The similarities between extant cells suggest that LUCA did not emerge from the primordial soup (Arrhenius et al. 1999). For instance, genes involved in transcription and translation (the so-called informational genes) are highly conserved among Archaea, Bacteria, and Eukarya and must have been present in LUCA. There is also powerful statistical evidence of the monophyly of universally conserved genes (Theobald 2010). However, the nature and the level of complexity of the last universal common ancestor have remained controversial. Proposals range from a progenote level of organization where horizontal gene transfer plays a prominent role (Woese 1998) to highly complex cells similar in nature to extant prokaryotes (Becerra et al. 2007). Other topics of discussion include the nature of its genetic material (Leipe et al. 1999), the nature of its cellular organization (Penny and Poole 1999;

Glansdorff et al. 2008), and the role played by viruses in the evolution of LUCA (Forterre 2006).

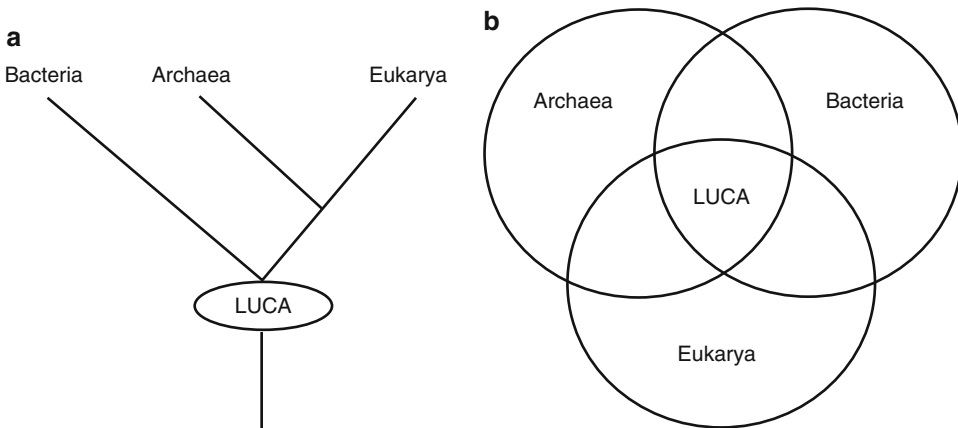
Basic Methodology

In principle, the nature of LUCA can be inferred by identifying those genes universally conserved among Bacteria, Archaea, and Eukarya (Fig. 1). Drawbacks to this methodology include secondary gene loss (which leads us to underestimate LUCA's gene content) and lateral gene transfer (which, on the contrary, leads us to overestimate LUCA's gene content). See Fig. 2.

Key Research Findings

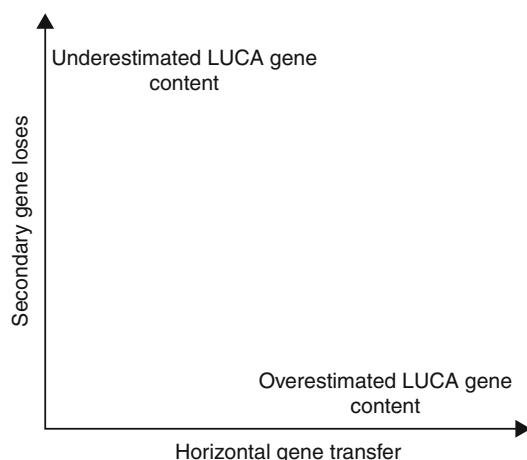
This is a (nonexhaustive) chronological list of key research findings in this field:

- The concept of the progenote as universal ancestor is suggested (Woese and Fox 1977a).
- The division of life into three domains (Archaea, Bacteria, and Eukarya) is discovered by using a small subunit of rRNA as a phylogenetic marker (Woese and Fox 1977b).
- By using paralogous genes, the root of the tree of life is positioned in the bacterial branch (Gogarten et al. 1989; Iwabe et al. 1989).
- Comparison of homologous genes from the three domains of life indicates a last common ancestor similar in complexity to extant prokaryotes (Lazcano et al. 1992).
- By comparing the first two completely sequenced genomes with gene sequences available in databases, a LUCA with an RNA-based genome is proposed (Mushegian and Koonin 1996).
- An important argument is provided to support the theory that proteins predate DNA (Freeland et al. 1999).
- The first inference of the gene complement of the last common ancestor by using genomes from the three domains of life is made. An ancestor similar in complexity to extant prokaryotes is suggested (Kyrpides et al. 1999).
- The inferred G + C content of LUCA appears to be incompatible with hyperthermophily (Galtier et al. 1999).
- The genetic core of the last common ancestor (as inferred from universally conserved genes showing three domain phylogenies) is comprised of mostly ribosomal proteins and a few proteins involved in DNA polymerization, (Harris et al. 2003).
- Most estimates of the gene complement of the last common ancestor are comprised of between 500 and 1,000 protein-coding genes (Mushegian 2008).



Last Universal Common Ancestor, Fig. 1 (a) Phylogenetic position of LUCA (in this case the root of the universal tree of life is shown in the Bacterial clade);

(b) The gene complement of LUCA can be inferred from conserved homologous traits among Archaea, Bacteria and Eukarya



Last Universal Common Ancestor, Fig. 2 Our accuracy to reconstruct the gene complement of LUCA is inversely related to the number of secondary gene losses and lateral gene transfer events along the history of life on earth

- Statistical evidence of the monophyly of universally conserved genes is provided (Theobald 2010).

Applications

Understanding the nature of LUCA: its level of complexity, the chemical nature of its genome, its gene complement, and its level of similarity to modern cell lineages, among other aspects of its biology, are central questions in evolutionary biology.

Future Directions

There has been much debate on the level of complexity (number of genes) and the chemical nature (DNA or RNA) of the genome of LUCA, and the debate is far from over (Vanechoutte and Fani 2009; Morange 2011). Understanding the role played by lateral gene transfer along prokaryotic evolution, and whether it affects all kinds of genes or not, is central to backtracking characteristics of the cenancestor. More research in this direction is clearly needed. The chemical nature of membranes in LUCA is another aspect of its biology that deserves more attention (Peretó et al. 2004).

Finally, LUCApedia, which is a detailed database comprising genes likely to be inherited from the cenancestor, will, in all probability, be of great importance in the reconstruction of the genetic complement of LUCA, since LUCApedia has the potential to accelerate research into the nature of our universal ancestor (Goldman et al. 2013).

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Cenancestor](#)
- [Common Ancestor](#)
- [Darwin's Conception of the Origins of Life](#)
- [Domain \(Taxonomy\)](#)
- [Eukarya](#)
- [Evolution, Biological](#)
- [Genome](#)
- [Genotype](#)
- [Lateral Gene Transfer](#)
- [Origin of Life](#)
- [Paralogous Gene](#)
- [Phenotype](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Prokaryote](#)

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Late Heavy Bombardment

Alessandro Morbidelli¹ and Philippe Claeys²

¹Laboratoire Lagrange, Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, Nice, France

²Analytical-Environmental and Geo-Chemistry, Vrije Universiteit Brussel, Brussels, Belgium

Keywords

Asteroids · Comets · Gas planets · Impact craters · Impact process · Meteorites · Moon · Small bodies · Solar system dynamics

Synonyms

LHB; Lunar cataclysm

Definition

The term *late heavy bombardment* (or LHB) corresponds to an elevated frequency of collisions that affected the inner solar system between 4.0 and 3.8 billion years ago. The Earth preserved no trace of these major impacts. Traces of the LHB can be found on the highly cratered surfaces of the Moon and other planets such as Mars or in the age of the impact melt measured on meteorites originating from the asteroid belt. The LHB represents

either the slowly decreasing tail end of planetary accretion or a cataclysmic event localized in time, perhaps triggered by a readjustment of the orbits of the giant planets long after the formation of the solar system.

Overview

The current stratigraphic timescale places the late heavy bombardment (LHB) period in the beginning of the Archean (in the Eoarchean Era), coeval, or slightly before the occurrence of the oldest metamorphosed terrestrial sediments outcropping in Isua (Greenland). The lunar crust started to crystallize around 4.44 Ga ago, and the morphology of the highlands displays a dense concentration of impact craters excavated prior to the emplacement of the first volcanic flows of the mare plains after 3.8 Ga. The LHB is now clearly established all over the inner solar system; it is recorded on the Moon, Mars, and in meteorites (Marchi et al. 2013), whose parent bodies originated in the asteroid belt.

However, the magnitude and frequency of the collisions taking place between the end of planetary accretion around 4.5 Ga ago and the start of the Archean at 4.0 Ga has been a matter of controversy for a long time. Two end-member views compete (Fig. 1), although other intermediate scenarios have also been proposed. The first hypothesis assumes that the frequency of impacts declined slowly and steadily after the end of planet accretion, in such a way that the bombardment frequency remained high (relevant to current) until 3.9 Ga ago (e.g., Hartmann et al. 2000). According to this view, the so-called LHB is not an exceptional event. Rather, it forms the tail end of a ~500 million year period, during which the Earth and the inner solar system were subject to devastating collisions, with possible major consequences such as melting of the crust, ejection of the atmosphere, and vaporization of the oceans.

The second hypothesis advocates a post-accretion rapid decline in the frequency of impacts, down to a value possibly only slightly higher than today. This low impact rate might have persisted throughout the entire Hadean. The

LHB period around 3.9 Ga thus represents an exceptional and cataclysmic event, characterized by a huge increase in the rate of collisions.

Basic Methodology

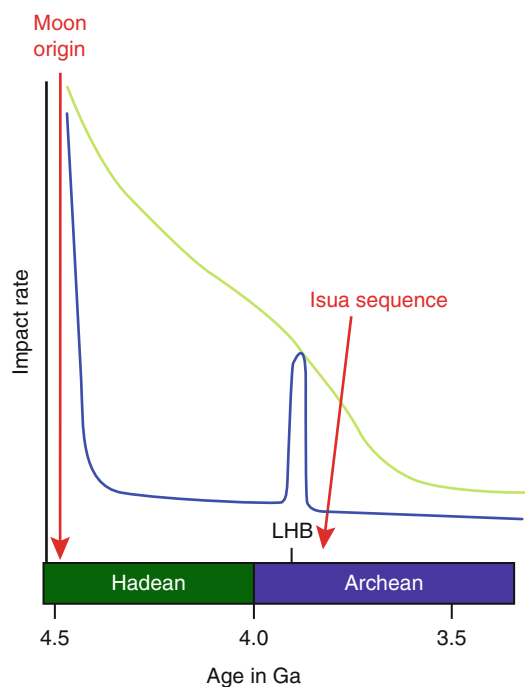
To establish a bombardment timeline on any planetary body, scientists have two possibilities. The first is to date impact events that affected whole rocks or their components and to compile statistics on the number of impact events as a function of age. An impact event is dated using isotopic chronometers that are sensitive to shocks. The other possibility is to count the number of craters on different surface units of known ages. The unit ages are established through isotopic analyses that reveal the crystallization age of its rocks.

Unfortunately, neither of these methods provide an unambiguous answer on the timeline of the ancient lunar bombardment.

The isotopic dating of impact melt rocks returned by the Apollo and Luna missions failed to identify impact events older than 3.92 Ga, suggesting the idea of a spike in the number of impact events at that epoch, i.e., the cataclysmic view (Tera et al. 1974). However, the argument can be made that most Apollo samples are related to the formation of the Imbrium basin, the largest “young” basin on the Moon and the only one precisely dated at 3.85 Ga. The melt phases in lunar meteorites confirm the deficit of impact ages older than 4 Ga (Cohen et al. 2000). This is important because meteorites likely originated from random locations on the Moon compared to the samples collected at a few landing sites. However, the impact age histogram provided by meteorites is much smoother than that derived from lunar samples, with some impact ages older than 4 Gy. Thus, it could be explained if there is a strong bias against recovering samples associated to the oldest events. Recent analyses of meteorite components (e.g., clasts in breccias) also reveal evidence for old impact events up to 4.2 Gy ago (Norman et al. 2006, 2016) and lunar zircons witness heating events, possibly associated to shocks, up to 4.3 Gy ago (Hopkins and Mojzsis 2015). These sporadic measurements of old

impacts, however, cannot be used to quantify how intense was the bombardment before 4 Gy and therefore to assess which of the two scenarios illustrated in Fig. 1 is correct.

The analysis of lunar crater densities also fails to yield an unambiguous view of the temporal evolution of lunar bombardment. There are ~12 basins which formed, according to stratigraphic analyses, between Nectaris basin and Orientale (the youngest basin on the Moon). Unfortunately, the age of Nectaris is not well known. If it is assumed to be 4.1 Ga, these 12 basins had ~300 Ma to form, and the decline of the bombardment rate (as measured from the densities of craters on Nectaris and Imbrium, respectively)



Late Heavy Bombardment, Fig. 1 Schematic representation of the flux of projectile on Earth between 4.5 and 3.5 Ga, (Modified after Kring 2003) both potentially explaining the intense bombardment around 4.0–3.8 Ga known as the LHB. The green curve shows a slow decrease of the bombardment, while the blue curve illustrates the hypothesis of a rapid decrease of the flux followed by a peak at the LHB time. In this case, the LHB would be due to some cataclysmic event shaking the structure of the solar system. It cannot be excluded that other cataclysmic events took place during the Hadean, but then their traces have been fully erased by the complete resetting of the Earth surface caused by the last event

occurred slowly. In this situation, it can be envisioned to extrapolate the bombardment rate backward in time till the Moon formation age, ~4.5 Ga ago. This has been done by Neukum and Ivanov (1994), whose proposed bombardment timeline has become the reference for the no-cataclysm hypothesis. Instead, if one assumes that Nectaris occurred at ~3.9 Ga, the 12 basins had less than ~100 My to form, and the bombardment rate declined so quickly between the Nectaris formation time and the Imbrium formation time that its extrapolation back to 4.5 Ga would lead to unrealistic predictions. For instance, the Moon would have accreted more than a Moon mass after its formation (!). In this case, the LHB can only be a cataclysmic event. Unfortunately, dating Nectaris radiometrically will not be possible until a new dedicated lunar mission is done.

In absence of an unambiguous empirical discrimination of the two bombardment scenarios, dynamical models can be useful to assess which scenario is more likely.

To explain a cataclysmic spike in the bombardment rate, a massive reservoir of planetesimals must remain intact during the planet formation epoch and the subsequent ~500 Ma and then, all of a sudden, be destabilized. This seems to be in conflict with the classical view according to which the solar system did not undergo substantial modifications after its formation. Gomes et al. (2005; the “Nice model”) designed a scenario that explains the origin of a cataclysmic LHB. In the Nice model, the giant planets formed on (or migrated to) quasi-circular, coplanar orbits, between approximately 5.5 and 12 AU. This orbital configuration was much more “compact” than the current one, where the planetary orbits are located from 5.2 to 30 AU. A massive disk of planetesimals surrounded the planetary system, extending outward from a few AUs beyond Neptune. Perturbations between planets and planetesimals eventually drove the planets into an unstable configuration. This led to a short phase of close encounters among the giant planets. As a result of these encounters, the orbits of Uranus and Neptune became eccentric, and the farthest planet penetrated into the disk. This event dispersed the

disk completely. The interaction between planets and planetesimals eventually parked the planets onto their current orbits. About 10^{-3} of the original planetesimals probably remained trapped in the Kuiper belt. The change in the dynamic structure of the giant planet system also depleted severely the main belt asteroid population, particularly its innermost region (Bottke et al. 2012). Escaping asteroids dominated the impact flux onto the terrestrial planets, causing an impact spike.

If there is ample evidence that a Nice model-like dynamical instability of the giant planets really occurred in the solar system (see for instance Nesvorný 2018, for a review), it is not sure that such an instability occurred after 500 My, i.e., at the LHB time. The timing of the instability depends critically on the distance between the original orbit of Neptune and the inner edge of the trans-Neptunian planetesimal disk. What this distance was is not known a-priori, leaving again an ambiguity on which of the scenarios illustrated in Fig. 1 is correct.

Key Research Findings

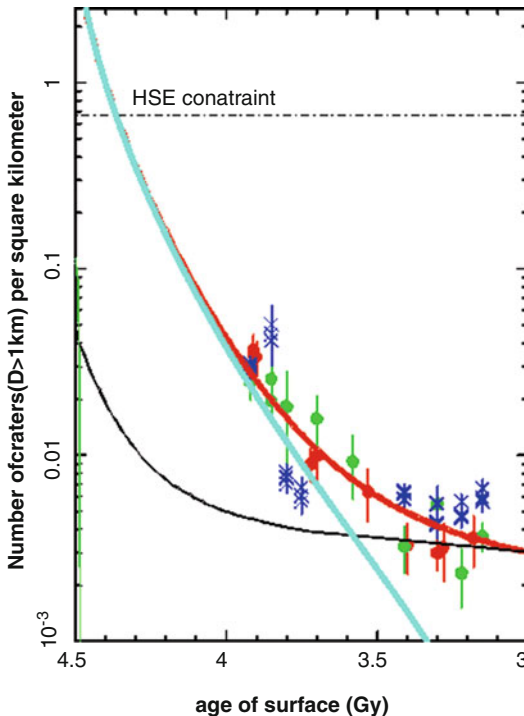
An important argument against Neukum and Ivanov's extrapolation of the bombardment timeline was that, assuming that the projectiles had an asteroid-like size distribution, it would imply the Moon accreted after its formation a mass of 1.3×10^{20} kg, which is five times larger than that inferred from the abundance of highly siderophile elements (HSE) in the Moon's mantle and crust (Morbidelli et al. 2012). However, Morbidelli et al. (2018) showed that the HSEs accreted prior to the final crystallization of the lunar mantle might have been sequestered in iron sulfides accumulated in the mantle's subsurface layer; the subsequent lunar mantle overturn would have brought this material to the core-mantle boundary from where iron sulfide and HSEs passed into the core. Thus, only the material accreted after the mantle overturn would reflect in the current HSE mantle budget. Consequently, if the lunar mantle completed its crystallization and overturned 4.35 Gy ago – as argued in some thermal evolution models (Elkins-Tanton et al.

2011) and deduced from various lines of evidence (Borg et al. 2015) – the current HSE budget of the Moon would be consistent with the declining bombardment envisioned by Neukum and Ivanov (Zhu et al. 2019).

Similarly, the Neukum and Ivanov bombardment timeline predicts the formation of more than 150 basins on the Moon. The recent GRAIL mission, that detected impact structures by measuring gravitational anomalies, inferred the existence of only 38–50 basins all over the Moon surface (Neumann et al. 2013), but recent work (Miljković et al. 2021) showed that all basins formed prior to the complete crystallization of the lunar mantle would leave no signature in the gravitational field of the Moon.

An important constraint on the timing of the dynamical instability of the giant planets, possibly associated to the lunar bombardment spike, has been recently obtained by combining dynamical and collisional evolution models. The idea is that the later was the instability, the longer the trans-Neptunian disk remained massive and collisionally evolved. In particular, collisions can dissociate the components of binary planetesimals; thus, assuming that all planetesimals formed as binaries, the current binary fraction observed in the Kuiper belt and among Jupiter's Trojans – which are populations trapped from the original trans-Neptunian disk – gives an upper bound on the number of collisions that the original trans-Neptunian population suffered. Using this approach, Nesvorný et al. (2018) found that the dispersal of the trans-Neptunian disk, and hence the giant planet dynamical instability, should have occurred no later than 100 My. This is much earlier than the LHB time. This result has put serious doubts on the cataclysm scenario for the origin of the LHB.

For a long time, a dynamical argument against the scenario of the tail-end bombardment was that any unstable population of small bodies in the inner solar system would have decayed faster than assumed by Neukum and Ivanov (1994), particularly when collisional grinding is also taken into account (Bottke et al. 2007). A faster decay would imply an unrealistically large initial projectile population, perhaps with a total mass up to an Earth



Late Heavy Bombardment, Fig. 2 Number of craters larger than 1 km in diameter that should have formed on the Moon per unit surface, as a function of terrain age, in the case the giant planet instability occurred at about the Moon formation time (about 4.5 Gy ago). The black, cyan, and green curves show respectively the density of craters produced by asteroids, planetesimals leftover from the terrestrial planet formation process, and trans-Neptunian comets. The red curve shows the sum of these three contributions. The colored dots show the measured densities of craters on units of known radiometric ages. The horizontal line labelled “HSE constraint” shows the crater density corresponding to the delivery of a mass equal to that inferred from the HSE budget in the lunar mantle and crust, assuming an asteroid-like size distribution. The crossing of this line by the red curve at the age of 4.35 Gy shows that, in this scenario, HSEs must have been retained in the lunar mantle only since this date. (Adapted from Morbidelli et al. (2018))

mass. However, studies of terrestrial planet formation (Morbidelli et al. 2018) revealed that the planetesimals leftover from the planet accretion process do decay dynamically on a timescale comparable to that envisioned by Neukum and Ivanov (1994). Moreover, collisional grinding is important only for planetesimal populations initially carrying more mass than 0.1 Earth masses. For this amount of initial mass, and a size distribution similar to that of main belt asteroids, the dynamical decay of the

population allows to reproduce quantitatively well the density of craters at the surface of the Moon as a function of lunar-surface age (Morbidelli et al. 2018; Fig. 2).

Future Directions

Although modern models tend to prefer the tail-end bombardment scenario over the cataclysmic scenario, a definitive conclusion on the real timeline of the lunar bombardment can only be achieved with more data. The new surge of lunar space mission can bring decisive measurements in the next decade. Many of them will land in the South-Pole Aitken (SPA) impact basin, the largest and oldest unambiguous impact structure on the Moon. Dating SPA could be decisive. The tail-end-bombardment scenario predicts that it formed 4.35 Ga ago. A significant older or younger impact age would instead strengthen the cataclysmic scenario. Similarly, dating old surface units, for instance the highlands on the far side of the Moon, or dating the Nectaris basin precisely, could allow extending beyond 4 Ga the database of the density of craters as a function of age, solving, once forever, this long-standing controversy on the nature and the origin of the late heavy bombardment of the Moon.

Cross-References

- [Asteroid](#)
- [Giant Planets](#)
- [Isua Supracrustal Belt](#)
- [Meteorites](#)
- [Moon, The](#)
- [Nice Model](#)
- [Planetesimals](#)
- [Siderophile Elements](#)
- [System Solar Formation, Chronology of](#)

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Late Veneer

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

The term *late veneer* refers to the late accretion of asteroidal or cometary material to terrestrial planets. Iron and nickel segregation during core

formation leaves the mantle of the planets depleted in siderophile elements, notably platinum-group elements. The modern abundances of these elements in the terrestrial mantle greatly exceed the level expected from such a wholesale removal of metal. It is therefore surmised that 0.5–1.5% of chondritic or cometary material was brought to the planet by the late veneer after core formation (Dauphas and Marty 2002; Maier et al. 2009). This hypothesis is germane to the issue of water delivery to the Earth.

History

Ringwood (1966) pointed out that the abundances of siderophile elements such as Ni, Co, Pt, and Os in the upper mantle are remarkably higher than the values indicated by low-pressure partitioning experiments of these elements between metal and silicate phases. Chou (1978) suggested that about one percent of material resembling ► [carbonaceous chondrites](#) was added to the Earth after core formation.

Overview

The excess of siderophile elements in the terrestrial mantle (the crust allotment may safely be neglected) with respect to the level of abundance expected from metal/silicate equilibration in the course of core segregation stirred strong debates (e.g., Drake and Righter 2002) and generated abundant experimental work. There is nothing really contentious about highly siderophile elements, such as platinum-group elements (Pt, Os, Ir, Pd, Ru, Rh), for which the metal/silicate distribution coefficient is in the range 10^4 – 10^6 (Holzheid et al. 2000). The very existence of the excess was, however, challenged for transition elements such as Ni and Co (Li and Agee 1996) with the assumption that core segregation took place under pressures in excess of 35 GPa, which corresponds to mid-mantle depth (Wade and Wood 2005). The best estimate of the proportion of late veneer in the Earth is therefore given

by the platinum-group elements excesses and is about 0.7%.

Dynamic models of planetary accretion can accommodate such a late delivery of chondritic material. At the end of the oligarchic stage of planetary accretion, a few tens of million years after the formation of the Sun, when only a few tens of Mars-sized bodies were left to plow into disks of asteroids, the main effect of Jupiter's attraction (resonances) was to knock asteroids off their orbits and sling them out of the Solar System or into the inner Solar System and the Sun itself (Morbidelli et al. 2000). Earth's capture cross section is thought to have been large enough that some of these projectiles hit our planet. Precisely how many of these landed on Earth is not well understood, but the tail of the asteroid shower seems to have lasted well beyond the formation of the terrestrial core.

The relevance of the late veneer to the delivery of water to the Earth is clear. Because most of its constitutive material accreted in the hot inner Solar System, our planet should be even more depleted in volatile elements, such as S, C, N, Cl, Zn, Pb, and, most significantly, water, than the presence of conspicuous ocean and atmosphere indicates. ► [Comets](#) were the preferred volatile carriers (Owen and Bar-Nun 1995) until it was realized that water from these objects was twice too rich in deuterium with respect to hydrogen compared to seawater. Attention then turned to chondritic asteroids from the outer Solar System, which carry water in excess of 10% (Morbidelli et al. 2000). Not everybody agrees that water came in late with the late veneer rather than early, but the record of a process that fractionated terrestrial volatile from refractory elements some 100 ± 50 million years after the formation of the Solar System is clearly found in both U-Pb and the I-Pu-Xe chronometers (Albarède 2009).

The late veneer should not be confused with the ► [Late Heavy Bombardment](#), which is dated at about 3.9 Ga on the Moon. The LHB is responsible for the largest lunar craters such as Imbrium. Abundant and large impacts of similar age are observed on Mars and inferred on some asteroids. The LHB is thought to be associated with the

disruption of a large asteroid or to the perturbation of the asteroid belt by the rapid migration of the giant planets (Gomes et al. 2005).

Cross-References

- [Carbonaceous Chondrite](#)
- [Comet](#)
- [Deuterium/Hydrogen Ratio](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Impact Degassing](#)
- [Late Heavy Bombardment](#)
- [Oceans, Origin of](#)
- [Siderophile Elements](#)
- [Water, Delivery to Earth](#)

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Late-Stage Accretion

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Late-stage chaotic growth](#)

Definition

Late-stage accretion refers to the final stage in the formation of ► [terrestrial planets](#). At the beginning of this stage, the solid mass in the ► [protoplanetary disk](#) is roughly equally divided between ► [planetary embryos](#) and smaller ► [planetesimals](#). Embryos grow large enough to gravitationally perturb each other onto crossing orbits, triggering a phase of giant embryo–embryo collisions. In most cases, the chaotic growth stage is thought to start 1–10 million years after the start of accretion and to last for another 10–100 million years, generating amounts of collisional debris. The impact that formed the Earth–Moon system is thought to have been the last giant impact on Earth. It occurred during the chaotic growth stage, 4.45 Gy ago.

Cross-References

- [Giant Impact](#)
- [Moon, Origin of](#)
- [Planetesimals](#)
- [Planet Formation](#)

Latent Heat

Raymond Pierrehumbert

Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, UK

Keywords

Clouds · Latent heat · Phase change

Definition

When a substance changes from one form to another (e.g., gaseous carbon dioxide condensing into dry ice), energy is released or absorbed even if the temperature of the mass is unchanged after the transformation has taken place. This happens because the amount of energy stored in the form of intermolecular interactions is generally different from one form, or phase, to another. The amount of energy released when a unit of mass of a substance changes from one phase to another, holding temperature constant, is known as the latent heat associated with that phase change (J/kg in mks units).

Overview

Condensable substances play a central role in the atmospheres of many planets and satellites. On Earth, it is water that condenses, both into liquid water and ice. On Mars, CO₂ condenses into dry ice in clouds and in the form of frost at the surface. On Jupiter and Saturn, not only water but also ammonia (NH₃) as well as a number of other substances can condense. The thick clouds of Venus are composed of condensed sulfuric acid. On Titan, it is methane, and on Neptune's moon Triton, nitrogen itself condenses. Water has an unusually large latent heat; the condensation of 1 kg of water vapor into ice releases nearly five times as much energy as the condensation of 1 kg of carbon dioxide gas into dry ice. This is why the relatively small amount of water vapor in Earth's atmosphere can nonetheless have a great effect on atmospheric structure and dynamics. Ammonia also has an unusually large latent heat, similar to water's. In both cases, the anomalous latent heat arises from the considerable energy needed to break hydrogen bonds in the condensed phase. When air rises, it cools by adiabatic expansion, and if it gets cold enough that one of the components of the atmosphere begins to condense or the partial pressure of one of the compressed atmospheric components surpasses the saturation vapor pressure, latent heat is released. This makes the rising air parcel warmer than the dry adiabat (no energy input to the parcel) would predict. If we assume further that the

condensation is efficient enough that it keeps the system at saturation, the resulting temperature profile is commonly referred to as the moist adiabat, regardless of whether the condensing substance is water vapor (as on Earth) or, e.g., CO₂ on Mars or methane on Titan.

Cross-References

- [Ammonia](#)
- [Clouds](#)
- [CO₂ Ice Clouds \(Mars\)](#)
- [Ice](#)
- [Phase Transition](#)
- [Venus Clouds](#)
- [Water](#)

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Lateral Gene Transfer

Purificación López-García
Unité d'Ecologie, Systématique et Evolution,
CNRS UMR8079 Université Paris-Sud 11, Paris,
France

Keywords

Conjugation · Transduction · Transfection · Transformation

Synonyms

[HGT](#); [Horizontal gene transfer](#)

Definition

Lateral or horizontal gene transfer is the acquisition of genetic material from another organism without being its offspring, although it frequently

refers to transfer from organisms belonging to another species. It contrasts with vertical gene transfer, which is the acquisition of genetic material from an ancestor.

Overview

There are three known mechanisms of lateral gene transfer: ► [transformation](#), ► [transduction](#), and ► [conjugation](#). Transformation implies the acquisition of naked DNA, for example, from lysed cells, by a recipient cell. Transduction implies the acquisition of ► [DNA](#) via ► [virus](#) intermediaries, which may infect one host, recombine with its ► [genome](#), and pick up some genes that can then be transferred to a second host. Conjugation involves the transfer of large DNA segments via specialized (conjugative) plasmids that are mobilized between cells through particular ► [pili](#). Thought to be a relatively minor process some years ago, lateral gene transfer is known today to play and have played a very important role in both prokaryotic and eukaryotic evolution. In the case of eukaryotic cells, the nuclear genome acquired massive amounts of foreign genes from the endosymbiotic ancestors of organelles (mitochondria, primary and secondary plastids). In the case of prokaryotes, gene transfer is very active and plays a readily adaptive role under particular selective pressures (e.g., the transfer of antibiotic resistance genes when faced with antibiotic pressure). Lateral gene transfer in prokaryotes appears so widespread that some authors even question the possibility of reconstructing a tree of life proceeding by bifurcation and think that organismal evolution would be better depicted by a “web of life” with anastomosing (reconnecting) branches. Other authors think, on the contrary, that although lateral gene transfer is important, it is not rampant. In that case, the reconstruction of a tree of life using a “core” of conserved genes would be possible.

Cross-References

- [Conjugation](#)
- [Endosymbiosis](#)

- [Evolution, Biological](#)
- [Genome](#)
- [Phylogenetic Tree](#)
- [Pili](#)
- [Plasmid](#)
- [Recombination](#)
- [Transduction](#)
- [Transformation](#)
- [Virus](#)

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Laterites

- [Regolith, Terrestrial](#)

Late-Stage Chaotic Growth

- [Late-Stage Accretion](#)

Laurasia

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

Laurasia is the ► [supercontinent](#) composed of the landmasses of the northern hemisphere (Eurasia

and North America). Between about 500 and 200 Ma, Laurasia and Gondwana together formed part of a single supercontinent called ► [Pangea](#). This later was assembled around 500 Ma ago and its breakup started 180–200 Ma ago, when Laurasia split from ► [Gondwana](#). North America split from Eurasia about 62 Ma ago with the opening of the North Atlantic Ocean.

Cross-References

- [Gondwana](#)
- [Pangea](#)
- [Supercontinent](#)

Lava Tube

- [Rille](#)
- [Rima, Rimae](#)

Lava Tubes

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V, Institut für Planetenforschung, Berlin,
Germany

Definition

Lava tubes are natural conduits through which lava travels beneath the surface of a lava flow (definition by U.S. Geological Survey). When the lava supply stops, the lava drains downslope and leaves a partially empty conduit (a lava cave). When the roof of a lava tube collapses, a so-called *skylight* (an opening in the roof) is formed. Skylights have been identified in high-resolution images from orbit on the Moon and Mars. Lava tubes are thought to exist on all terrestrial planets and the Moon, and perhaps even on the Jovian satellite, Io.

Cross-References

- [Basalt](#)

Law of Mass Action

- [Thermodynamical Chemical Equilibrium](#)

LC

- [HPLC](#)

LC/MS

- [Liquid Chromatography-Mass Spectrometry](#)

LCA

- [Last Universal Common Ancestor](#)

LDEF

- [Long Duration Exposure Facility](#)

Leeuwenhoek, Antony van

Erin Amato and Susan Leschine
Veterinary and Animal Sciences, University of
Massachusetts Amherst, Amherst, MA, USA

Keywords

Animalcules · Microscope · Microbes ·
Microbial world · Bacteria · Protozoa

Synonyms

Anthony van Leewenhoek; Antonie van Leeuwenhoek; Antonius a Leeuwenhoek; Antontj Leeuwenhoeck

Definition

Antony van Leeuwenhoek (1632–1723) is one of the most influential men in the foundation of biology. Leeuwenhoek's unique method of grinding lenses into his own microscope design led to his discovery of ► [bacteria](#) and other ► [microorganisms](#). Born in Delft, Holland, Leeuwenhoek lacked formal science training and worked as a draper, while making remarkable microscopy discoveries by night. Leeuwenhoek was meticulous in recording his findings and corresponded with the Royal Society of London for decades. Through his work, Leeuwenhoek has ultimately been regarded as the “Father of Microbiology.”

Overview

Over the last few decades, numerous discussions have taken root regarding the vast diversity of microorganisms and their essential role in biogeochemical systems, the environment, and health. Earth has been inhabited by microbes, the ancestors of present-day bacteria and ► [archaea](#), for more than three billion years, and yet their existence was unknown before Leeuwenhoek's observations. The significance of his discoveries cannot be overstated: no one suspected the presence of microscopic life even though most of life is microbial. Leeuwenhoek was the first to see the enormous numbers and diversity of microbes, organisms that had no name. He called them “diergens,” diminutive of “dier,” the Dutch word for “animal,” in English, “little animals” or “animalcules.”

Soon after its founding in 1660, The Royal Society of London began asking men from surrounding countries to offer any knowledge they had in science. At this point, Leeuwenhoek had been grinding, polishing, and mounting lenses to

create microscopes in his spare time between selling buttons and ribbon. A surviving Leeuwenhoek microscope magnifies 266 times to a resolution of approximately 1 μm . In 1673, Dr. Reinier de Graaf, a Dutch Physician familiar with Leeuwenhoek, wrote to Henry Oldenburg, Secretary of The Royal Society, encouraging Oldenburg to reach out to him. Leeuwenhoek recorded his findings over the next 50 years in letters to The Royal Society, which published his letters.

Leeuwenhoek discovered protozoa in 1674 while looking at rainwater and in 1676 he discovered bacteria in pepper-infused water during an investigation of “the cause of the hotness or power whereby pepper affects the tongue. . .” Another noteworthy contribution was the discovery of intestinal protozoa and bacteria of humans through observations of excrement. In 1681 he wrote in a letter to the Royal Society, “I have also seen a sort of animalcules that has the figure of our river-eels: these were in very great plenty and so small withal. . .” He goes on to say, “These had a very nimble motion, and bent their bodies serpent-wise, and shot through the stuff as quick as a pike does though the water.” It is likely that Leeuwenhoek had discovered spirochetes, the first indication of the existence of bacteria as normal residents of the intestines of humans.

Leeuwenhoek continued documenting his findings in rapt succession, always challenging his predictions in hopes of making more connections. He documented and quantified rapid microbial growth and conducted experiments relevant to his observations, never attributing the appearance of vast numbers of microbes to spontaneous generation. He looked at spittle from his mouth as well as from his wife and daughter; people he considered to have “clean teeth” and illustrated the existence of unique microbes. Despite his age, Leeuwenhoek never stalled in his work. Although his letters to the Royal Society were not as timely as in the past, they never stopped. Leeuwenhoek set the foundation for microscopy, microbiology, and biology, as we know it. His work surrounding bacteria, protozoa, parasitic, and anaerobic organisms, the human body, and the diversity of life was revolutionary. It is a marvel to comprehend how

much Leeuwenhoek covered with such limited means at his disposal. Leeuwenhoek's work set the stage for advancing understanding of the origin and evolution of life on Earth.

Cross-References

- [Anaerobe](#)
- [Archaea](#)
- [Bacteria](#)
- [Metabolic Diversity](#)
- [Microorganism](#)
- [Prokaryote](#)
- [Protists](#)

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Lemaître's Theory of Expanding Universe (History)

Stéphane Le Gars
Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Astrophysics · Big Bang · Cosmogony ·
Cosmology

History

Today, Lemaître's name is closely connected to the idea of Big Bang. Indeed, Lemaître's works concerned the structure of the Universe and its origin, i.e., problems about cosmology and cosmogony.

After his studies at the Jesuit College of Charle-roi, in Belgium, he began studies at the Engineer School from the University of Louvain, but he gave

them up after World War I to dedicate himself to physics and mathematics. After his Ph.D., he received a grant from the Belgian government which let him take a course with Arthur Eddington for 1 year and made possible for him to complete his attainment in astronomy and general relativity fields. In 1924, he went to the USA, where he was a student at the Harvard College Observatory and at the MIT. He discovered at this time Hubble's recent works which showed that nebulae are distant galaxies, but not objects in our own galaxy. This discovery will be crucial for his further works.

For this purpose, in 1927, 2 years after being back in Belgium, Lemaître published an article titled "Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extragalactiques" ("A homogeneous universe with a constant mass and a growing radius, accounting for the radial speed of the extragalactic nebulae"). In this article, Lemaître explained his innovating ideas: Unlike the static universes taken off the general relativity by Albert Einstein and Willem De Sitter, Lemaître imagined a finished and expanding universe. Then, he drew every inference from this idea of expansion. As early as 1931, Lemaître suggested that the universe comes from a "primeval atom." Taking his knowledge of the general relativity, the new quantum theories and the first microphysics results into account, but also the recent observation data about the galaxy's speed removal, Lemaître was the first to establish significantly the idea of a beginning of the Universe. He even affirmed that cosmic rays are the relics of this first explosive stage of the cosmic history and emphasized the role of a nonzero cosmological constant.

Both priest and scientist, Lemaître has never had problem to conciliate at a personal level science and faith, avoiding always assimilating his cosmogonist ideas to any divine creation of the world.

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Lenticula, Lenticulae

Roland J. Wagner

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

Lenticulae are small, dark pits, domes, and spots only found on ► [Jupiter's](#) satellite ► [Europa](#). These features could have been created by ► [cryovolcanism](#), intrusion, or ► [diapirism](#).

Cross-References

- [Albedo Feature](#)
- [Cryovolcanism](#)
- [Diapirism](#)
- [Europa](#)
- [Facula, Faculae](#)
- [Jupiter](#)
- [Macula, Maculae](#)
- [Satellite or Moon](#)

LET

- [Linear Energy Transfer](#)

Leuchs' Anhydride

- [Amino Acid N-Carboxy Anhydride](#)

Leucine

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

Leucine is one of the 20 protein amino acids. Its three-letter symbol is Leu, and the one-letter symbol is L. Its chemical formula is $\text{HO}_2\text{CCH}(\text{NH}_2)\text{CH}_2\text{CH}(\text{CH}_3)_2$, which gives a molecular weight of 131.17, and its isoelectric point (pI) is 5.98. Among the 20 protein amino acids, leucine belongs to the group of amino acids whose side chains are simple hydrocarbons, together with glycine, alanine, valine, and ► [isoleucine](#). Leucine (side chain: $-\text{CH}_2\text{CH}(\text{CH}_3)_2$) and isoleucine (side chain: $-\text{CH}(\text{CH}_3)\text{CH}_2\text{CH}_3$) are isomers. Leucine has in addition 29 nonprotein ► [amino acid](#) isomers, such as norleucine (side chain: $-\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$). Many of them have been identified in extracts from the Murchison meteorite.

Cross-References

- [Amino Acid](#)
- [Isoleucine](#)
- [Meteorites](#)
- [Protein](#)

LHB

- [Late Heavy Bombardment](#)

LHS-1140b

Emeline Bolmont

Observatoire de Genève, Université de Genève,
Sauverny, Switzerland

Definition

LHS-1140b is a transiting planet which was discovered by the MEarth project in 2017 (Dittmann et al. 2017). It is a super-Earth 1.4 times the size of the Earth and with its orbital period of 24 days, it sits in the habitable zone of its small host star (only 15% the mass of our Sun). The planetary system is located 49 light years away, which makes this planet one of the closest habitable zone planet to our Earth.

In 2019, another planet was detected in the system, LHS-1140c, on a shorter orbit and therefore too hot to sustain surface liquid water (Ment et al. 2019).

Together with the TRAPPIST-1 planets, LHS-1140b is a good target for atmospheric characterization with the James Webb Space Telescope and the European-Extremely Large Telescope (e.g., Wunderlich et al. 2021).

Cross-References

- JWST
- MEarth
- Super-Earths
- Transit
- Transiting Planets
- TRAPPIST-1 System

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Libration

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Libration is the oscillation of an angle about a fixed value (as opposed to circulation, meaning the angle cycles through all possible values). In celestial mechanics, libration of certain angles such as the ► [apsidal angle](#) or certain resonant angles means that the system is in a state with a particular configuration. In other words, it is the libration of one or more resonant angles which indicates if a system of planets is in resonance.

Cross-References

- [Apsidal Angle](#)
- [Mean Motion Resonance](#)
- [Orbit](#)

Lichens

Leopoldo G. Sancho

Faculty of Pharmacy, Section of Botany,
Universidad Complutense, Madrid, Spain

Keywords

Symbiosis · Algae · Fungi · Poikilohydric ·
Extremophiles

Definition

Lichens are mutualistic symbiotic organisms composed of a fungus, usually an Ascomycete, which is intimately associated with a photosynthetic partner that is an alga or a cyanobacteria (also called blue-green algae), or sometimes both. The result is a stable, autotrophic form of life that uses carbohydrates produced by the photosynthetic partner to live and grow. Lichen symbioses involve around 20,000 species of fungi and around 100 species of green algae and cyanobacteria (Hawksworth and Lücking 2017). In addition to these fundamental components, other microorganisms such as bacteria, yeasts, and lichenicolous fungi have been identified in numerous lichen species (Grube and Wedin 2016; Spribille et al. 2016). The complexity of lichen symbiosis introduces some conceptual problems in the delimitation of lichen-forming species (Lücking et al. 2021).

Overview

In lichen symbioses, the fungal partner (mycobiont) makes up most of the structure of the lichen and absorbs water and nutrients from the surroundings as well as providing a suitable environment and protection for the metabolic activity of both partners. Many of the lichen-forming ascomycetes reproduce sexually producing ascomata mostly on the upper surface of the lichens. A high percentage of lichens can asexually reproduce the symbiosis via symbiotic propagules such as soredia and isidia. Lichens are extraordinarily diverse in size, color, and morphology and are divided into three main forms, crustose (deeply attached to surfaces), foliose (flattened leaf-like), and fruticose (bushy lichens usually attached by one point to the substrate) (British Lichen Society web page 2018). They show a wide ecological range, from the intertidal zones to the highest summits of the world and from the tropics to the poles, and can grow on soil, tree bark, leaves, mosses, and rocks as well as artificial substrates such as concrete and glass. In polar and alpine, tundra lichens are often the dominant vegetation (Green et al. 2007). They are also

an important component of the biological soil crust in arid areas (Maestre et al. 2012). Lichens are known for their slow growth that ranges from an increment in diameter of 0.01 mm year⁻¹ in some Antarctic crustose species to several centimeters per year by foliose and fruticose species (Green et al. 2011; Sancho et al. 2019). Lichenometry takes advantage of the slow growth and longevity of crustose lichens to estimate the exposure age of stone surfaces (Armstrong and Bradwell 2010). Lichens are also widely used as bioindicators of the air quality due to their sensitivity to oxidant pollution, mainly SO₂ (Cislaghi and Nimis 1997).

Lichens are poikilohydric organisms, that is, they desiccate and remain dormant, when their environment dries out, but can rehydrate when water becomes available again. Upon ► [desiccation](#), the lichens become dehydrated to a degree that halts most biochemical activity. In this dehydrated state, many lichens are highly tolerant to stress conditions and have even survived full exposure to space conditions (Sancho et al. 2007; de la Torre et al. 2020) and to simulated Mars atmosphere (de Vera et al. 2019). The reasons for this resistance are both molecular, special metabolites protect important molecules, and structural, where accumulation of lichen substances, especially in the upper cortex, account for the ability of these organisms to survive high radiation, including UV, and high vacuum. Many lichens can hydrate directly from water vapor or from snow crystals and, after rehydration, lichens from the most extreme habitats can resume their activity in minutes, even having been inactive for months or years. These features make lichens suitable material for experiments in astrobiology.

Cross-References

- [Algae](#)
- [Biological Indicator](#)
- [Biopan](#)
- [Cyanobacteria](#)
- [Desiccation](#)
- [Epilithic](#)
- [EXPOSE](#)
- [Exposure Facilities](#)

- [Extreme Environment](#)
- [Hypolithic](#)
- [Planetary and Space Simulation Facilities](#)
- [UV Climate](#)

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Life

Kepa Ruiz-Mirazo¹ and Alvaro Moreno²

¹Department of Logic and Philosophy of Science, FICE, UPV-EHU, Biophysics Research Unit (CSIC – UPV/EHU), Donostia, San Sebastián, Spain

²Departamento de Lógica y Filosofía de la Ciencia, Universidad del País Vasco, San Sebastián, Spain

Definition

Although it is rather controversial whether the term “life” will ever fit into a definition, it could be conceived as “autonomy in evolution”: a complex network of self-reproducing *autonomous* agents whose individual (far-from-equilibrium, metabolic) organization is instructed by material records generated through an *open-ended*, historical process, in which that complex (collective-ecological) network evolves. In a minimal – and more operational – sense, this involves that any living system should be ultimately based on the dynamic intertwinement of a semi-permeable boundary (membrane), an energy transduction apparatus, and, at least, two complementary types of macromolecules: (enzyme-like) catalysts and (gene-like) templates.

Overview

In spite of its multifarious meanings and the intrinsic difficulty it has shown over the years to become a well-defined unanimous generalization, the concept “life” can still be regarded as a proper scientific target, with its own specific weight and implications, not only for biology (and closely

related disciplines) but for other fields of knowledge and research. Acknowledging that it is a notion that needs to be refined, made more precise and possibly further developed in the future, we consider that progress in the understanding of life is a scientifically relevant goal. This position is in contrast to the always present skeptical voices, e.g., those who think that life is simply a wrong category, because it does not help as a demarcation criterion; or that life cannot be linked to any “natural kind,” arguing on grounds of an “apparent” arbitrary or conventional character. In any case, the discussion below will just highlight several open problems linked to an interpretation of this concept in positive terms; several open problems that the investigation in Synthetic Biology, Artificial Life, Origins of Life, and, in particular, Astrobiology should contribute to solve in years to come.

The first problem is determining the universality of life. Although the planet Earth hosts a biosphere composed of an incredible variety of living forms, molecular biology has shown that they all share the same biochemical core, and the evolutionary theory proposes that they all derive from a common type of ancestral organism. Therefore, it becomes reasonable to wonder whether we are dealing with a single example of life, after all. Nobody has been able to synthesize alternative, completely different, living forms in the lab, so far, or to detect them elsewhere in the universe. And this poses a severe difficulty: how to discern the particular or contingent from the general and necessary attributes that characterize the living phenomenon. Comparative analyses across the huge diversity of organisms on Earth can be very helpful in that sense: they should give good indications of which are the indispensable set of mechanisms involved in the strikingly complex *organization* and *way to change over time* of living systems (in relation to non-living ones). Complexity sciences and, in general, bottom-up approaches coming from physics and chemistry should also add to that aim, showing that, whenever certain boundary conditions are met (during a suitable time span), matter tends to create organized structures; and only if these self-organized

structures bring about additional mechanisms for their long-term persistence can a minimal biological threshold of complexity and robustness be crossed.

A second problem, clearly connected with the first, regards finding out the adequate level of abstraction or specificity of the concept. In the last decades, the great advances in computational tools and simulation (*in silico*) techniques to analyze living systems, complementing traditional (in vitro and in vivo) experimental approaches, have raised the question of whether some biological features, or life itself, might be captured or even implemented at a symbolic, materially detached level. The strongest theses coming from the field of ► [Artificial Life](#) in the nineties pointed in that direction, proposing to conceive of life “as it could be” and not only as “we actually know it.” That debate is still open, but now shifting to a somewhat different arena: even if we acknowledge (as it is being generally acknowledged) that materiality plays an important role, what is the actual level of molecular specificity required for life? Are there chemical alternatives to ► [RNA](#), ► [DNA](#), ► [protein](#), etc. (that could play similar functional roles, as templates, catalysts, etc.)? Can a cell-free (or compartment-free) organism be built? Equivalently, can a genome-free organism be put together? If ever possible, for how long? What properties would these new kinds of “quasi-biological” systems have/lack? The now emerging discipline of Synthetic Biology (together with other novel enterprises, like Systems Chemistry) will hopefully address some of these questions soon. And Astrobiology, from its foundational steps, has also included them (or similar ones) in its research agenda: why water, why carbon, etc. (as key ingredients for life)? What minimal size (i.e., minimal internal molecular machinery) could an organism have? In so far as science provides means to answer these open issues, possibly through the fabrication of intermediate or semi-synthetic systems, or through the detection of extra-terrestrial systems with some life-like properties, it will be giving new clues to advance in our way of handling and maturing the general “life” question.

Finally, a third big difficulty of the concept “life” lies in its inescapable twofold dimension. All living phenomena relate, one way or the other, to the physically bounded organization of individual organisms, but are also embedded in the temporally and spatially much wider network of systems and relationships comprising the whole history of the biosphere. The former involves fundamental features that we, as organisms, naturally recognize in other living systems, like metabolism and adaptive agency, whereas the latter reflects larger-scale (but no less important) aspects, like the capacity to change and evolve through generations, or the more global interactive dynamics at the ecological level.

In reality, these two dimensions of life are deeply entangled. On the one hand, any known living being cannot exist but in the context of a collective network of similar systems. And this is clearly reflected in the fact that genetic components (which specify the metabolic machinery and organization of single biological entities), in order to be operational, must be shaped through a process that involves a great amount of individual systems and many consecutive generations, or reproductive steps. The unfolding of an evolutionary process by natural selection, based on heritable modular templates and genetic mechanisms, allows this peculiar form of organization we call “living matter” to explore many possible combinations and formulas to survive, providing extreme examples of adaptation that make any borderline within the living domain rather diffuse. Actually, evolution, beyond that intrinsic competitive/selective dynamics, weaves a collective network of increasingly complex and entangled cooperative relations among entities at different phenomenological levels and with different cohesive strength.

But, on the other hand, the organismic dimension of life, namely, its expression in the form of individual agents, is also crucial to understand it. However embedded in evolutionary and ecological webs living systems might appear, their metabolic functioning still points to a basic organizational core that should be properly characterized. If the essence of biological organization is conceived as a web of diverse interactions

among – rather than *within* – different bio-entities (extending the idea of living system to molecular replicators, viruses, organelles, parasites, symbionts, etc.), it will not be possible to determine whether organisms should be taken as a basic starting point (i.e., as a highly integrated and cohesive type of organization that gets progressively complex) or just as some occasional result of that ongoing dynamics of loose cooperative relations among a plurality of bio-entities. This is an important issue, because without such a highly integrated and cohesive individual organization, it would be very difficult to give a proper account of metabolism, development, agency, unit of selection, etc., or to make a clear-cut distinction between organisms and other forms of cooperative or “ecological” networks. Furthermore, life seems to demonstrate, in the course of evolution, that increasingly complex kinds of individual agents have emerged and developed, bringing forth progressively sophisticated interactive capacities (cognitive ones included).

Nevertheless, the apparent tension between these two aspects or conceptions of life can be channeled constructively. Indeed, what really matters is their deep entanglement, since a process of open-ended evolution cannot occur except in the context of a population of individuated metabolic systems (i.e., organisms); and, conversely, the unfolding of organisms and their long-term maintenance depend on their insertion in an open-ended evolutionary pathway. So it is really the integration of these two dimensions that provides a complete, rich enough picture of the phenomenon of life. Such a synthetic conception could be interpreted, in addition, as an attempt to bring together the main results and theoretical legacy of two different traditions in biology: the physiological-biochemical tradition, focused on immediate or “proximate” causes, and the evolutionary-historical tradition, interested in the final or “ultimate” ones.

Cross-References

- [Chronological History of Life on Earth](#)
- [Complexity](#)

- [Evolution, Biological](#)
- [Metabolism](#)
- [Origin of Life](#)
- [Replication \(Genetics\)](#)
- [Self-Assembly](#)
- [Self-Replication](#)

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Life in the Solar System (History)

Florence Raulin-Cerceau

Maître de Conférences, Centre Alexandre Koyré (UMR 8560-CNRS/EHESS/MNHN/CSI)
Muséum National d’Histoire Naturelle, Brunoy, France

History

Since Copernicus demonstrated in 1543 that the Earth was not located at the center of the universe but was revolving around the Sun like the other planets, the Earth took the status of a simple planet among the others. Stars became suns and planets became earths that could be inhabited. The consequence of this view of the universe was that each planet of the solar system could be peopled with various inhabitants. In fact, this changing in the position of the Earth was not a rapid scientific revolution. The heliocentric theory of Copernicus produced a slow shift in the religious, philosophical, and scientific mentalities. The unfortunate pioneer of the extraterrestrial debate at the end of the sixteenth century, Giordano Bruno (1548–1600), who supported the Copernican system, had to come up against the religious dogma and to try to remove a very deep-rooted belief about our place in the universe.

A new epoch of observations was born in 1609 when Galileo Galilei (1564–1642) began to study in details the surface of the Moon thanks to his telescope recently devised. He also discovered four satellites orbiting ► [Jupiter](#) and the impact of this discovery was decisive to provide confirmation of the triteness of our planet among the celestial bodies of the solar system. The

seventeenth century saw the definitive affirmation of the Copernican theory thanks to Kepler's works demonstrating that planetary orbits were not circles but ellipses. Planetary motions were completely demystified and the position of the Earth as an ordinary planet going around the Sun could no more be challenged.

Galileo's observations and Kepler's works led to a new debate about the plurality of worlds. Literary and scientific works flourished about the habitability of our neighbor the Moon in a context however still controlled by religious authority.

Fascinated by the new paradigm of heliocentrism, Kepler (1571–1630) wrote a little book mixing didactic and fiction style, named *Somnium, Sive Astronomia Lunar* (*The Dream, or The Astronomy of the Moon*). This book, which could have been considered as provocative during Kepler's life, was published posthumously by his son in 1634 (whereas it was started in 1609). The interesting point was that Copernican astronomy was illustrated by a transposition in order to make clear the heliocentric viewpoint: how does the Earth look from the lunar surface for inhabitants called Selenites studying astronomy? The fiction story imagined by Kepler was strongly consolidated by astronomical data (scientific footnotes are more numerous than the text itself) and lunar habitability was discussed with scientific arguments. But this book was more a support of the Copernican theory than a convincing demonstration of the plurality of worlds.

The second part of the seventeenth century led to accept the plurality of worlds with less and less hostility from a scientific viewpoint as well as a popular angle, in spite of a continuous reluctance from the Roman Catholic Church.

The first writing attempting to be liberated from this religious ascendancy came from the French philosopher Bernard le Bovier de Fontenelle (1657–1757). He published his *Entretiens sur la pluralité des mondes* (*Conversations on the Plurality of Worlds*) in 1686 which soon became very popular. In spite of this success, the book was still regarded as dangerous by the Roman Catholic Church, which placed it on the Index of Prohibited Books in 1687.

The book presented a series of conversations between a gallant philosopher (Fontenelle himself) and a Marchioness and looked like a didactic entertainment about astronomy. The central question was dealing with the differences between the inhabitants of each planet, according to its proximity to the Sun. Fontenelle populated all the planets of the solar system and the Marchioness was at the same time filled with wonder and overwhelmed in front of this "unlimited number of inhabitants likely to be on all these planets." She was also dubitative when she asserted, "it's a lot of ignorance based on very little science." How can we imagine these planet dwellers so various indeed, if nature is opposed to repetitions, questioned the Marchioness? Fontenelle enjoyed himself imagining that differences increased as the planets became more and more distant from the Sun. But he spent very little time on the case of ► [Mars](#), a planet which seemed to be very similar to the Earth. According to him, Mars had nothing special and it was not worth mentioning it.

Eventually, Fontenelle offered to the reader a very broad plurality of living worlds and its merit is to have been the first to popularize in a pleasant style the idea of diversity of life in the universe.

At the very end of this century, the Dutch physicist, mathematician, and astronomer Christiaan Huygens (1629–1695), who discovered the largest moon of ► [Saturn](#) (► [Titan](#)), worked on a philosophical treatise entitled *Cosmotheoros* (or *Treatise on the Plurality of Worlds*), posthumously published in 1698. This essay dealt with the consequences of the Copernican system and proposed a model for the construction of the universe. Every star was considered as a world with other possible forms of life. Huygens speculated on the habitability of the solar system and thought that the other planets were the abode of creatures quite similar to those living on Earth. The differences were supposed to come, as for Fontenelle, from the more or less great distance from the Sun and its influence on planetary solar heating.

One of the most significant centuries about the question of the habitability of the solar system was the nineteenth century. Developments in planetary observation, especially the first publications of

maps of the Martian surface, built a new scientific field named *areography* (or Martian geography). The surface of Mars was supposed to be covered by oceans and continents (the darker regions were assumed to be seas and the lighter parts continents). This planetary world, which seemed to be very similar to ours, appeared to be a very good candidate to be the abode of life.

The British astronomer Richard A. Proctor (1837–1888), famous for having produced one of the earliest maps of Mars in 1867, wrote many popular books. Among them, *Other Worlds Than Ours*, *The Plurality of Worlds Studied Under The Light of Recent Scientific Researches*, published for the first time in 1870, immediately attracted attention not only of the scientific world but also of a very wide audience. Proctor used a poetical description to show what astronomy taught us about the Sun and its planets and discussed the probability that other worlds could be inhabited. According to him, habitability would be the key argument able to answer the question of the possible life forms on other planets. Habitability could be defined in considering analogies with the Earth, i.e., parameters resembling those existing upon our planet.

Proctor studied the habitability of every planet of the solar system. He suggested that the existence of organized forms of life depended on the conditions supposed to have an effect on the planetary surface, such as climate, seasons, atmosphere, geology, and gravity. For instance, the physical conditions of Venus seemed to show very close resemblances to the terrestrial ones. Arguments coming from analogy allowed him to conclude that this planet could be inhabited.

But it clearly appeared that the best candidate to be the abode of life was ► [Mars](#), “the miniature of our Earth” said Proctor. With seasons equivalent to terrestrial ones, water vapor in the atmosphere, and forms of vegetation growing abundantly (these last points were supposed to be possible), Proctor’s Martian world was perfectly fitted for complex life.

Proctor admitted also life on ► [Jupiter](#). This giant planet might be inhabited by “the most favored races existing throughout the whole range of the solar system,” thanks to the very

symmetry and perfection of the Jupiterian system. He attempted to imagine what kind of forms of life could populate this huge planet. However Proctor wanted to stay under the control of exact knowledge. He thought we could only claim that “the beings of other worlds are very different from any we are acquainted with, without endeavoring to give shape and form to fancies that have no foundation in fact.”

Numerous writings dealing with the habitability of ► [Mars](#) were proposed during this century, especially after the canals controversy launched in the 1880s following Schiaparelli’s observations. Among the most prolific writers on that topic, the French astronomer Camille Flammarion (1842–1925), who founded the Juvisy Observatory (France) in 1883 and the *Société Astronomique de France* (SAF) in 1887, was well-known for his *Pluralité des Mondes habités* (Plurality of Inhabited Worlds) published in 1862, when he was only 20 years old. This book, translated in many languages, explained the conditions of habitability of earthlike celestial bodies discussed from the astronomical, biological, and philosophical viewpoint. A comparative study of the planets of our solar system led him to state that “the Earth was, considering its physical characteristics, a planet of medium kind, without anything remarkable.” Following this idea, life would have been present everywhere in the solar system.

He studied the habitability of the planet Mars while the Martian canals controversy was still running. He published *The planet Mars and its conditions of habitability* (first tome in 1892 – second in 1909) in which he presented the whole collected observations about the surface of Mars and its possibilities to be the abode of life. According to Flammarion, the planet Mars was a “living world” in which the climate and the supposed surface characteristics (seas, canals, continents) offered enough analogies with our planet to authorize the existence of living species not so different from the terrestrial ones. He was very concerned by the canals hypothesis but remained cautious as regards its interpretation.

As a final point, spectroscopic methods were developed by astronomers such as Janssen (1824–1907) or Huggins (1824–1910) during the

end of the nineteenth century and gave new parameters related to habitability and led to reconsider the question of life elsewhere in the solar system.

Cross-References

- [Habitability of the Solar System](#)
- [Jupiter](#)
- [Mars](#)
- [Saturn](#)
- [Titan](#)

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Life Support Systems

Billi Daniela
University of Rome Tor Vergata, Rome, Italy

Keywords

Space exploration · ISRU · Life support ·
Bioregenerative · MELiSSA

Definition

Life Support Systems encompass all technologies and processes which enable human presence and activity in space environment.

Overview

Mastering Life Support Systems (LSS) technology is a prerequisite for future sustainable human space exploration by guaranteeing a minimal

dependency from Earth of Lunar and Martian outposts. Various LSS based on physiochemical or biological approaches are or have been under development to convert waste elements to resources that can be used by crew members. The goal of Closed Ecological Life Support Systems (CELSS) based on living organisms and physical-chemical processes is: (i) production of O₂ and biomass with high nutritional value; (ii) use of light as a source of energy for microbiological and plant biosynthesis; and (iii) limited O₂ consumption. This should be achieved with the development of reactor allowing the reconversion of waste, CO₂, and minerals in simplified recycling steps, by using preferentially, well-characterized organisms that possess a certain degree of “space robustness” (Wheeler 2019).

An example is the Micro-Ecological Life Support System Alternative (MELiSSA) program of ESA, which is aimed to develop a CELSS that will provide fresh food, oxygen, and potable water from organic and inorganic waste recycling during long distance space exploration (Lasseur et al. 2010). The MELiSSA project was started in 1989 and has advanced knowledge and understanding of regenerative systems leading to a fully closed loop system. The loop is made up of four compartments with the crew members at the center. The first compartment is the liquefying one that collects the mission waste (i.e., urea, kitchen waste, etc.) as well as the nonedible parts of the higher plant compartment (i.e., straw and roots) and anoxically transforms the waste to ► [ammonium](#), H₂, CO₂, ► [volatile fatty acids](#), and minerals. Then, the photoheterotrophic compartment eliminates the terminal products of the liquefying compartment, and it is followed by the nitrifying compartment that produces nitrates used as nitrogen source by the higher plants and the cyanobacterium *Arthrospira platensis*, e.g., the photoautotrophic compartment regenerates oxygen and produces food.

To date, a stable environment has not been achieved in ground-based demonstrators and test beds developed in various countries [e.g., Russia’s BIOS-1, 2, 3, and 3 M, NASA’s Bioregenerative Life Support Systems Test Complex (BIO-Plex),

Japan's Closed Ecology Experiment Facility (CEEFF), and Biosphere-2 in the USA (Escobar and Nabby 2017)]. Until now, many CELSS containing different types of biological elements (e.g., microalgae, higher plants, fish, and microorganisms) have been proposed.

In this context, the EDEN ISS project has proven the feasibility of a space greenhouse realized in Antarctic, which could also be used on the Moon and Mars, in order to locally grow food by using nutrient delivery, LED lighting, biodegradation and decontamination systems, food quality, and safety procedures as well as operation procedures for safe food production (Zabel et al. 2015; Meinen et al. 2018).

Basic Methodology

LSS are made of elements (systems, subsystems) whose technologies and processes enable human presence in space, and they cover the following key functions: (i) Atmosphere revitalization, e.g., CO₂ removal, O₂ generation, chemical/microbial/physical contamination monitoring and control, and environmental control (temperature/pressure/humidity); (ii) Water recovery and recycling, e.g., collection, processing, and quality control (microbial, chemical); (iii) Food production and preparation, e.g., food production, transformation and storage, and quality control; (iv) Waste recovery and recycling, e.g., collection, storage, and processing of organic wastes generated during the mission; and (v) In situ Resource Utilization (ISRU), e.g., extraction and processing of local resources for Environmental Control & Life Support Systems (ECLSS).

Key Research Findings

The cyanobacterium *Arthrospira platensis* was loaded into a photobioreactor onboard the International Space Station, and for a month the microorganism converted the light into energy, producing oxygen as a byproduct at the same speed as it would on Earth.

Applications

LSS to support human exploration of deep space encompasses numerous technological developments that are also crucial elements for tackling terrestrial challenges such as environment, water, food, safety, ecosystems, circular economy, health, and toxicology (Nelson et al. 2003).

Future Directions

The European Space Agency (ESA) has proposed a short-to-medium horizon mission scenario with the following destinations: Low Earth Orbit (LEO), the Moon (including lunar vicinity), and Mars. In the short term, the ISS will be used as a test bed for closed LSS technologies, mainly for CO₂ removal, water recovery, food production, and waste collection treatment. These activities are part of ECLSS, and systems and subsystems will be used on the Gateway, a NASA human-tended facility placed in the lunar vicinity, which in the medium term will support crew members for 30–40 days. Hence, LSS envisaged mainly technologies for water and atmosphere management that could be tested along with risk management protocols, in relative proximity to Earth in case of an emergency. On the one hand, technologies for waste management, food production, and ISRU are not required in future Moon Surface Operations where LSS could operate in either open- or closed-loop systems. On the other hand, ISRU-based technologies could be exploiting to link LSS to resources available on the ground by using extreme-tolerant cyanobacteria (Verseux et al. 2016). In the long term, LSS technologies validated at the Gateway will be used to support human outposts on Mars, where there will be the need for atmosphere and water revitalization, waste management, food production, and recycling as well as technologies based on ISRU. ISRU implies not only the water recovery but also the potential exploitation of regoliths to support the microbial photosynthesis, or as substrate for plant growth (after physicochemical and/or biological treatments) or as shielding material.

Cross-References

- [Geomicrobiology](#)
- [Nitrogen Cycle, Biological](#)
- [Oxygenic Photosynthesis](#)
- [Phototroph](#)

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Life, Artificial

- [Artificial Life](#)

Life, Concept of (from Antiquity to the Eighteenth Century)

David Dunér
Lund University, Lund, Sweden

Keywords

Definition of life · History of Biology · History of Science · Philosophy of Science

Synonyms

[Life, definition of \(from antiquity to the eighteenth century\)](#)

Definition

The concept of life has through the ages been defined in many various ways, each focused on specific characteristics that have been connected to something, whether physical or non-physical existence or process, that sustains life and that humans understand or interpret as constitutive for something being alive (Bognon-Küss and Wolfe 2019; Hall 1969; Tirard et al. 2010; Toellner 1980; Wolfe 2018). The concept of life is inextricably linked to a changeable world and the world-views and self-understanding of the human being. The biological concept of life is thus connected to philosophical, theological, cultural, societal, and political concepts of life.

History

The English word “life” has a Proto-Indo-European root, *leip-, meaning “to stick, adhere.” The

word is thus connected to “continuance, perseverance,” and “to live” then literally means “to continue, remain.” The same root is also the source for the Greek *liparein* “to persist, persevere” and *lipos* “fat,” Old English *lifer* “liver” (the secreting organ) and *læfan* “to allow to remain.” In Greek philosophy, there are two words for “life,” βίος (*bíos*) and ζωή (*zōē*). The former – that we find in words such as “biology” and “biography” – is associated with human life, particularly longevity and way of life. The latter word rather denotes the reality of life whether it concerns humans, animals, or plants. The Latin word “*vita*” encompasses the meaning of both these two Greek words.

In general, ancient philosophers made no distinction between being alive and having a soul. In the pre-Socratic philosophy, Thales, Anaximenes, and Heraclitus argued that all matter can in some respect be considered living, a notion known as *hylozoism*. Plato described life as an inner force of movement. The living is thus something with the ability for self-movement. And this capacity for self-movement is the soul. The ancient philosopher who delved most deeply into the question of what life is, about its various life forms and functions, was Aristotle in the fourth century BCE. In *De anima* (On the Soul) he identifies the soul as the principle of living beings (Aristotle 1986). He distinguishes between lifeless matter (*hyle*) and life as *entelechy* (*entelécheia*), or in other words that which has its purpose in itself and is a realization of a potential possibility. In Aristotle’s view, to be alive is to have a soul, which applies to humans, as well as to plants and animals. The soul is thus the body’s form (*eidos*), which means that when the soul (the form) leaves the body, the body therefore ceases to be alive. The plants have a vegetative soul that allows for growth and reproduction, the animals have a sensitive soul that allows for movement and sensation, while the human being alone has a rational soul that allows for thought and reflection. The Aristotelian doctrine of life dominated in medicine and biology for 2,000 years, with some modifications by, among others, Galen’s physiology and Theophrastus’s studies of plants.

Neoplatonism identified life with motion, as something changeable and unlimited. Life was

the mediating link between being and thinking. Neoplatonic philosophy was not least important for the Christian concept of life. John Scotus Eriugena in the ninth century CE specified four kinds of life on a scale from the higher to the lower, the *vita intellectualis* of angels, the *vita rationalis* of human beings, the *vita sensualis* of animals, and the *vita insensualis* of plants. Hugh of Saint Victor in the twelfth century distinguished two kinds of life, the earthly and the heavenly, one bodily and the other spiritual, one through which the body lives by the soul, the other through which the soul lives by God. During the Middle Ages, the active life, *vita active*, was set against the contemplative life, *vita contemplativa*. The scholastic and Dominican brother Thomas Aquinas gave the latter precedence. For Thomas Aquinas, life had its origin in God, and accordingly, no human being then has the full right to rule alone over his life. Human life is sacred and inviolable.

In medieval medicine, pieces of advice were given on how to preserve and prolong one’s life and health, based on a Hippocratic-Galenic humoral pathology and its identification of the four body fluids. During the sixteenth and seventh centuries, life was associated with the transformations of matter and the influences of the heavens, alchemy, and astrology. In astrology, the world was seen as a system of correspondences or connections. What happened in the heavens thus affected life on Earth. For the influential physician Paracelsus, heaven ruled earthly life in both theological and cosmological-astrological terms. The metals, according to Paracelsian alchemy, were born in the veins of the Earth of sulfur, mercury, and salt, and are multiplied by the heat of the Earth and the influence of the heavens. Stars, comets, eclipses, and other celestial bodies, according to this micro-macrocosmic worldview, had a concrete influence and impact on earthly life.

Life was commonly up to the scientific revolution, understood in accordance with an Aristotelian conception, life as having a soul, life as animation. Pierre Gassendi, for example, wrote in 1658 that “Life corresponds to the presence of the soul in the body, and death to its absence.” A standard conception of life from the Antiquity

to the eighteenth century, particularly in Galenic medicine, was the *pneuma* theory or the theory of animal spirits (*spiritus animalis*). The theory of animal spirits rests on the observation of life as associated with heat and breathing, while the dead body as something cold and immobile. With inhalation, a living principle, “spirits,” is adopted, which made the blood healthy and alive. There were, according to this theory, three kinds of “spirits” (equivalent to “*spiritus*” in Latin or “*pneuma*” in Greek). The natural spirit (*spiritus naturalis*) originates from the abdomen, a fine mist that is born in the liver and spreads through the blood vessels throughout the body. The vital spirit (*spiritus vitalis*) from the chest spreads through the arteries and makes the body lively. The heart is the source of heat and the vivid fluids, the origin of the veins, and the first cause of breath and pulse. And finally, the animal spirit (*spiritus animalis*) from the head, which is the finest and purest mist of the living spirit that is carried up to the brain and then spreads through the nerves throughout the body.

The natural philosopher René Descartes used the concept of *spiritus animalis*, but dressed it in mechanistic terms and explained it as something like “a very weak wind” or a pure, lively steam, which rises from the heart to the brain, then out through the nerves and sets the muscles in motion. Life as “spirits” came, however, during the latter part of the seventeenth century and the first half of the eighteenth century to be overshadowed by the idea of life as motion. The mechanistic concept of life did not describe life as something necessarily animated, but in short just as matter in motion. The new medicine of the scientific revolution, with William Harvey’s explanation in 1628 of the circulation of blood in the human body, came to emphasize the circulatory system as a characteristic feature of living things, as in the blood circulation, the respiration, the circulation of nutrients in the blood, and the sensory circulations of animal spirits through the blood and nerve fluids. Furthermore, Santorio’s quantitative experiments described nutrition and the life processes in terms of measure and weight. Crucial was not least Descartes’ mechanistic philosophy of nature which explained the living body as an extended substance, *res extensa*, that could be described in

geometrical and mechanical terms. Animals were automata and human bodies only matter in motion. However, the mechanical explanation of life had difficulty in explaining the body’s ability for self-movement, and how the interaction between body and soul could take place.

In *L’Homme* (Treatise on Man) from 1633, Descartes described the body as a system of pulleys, funnels, sieves, pipes, bellows, and other mechanical instruments. In a similar, but even more elaborate way, Hermann Boerhaave in *Institutiones medicae* (1708) described the solid part of the human body as pillars, props, axes, wedges, leavers, pulleys, cords, presses, bellows, sieves, strainers, pipes, etc. It was not that the bodily organs were such machines, instead they all, both the natural and the artificial machines, followed the same mechanical laws. According to this mechanistic explanatory model for the life processes in medicine, the so-called iatromechanics, it was motion that constituted life. Hobbes, in this reductionist mode, identified life with the motion of limbs. Robert Boyle insisted that the living body is a kind of hydraulico-pneumatic machine, where the vital fluids and motions differ the living from the dead body, but both were arrangements of same universal kind of corpuscular matter. According to Archibald Pitcairne, “Life consists in the Circulation of the Blood produced by the Motion of the Heart and Arteries.” Boerhaave, as well as the physician Friedrich Hoffmann, life was motion, and death was rest. Life, Hoffmann argued in 1729, consists in the circular motion of blood and body fluids, and death is stagnation, the cessation of movement. Iatromechanical understanding of what life is, was based on the dichotomy between the living and its opposite death, where the former stands for something in motion, is warm and breathing, while the latter is something immobile, cold, and not breathing. The most extreme exponent of this mechanistic view was Julien Offray de La Mettrie claiming that man was just a machine, and the soul as inseparable from the body.

Georges Louis Leclerc, Comte de Buffon identified life in his *Histoire naturelle* (1749) with certain “organic molecules” that were consumed by the organism and gave rise to the vital activity of living things (Tirard 2010). The living differs from the non-living, according to Denis

Diderot, due to just a difference in sensibility, in the activity or inactivity of the particles. Two distinctive capacities of living beings crystallized in the debate concerning the essence of life in the eighteenth century: life as the ability to move or life as the ability to feel.

During the last decades of the eighteenth century, vitalist conceptions of life came to dominate. For the mechanistic philosophers, life could merely be explained in chemical and physical terms. The vitalists, on the other hand, argued that chemical and physical properties were insufficient to describe and explain what life is. Instead, they assumed the existence of a necessary, essential vital force, a principle of life, as the explanation for the bodily processes and self-preservation, and in general the difference between a living and a dead body. The idea of vitality, the theory of vitalism, is thus linked to a longer tradition of life as the ability to self-movement. For Immanuel Kant, life was the ability of a substance to act and change based on an inner principle. Romantic philosophers, such as Friedrich von Schelling, understood life, a living being, as having an inner principle of self-movement. For Arthur Schopenhauer, the will to live was the universal drive of life. Life, Xavier Bichat claimed, is the total sum of functions that resist death. This life force governs organic life. Vitalist conceptions of life dominated biology until the middle of the nineteenth century.

Studies of the living and the life processes, the origin, course, and end of life, as well as the classification of life forms and their essential properties were performed in the seventeenth and eighteenth centuries without necessarily summarizing it in a science of the living, a general life science (Nachtomy and Smith 2014). Through the microscope, one discovered that every drop of water was full of life. Antonie van Leeuwenhoek, Robert Hooke, and other microscopists saw a countless number of microorganisms in this microcosmic world beyond the ordinary sight. A classic question concerned spontaneous generation, *generatio spontanea* or *generatio æquivoca*, that is, the extent to which living organisms can arise spontaneously from dead matter. Flies and larvae seemed to crawl out of rotten meat as if coming from nothing. Fungi grew from the soil, and frogs from swamps. In the

1740s, Abraham Trembley experimented with the freshwater polyp and demonstrated its ability to regenerate by division. Through experiments by John Needham and Lazzaro Spallanzani, later by Louis Pasteur and John Tyndall, the theory of spontaneous generation could finally be rejected, and the discovery of microbes led to modern microbiology.

Another central issue in the life sciences during the eighteenth century, in which Carl Linnaeus made important contributions, concerned the classification and systematization of life. Nature exhibited a variety of life forms. This chaotic diversity could, however, be arranged and named in accordance with the binary nomenclature and the division of nature into kingdoms, classes, orders, genera, and species. The classification and categorization of life was set in an all-encompassing system in Linnaeus's *Systema naturae* (1735) and subsequent editions.

The anatomy and physiology of the seventeenth and eighteenth centuries mapped the living body. In the late eighteenth century, there were several competing medical systems, such as humoral pathology, the Hippocratic-Galenic doctrine, iatromechanics, vitalism, Hoffman's tonus, Stahl's animism, Haller's irritability and sensibility, and many more. Many discoveries during the late eighteenth and early nineteenth centuries changed the view of what life is. Following the discoveries of Carl Wilhelm Scheele, Joseph Priestley, and Antoine-Laurent de Lavoisier, the function of oxygen in respiration was demonstrated. Luigi Galvani and Alessandro Volta demonstrated the muscle electricity. In the 1780s, Galvani did some experiments on frogs showing that the frog legs began kicking when they were exposed to electricity. This could be interpreted as there was a kind of electricity within the living animal, an "animal electricity," a vital force that endowed organic matter with life. Mary Shelley's famous novel *Frankenstein* from 1818 was inspired by the demonstrations of Galvani. A dead human corpse was brought to life by the application of electricity. Other important advances of science that change the conception of life were the discovery of microorganisms, and in its turn the establishment of microbiology and bacteriology as scientific disciplines, as well as Matthias Schleiden and Theodor Schwann's

development of cell theory which identified the cell as the basic unit of life, Karl Ernst von Baer's comparative embryology and the emergence of life from preformed structures, Georges Cuvier's paleontology, Jean-Baptiste de Lamarck and the evolution of life, demonstrating how new species are arising from old, extinct species. According to Lamarck, life could be defined as a certain organic movement that could be activated by an external cause, such as caloric (heat) or electricity. The spontaneous generation of the simplest living beings, he explained as an agitation of matter, the "l'orgasme vital," of subtle gelatinous matter (Tirard 2010).

A collective concept for the study of the living does not emerge however until around 1800, "biology," from the Greek *bios*, life, and the affix *logia*, doctrine, among others by Karl Friedrich Burdach, Gottfried Reinhold Treviranus, and Lamarck. During the latter half of the nineteenth century, the question of life came to be shaped by the new evolutionary biology, Charles Darwin's work on the origin of species, the selection theory and phylogeny. The evolutionary theory explained, even though Darwin lacked an explicit definition of life, how current life forms evolved from previous simpler forms. Darwin even ventured to an explanation of the origin of life from the primordial soup in Earth's early history. Ernst Haeckel put forward the basic biogenetic rule, about ontogeny as a recapitulation of phylogeny, how a human fetus during fetal development seems to undergo the same phases as during the evolution from simple organisms, over fish to mammals.

Overview

In its original sense, life is persistence, perseverance. Implicit in many of the philosophical and biological conceptions of life is the view of life as binary, life and death, warm and cold, and motion and immobility. Commonly one has identified life with certain organs, the heart, the lungs, or the brain, as something existing, something material, with chemical, essential properties, such as organic molecules, and in contrast to that, as a process, something that moves, changes, is becoming something, through fermentation, vital heat, or motion. Life has thus

been conceptualized mainly in two ways, as existence or process. Life has been seen as a mode existence, a state, or an activity, a vital force for self-motion, self-creation, and self-preservation. These concepts of life have given rise to philosophical and scientific questions concerning the essence of life, its material components, its characteristics and description, order and classification, and questions concerning the processes of life, what sustains life, its causes and transformations, its origin and future, and its possible existence elsewhere in universe (Dick 1982; Dick 1996).

Cross-References

- [Buffon's Conception of Origins of Life](#)
- [Cuvier's Conception of Origins of Life](#)
- [De Maillet's Conception of Origins of Life](#)
- [Diderot's Conception of Origins of Life](#)
- [Great Chain of Being](#)
- [Leeuwenhoek, Antony van](#)
- [Life in the Solar System \(History\)](#)
- [Origins of Life, History of](#)
- [Principle of Plenitude](#)
- [Spontaneous Generation, History of](#)
- [Vitalism](#)

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Life, Definition of

Erik Persson
Lund University, Lund, Sweden

Definition

There have through history been many attempts to define “life” but there is no generally accepted definition of “life” at this date. As a result, some have come to believe that defining “life” is not a fruitful endeavor. This seems to be a minority view, however, since the quest to find or create a definition of “life” is as active as ever.

Overview

The purpose of defining “life” varies, but the most common purpose is to find a *de re definition* that identifies a *natural kind*.

A natural kind is a grouping of phenomena according to demarcation lines that exist objectively in nature independently of us and can (in theory) be discovered by us, in contrast to a grouping that does not exist independently in nature and thus has to be invented by us.

A *de re* definition is sometimes also called a *real definition* and is contrasted with, for instance, *stipulative definitions* and *operational definitions*.

The purpose of a stipulative definition is to create a definition for a special purpose without

regard for whether the definition refers to any natural kind. Stipulative definitions can be used to define “life” in special situations but are probably not very useful for defining “life” in astrobiology, where life is the primary study object. Given that astrobiology’s ambition is to increase our knowledge about the real world, “life” should reasonably refer to a natural kind, not a grouping created by us for some particular purpose.

The purpose of operative definitions is basically the same as for stipulative definitions, but with the constraint that the definition is based on a particular method, instrument, or the like. It has, for instance, been suggested that different disciplines could define life in different ways. This does not come through as a suitable solution for astrobiology, however, partly because astrobiology is a multi-disciplinary project where the arguably most important term has to refer to the same thing for everyone involved, and partly because the study object of astrobiology is life in a very wide sense that covers the origin, evolution, and future of life on Earth as well as in the universe.

A *de re* definition typically takes the form of a list of properties that are supposedly individually necessary and jointly sufficient to identify the phenomenon in question, in our case, life. That is, each of the properties on the list needs to be shared by all life while no non-living entity can possess all of the properties on the list. It may seem surprising that no one has yet managed to compose such a list. One possible reason for why this is the case, is that we still only know about one instance of life, namely life on Earth, which is all related. This limitation makes it very hard to come up with a general definition of life. Another reason seems to be that life is constantly evolving, which means new properties emerge constantly, while other properties disappear. Life is in that way a moving target and given what we know today about life and evolution, we have no reason to believe that there are any core of properties (also called an *essence*) that is exempt from this process. Even so, many continue to search for one and hope that improved knowledge about life (including a discovery of extraterrestrial life) will reveal such a core of unchangeable properties. Others look for alternative ways of defining

life that are more flexible and do not assume a core of unchangeable properties.

One alternative form of definition is called an *ostensive definition*. An ostensive definition is performed by providing examples of the phenomenon that is to be defined. One can, for instance, point at a number of chairs and say for each of them, “that is a chair.” When confronted by other possible chairs we are then supposedly able to tell if they are chairs or not based on our experience of previous chairs. This is a type of definition that may work well for chairs but that is probably not of much use for a multi-faceted phenomenon like life. It may, however, be historically important as an explanation of how our forefathers started to distinguish between life and non-life. Likewise, it can have pedagogical value as a way of teaching children to distinguish between life and non-life.

Another alternative is the *list definition*. A list definition is provided by listing all the phenomena we want to include under our definition. This is, for obvious reasons, impossible to do with life. There is just too much life. Also, new life is born and old life dies off faster than we would have a chance to update the list. Finally, we can only include life that we know on the list. Life that has not yet been discovered, on or off Earth cannot be included, and even if we do discover extraterrestrial life, we will probably never be able to discover all non-extraterrestrial life. The list can therefore never be complete, and we will thus never have a complete definition of life.

Both the ostensive definition and the list definition can be seen as examples of “I-know-it-when-I-see-it” definitions. Though attractive in the sense that they provide a way of producing a definition without the need for identifying any core properties, there are also some important drawbacks. The most important drawbacks of “I-know-it-when-I-see-it” definitions for astrobiology are probably that:

1. They will not help us determine the tricky cases, that is, discoveries that are not obviously life, nor obviously non-life.
2. They will not help us search for extraterrestrial life. It will be very difficult to determine which experiments, instruments, etc. to choose if we do not know beforehand what we are looking for.

There are also some new alternative suggestions for how to define “life” as a natural kind without having to assume a core of unchangeable properties. These include, for instance, suggestions inspired by Ludwig Wittgenstein’s ideas of *family resemblance*, and Alan Turing’s ideas of how to test for Artificial Intelligence (the so-called *Turing test*). Because they are still not fully developed or tested, it is too early to assess these methods at this date.

Cross-References

- [Astrobiology](#)
- [Biosignature](#)
- [Evidence in Astrobiology](#)

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Life, Definition of (from Antiquity to the Eighteenth Century)

► [Life, Concept of \(from Antiquity to the Eighteenth Century\)](#)

Life, Limits of

► [Extremophiles](#)

Life, Value of

Erik Persson
Lund University, Lund, Sweden

Definition

The phrase “the value of life” can refer to, among other things, the value of life as a phenomenon, the value of particular life forms, the value of individual organisms, or the value of being alive. When used in connection with astrobiology, “the value of life” usually refers either to the value of life as a phenomenon or the value of a particular life form such as extraterrestrial life or a particular species of extremophile.

Overview

Value, whether of life or of other things, comes in many different forms. It is, for instance, common to distinguish between instrumental value and end value (also called final value, intrinsic value, or noninstrumental value) where the former refers to the value something has as a means for promoting something else that has value, while the latter refers to the value something has as an aim in itself, independently of whether it can also promote other values. End value is sometimes described as the final stage in a chain leading up to one or more ultimate values. What “ultimate” means in this sense is debated. Some argue there can only be

one ultimate value, and thus only one phenomenon that has value as an end in itself. This position is known as value monism. Happiness is a common candidate as the one ultimate value according to this position. If that is correct, life can only have instrumental value as being (presumably) a necessary condition for happiness. The opposite position is called value pluralism, and it states that there is no reason why there cannot be more than one end value. Typically, this position considers end value to be subjective and determined by the preferences of individual sentient beings, while others claim that even though there can be more than one phenomenon with end value, some things are suitable as having end value but others are not.

A basic tenant of astrobiology is that life has epistemic value, meaning that life can be used to forward the production of knowledge. The epistemic value of life is therefore a form of instrumental value. The knowledge achieved in this way can in turn be seen as having value in its own right (end value) or as a means to other things (instrumental value), for instance, helping us becoming better stewards of the living environment on our own planet.

It is also common, both among astrobiologists and among people in general, to assign end value to life. This is probably both a strong driving force for astrobiology, and a complicating factor because of the inherent impossibility of studying life without disturbing it in any way (see also the entries on research ethics and planetary protection).

Another common value distinction is that between inherent value (also called intrinsic value) and relational value (also called extrinsic value). The former refers to value that comes from an internal property of the phenomenon with value, while the latter refers to value that comes from some relational property of the phenomenon with value.

In astrobiology, a species can have inherent value, for instance, because of its ability to withstand extreme cold or because of a particularly interesting chemical composition (both inherent properties). If life is found on another planet or moon, it will (in addition to any inherent value it may have) have relational value because it is found on that particular planet or moon. Though some argue that end value can only supervene on inherent properties, it is usually acknowledged

that both inherent value and relational value can also be either instrumental or end value. The value a life form has because it is found on another world (relational value) can be seen as valuable in its own right (end value), and it can also be valuable for its ability to increase our understanding of life in general as well as our understanding of that world (instrumental value). The value a life form has because of its ability to withstand extreme cold (inherent value) is a fascinating fact that cannot only render its value in its own right (end value) but also increase our knowledge about life in general and about the limits for habitability in the universe (instrumental value).

For the question of moral status among living beings, see the entry on astrobioethics.

Cross-References

- ▶ [Astroethics](#)
- ▶ [Planetary Protection](#)

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Ligand

Henderson James CleavesII
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, a ligand is an ion or molecule that binds to a central metal atom forming what is called a coordination complex, which can be

neutral, cationic, or anionic. The complex, along with its counter ions, is called a coordination compound. The bonding between metal and ligand generally involves the donation of one or more of the ligand's electron pairs. Ligands in an ▶ [organometallic](#) complex often govern the reactivity of the central metal atom.

Ligands that are directly bonded to the metal form the first coordination sphere and are known as “inner sphere” ligands. “Outer-sphere” ligands are not directly attached to the metal but are bonded to the first coordination shell. Heme is an example of a biological coordination complex: the central iron ion is coordinated at the center of a ▶ [porphyrin](#) molecule by the latter's four pyrrole nitrogen atoms.

Cross-References

- ▶ [Organometallic](#)
- ▶ [Porphyrin](#)

Ligase

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In biochemistry, a ligase is a ▶ [catalyst](#), which could be a protein ▶ [enzyme](#) or ▶ [ribozyme](#), which joins together two molecules, for example, peptides or ▶ [nucleic acids](#). Important examples of this in molecular biology include DNA ligase and self-splicing introns. Ribozymes may have been evolved to carry out this reaction, as it is considered a potentially important means of constructing long RNA molecules before protein catalysts were available evolutionarily.

Cross-References

- [Intron](#)
- [RNA World](#)

Light Travel Time Effect

Nader Haghighipour
Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Definition

The light travel time effect, abbreviated by LITE or LTT (Irwin 1952, 1959), refers to the differences in the periodic mid-eclipse timing for an eclipsing binary star system that is perturbed by an external massive object (e.g., a third star in a tertiary system). For an unperturbed eclipsing binary star system, the two stars of the binary revolve around their common center of mass with a constant period. When the binary system

is perturbed by a third, massive object, the binary's center of mass wobbles around the center of mass of the entire three-body system. This causes the binary to be closer to the observer at times, while at other times, it will be farther away. This wobbling (or reflex motion) of the binary gives rise to time-varying light-travel paths resulting in differences in the periodic mid-eclipse timing for the binary stars. Figure 1 shows a schematic view of a LITE orbit.

Cross-References

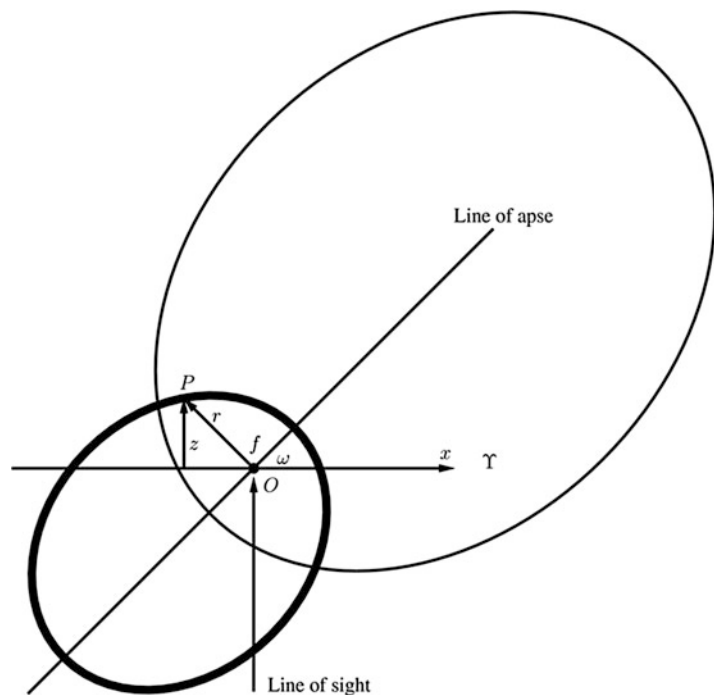
- [Eclipse](#)
- [Planets in Binary Star Systems](#)

References and Further Reading

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Light Travel Time Effect,

Fig. 1 Graphical outline of the LITE. The point O is the center of mass of the binary + companion in a triple star system. It also denotes the origin of the coordinate system. The x-axis points toward the line of reference. The (x, y)-plane coincides with the plane of the sky and is perpendicular to the line of sight. The LITE binary orbit is shown as a solid ellipse with the instantaneous position of the binary, denoted by a single point, at P. The angles ω and f denote the argument of pericenter and true anomaly, respectively. (Figure from Hinse et al. (2012))



Light Variation

► [Lightcurve](#)

Light-Year

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Lightyear](#)

Definition

The light-year is a unit of length used in astronomy; it corresponds to the distance traveled by light during 1 year in vacuum. A light-year (symbol: ly) is equal to 9.461×10^{15} m. It tends to be less and less used by professional astronomers who prefer the ► [parsec](#) (3.26 ly) and its derived units (kpc, Mpc), because they are more directly linked to observation.

Cross-References

► [AU](#)
► [Parallax](#)
► [Parsec](#)

Lightcurve

Maria Antonietta Barucci
LESIA, Observatoire de Paris, Université PSL,
CNRS, Université Paris Cité, Sorbonne
Université, Meudon, France

Synonyms

[Light variation](#)

Definition

The lightcurve describes the temporal variation of the brightness of an object.

Overview

The lightcurve shows the temporal variation of the brightness of a celestial body at a given wavelength. Due to the rotation of an object, the lightcurve generally has a sinusoidal periodic behavior with two maxima and two minima. In planetary science, the lightcurve is the most useful tool for investigating the rotational properties and the shape of a body, mainly of small ones: ► [asteroids](#), satellites, ► [comets](#), and transneptunian objects.

Most small bodies cannot be resolved since the apparent angular size of the object is in general smaller than the observer's angular resolution; therefore, analysis of the lightcurve can be used to determine the shape and the surface spots of the observed body.

For an airless body, each point of the lightcurve represents the fraction of the sunlight reflected by the illuminated portion of the body surface in the direction of the observer. The received flux depends on physical (shape, albedo, surface morphology) and geometrical (rotational phase, polar axis orientation) characteristics of the body. All this information can be extracted from a lightcurve by using a well-established inversion technique (Kaasalainen et al. [2002](#)).

The difference between the maximum and the minimum brightness is called the amplitude of the lightcurve and it is measured in magnitudes. The amplitude, however, varies considerably depending on the aspect angle at which the object is observed. It will have, for a given object, the biggest value for an equatorial view and it will be flat (lightcurve with no variation) when the object is observed on a polar view (rotational axis toward the observer). The amplitude of a lightcurve is an indicator of a body's elongation and allows the computation of the axis ratios of the osculating

ellipsoids approximating the shape of the observed object.

The light variations can also be due to the presence of a satellite around the primary body, as well as to complicated rotations, as in the case of tumbling asteroids or active comets. Moreover, seasonal variation of a lightcurve can be produced by activity depending on the heliocentric distance of the observed body. For example, from Pluto's lightcurve, strong evidence for albedo changes over time has been inferred, which is interpreted as a systematic sublimation of frosts from the sunward pole (seasonal variation).

Lightcurve can be also obtained on star occultation by an object of the solar system and can be used to measure the diameter of the body, the existence of an atmosphere, rings, and/or satellites.

In stellar astrophysics, the temporal variation in the brightness of an object such as a variable star or a nova or supernova is also called the lightcurve.

Cross-References

- [Asteroid](#)
- [Comet](#)
- [Comet \(Nucleus\)](#)
- [Kuiper Belt](#)
- [Pluto](#)
- [Trans-Neptunian Object](#)

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Lightyear

- [Light-Year](#)

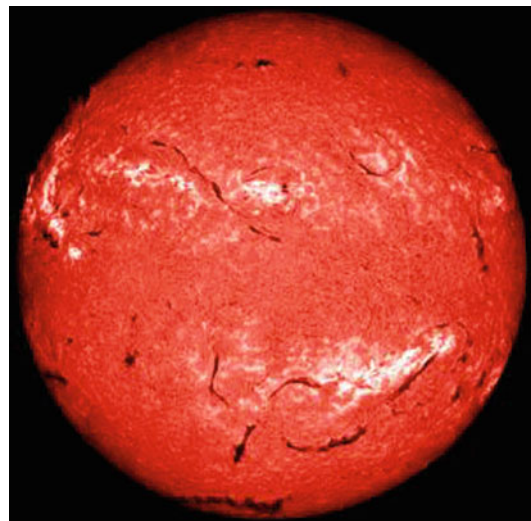
Limb Darkening

Daniel Rouan

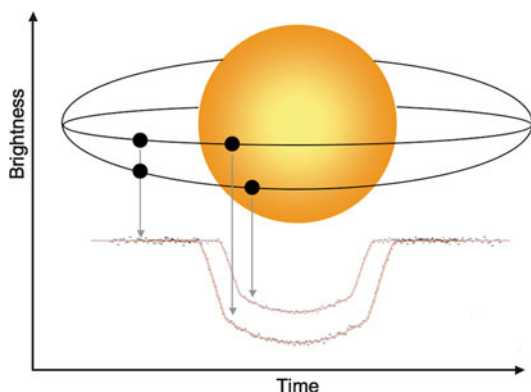
LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Definition

The limb darkening phenomenon is a decrease in brightness at the edge (the limb) of the surface of a star or planet. The effect is best studied on the Sun, but has also been put in evidence on other stars. It gives to an image of the Sun the misleading appearance of a sphere illuminated by the observer with a gradual shading on the edge (see Fig. 1). For a star, it occurs because the light at the edge comes on average from cooler – and thus less bright – layers of the ► [photosphere](#). Jupiter also exhibits a limb darkening effect. The limb darkening effect is actually observed when detecting planets by the ► [transit](#) method and must be taken into account to derive the proper planet's size (see Fig. 2).



Limb Darkening, Fig. 1 The limb darkening effect is clearly seen on the Sun: the surface brightness decreases toward the outer part of disk



Limb Darkening, Fig. 2 The limb darkening effect modifies the depth of the light decrease observed when a planet transits in front of the disk of a star. The effect depends on the precise trajectory of the planet across the disk, as illustrated by the two cases

separates the dayside from the nightside: e.g., the moon's crescent is bounded by the limb on one side and by the terminator on the other.

Limestone

► [Carbonate on Mars](#)

Limonite

► [Goethite](#)

Cross-References

- [Photosphere](#)
- [Radiative Transfer](#)
- [Stars](#)
- [Transit](#)

Limb, Astronomical

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

In astronomy, the limb of an object such as the Sun, a planet, or a satellite is the object's apparent edge as seen against the dark sky background. The solar ► "[limb darkening](#)" refers to the fact that the Sun is less bright (because of ► [radiative transfer](#) effects) toward its edge than toward its center. The limb may be compared to the "terminator." For a planet or satellite that is not observed at zero phase angle (i.e., at full phase), the terminator is the locus of points on the object where the line to the Sun (or other source of illumination) is tangent; it thus

Lindblad Resonance

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Lindblad resonances are the source of spiral density waves in disks. For the case of a planet orbiting a star within a ► [protoplanetary disk](#), Lindblad resonances are found at the location where the disk's natural epicyclic frequency (the frequency at which a radially displaced fluid parcel will oscillate) is a commensurate multiple of the planet's orbital period. This is the same case as for mean motion resonances, but altered by pressure support in the gaseous component of the disk. Density waves triggered at inner and outer Lindblad resonances act, together with matter in the co-orbital region, to torque the planet's orbit and lead to (type 1) orbital migration for planets with masses between roughly 1 and 50 Earth masses.

Lindblad resonances are postulated to drive spiral density waves in galaxies.

Cross-References

- ▶ [Corotation Torque](#)
- ▶ [Planetary Migration](#)
- ▶ [Protoplanetary Disk](#)

Line Emission

Stefanie N. Milam
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

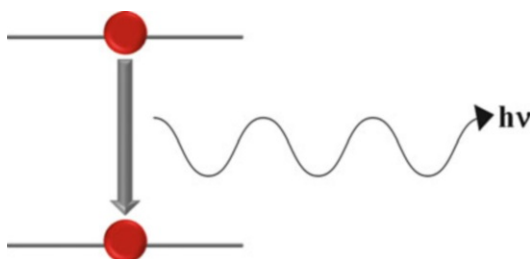
Line emission is the process by which an atom or molecule moves from a higher energy state to a lower one by emitting a photon. The emitted photon has a discrete energy (E) that is equal to the difference of the two states, and a corresponding frequency (ν). The energy is defined as (Fig. 1):

$$E = h\nu,$$

where h is Planck's constant (see General Data Table 4).

Cross-References

- ▶ [Absorption Cross Section](#)
- ▶ [Spectral Line](#)
- ▶ [Spectroscopy](#)



Line Emission, Fig. 1 The transition from the upper to the lower energy state produces a photon of energy $h\nu$

Line of Sight

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The line of sight is the imaginary straight line between an observer and the celestial object he/she is pointing at.

Line Profile

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Line shape](#)

Definition

The line profile for a ▶ [spectral line](#) is a representation of its spectral intensity as a function of frequency or wavelength. The line may appear in emission or absorption toward an astronomical source. Various physical processes can act to modify the natural line profile, such as ▶ [Doppler](#), turbulent, or collisional broadening.

Cross-References

- ▶ [Doppler Shift](#)
- ▶ [Spectral Line](#)

Line Shape

- ▶ [Line Profile](#)

Line Shielding

Steven B. Charnley
Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Line shielding refers to the situation in which molecules whose photo-destruction is controlled by absorption of radiation in spectral lines can have their destruction rates greatly reduced in interstellar clouds. This arises when there is sufficient material between the source of UV radiation and the cloud interior such that molecules in the exterior layers of the cloud preferentially absorb the dissociating photons, thus leading to molecules in the cloud interior experiencing a greatly attenuated photon flux. Line shielding is important for the survival of H₂ and CO in ► [molecular clouds](#) near energetic astrophysical sources.

Cross-References

- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Molecular Cloud](#)

Linea, Lineae

Roland J. Wagner
Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Definition

A linea is a bright or dark curved or linear surface marking with or without topographic expression. On the ► [terrestrial planets](#), lineae primarily occur on ► [Venus](#) but the majority of features termed lineae are observed on Jupiter's satellite Europa. Seen at high resolution, these lineae are ridges – either single, double, or complex – which were created by tectonism and/or ► [cryovolcanism](#).

Lineae on Venus and Europa can extend over several thousands of kilometers.

Cross-References

- [Albedo Feature](#)
- [Cryovolcanism](#)
- [Europa](#)
- [Jupiter](#)
- [Satellite or Moon](#)
- [Terrestrial Planet](#)
- [Venus](#)

Linear Energy Transfer

Gerda Horneck
Institute of Aerospace Medicine, Radiation
Biology, DLR German Aerospace Center, Köln,
Germany

Synonyms

[LET](#); [Stopping power](#)

Definition

During its passage through matter, a heavy charged particle loses its kinetic energy via a sequence of small energy transfers to atomic electrons in the medium. Most energy is deposited in a narrow region around the particle's trajectory, the so-called particle track. The energy loss per unit length of particle track is termed the stopping power in nuclear physics and linear energy transfer (LET) in ► [radiation biology](#). LET is expressed in units of keV/μm. Heavy charged particles are referred as “high LET radiation,” while x-rays, gamma-rays, and fast electrons are known as “low LET radiation”.

History

The dependence of LET on the energy and electric charge of the flying particle was developed by

H. A. Bethe and F. Bloch in the 1930s (Bethe–Bloch equation).

Cross-References

- [Biostack](#)
- [Cosmic Ray, Ionization Rate](#)
- [Cosmic Rays in the Heliosphere](#)
- [DNA Damage](#)
- [HZE Particle](#)
- [Ionizing Radiation, Biological Effects](#)
- [Radiation Biology](#)

Line-of-Sight Velocity

- [Radial Velocity](#)

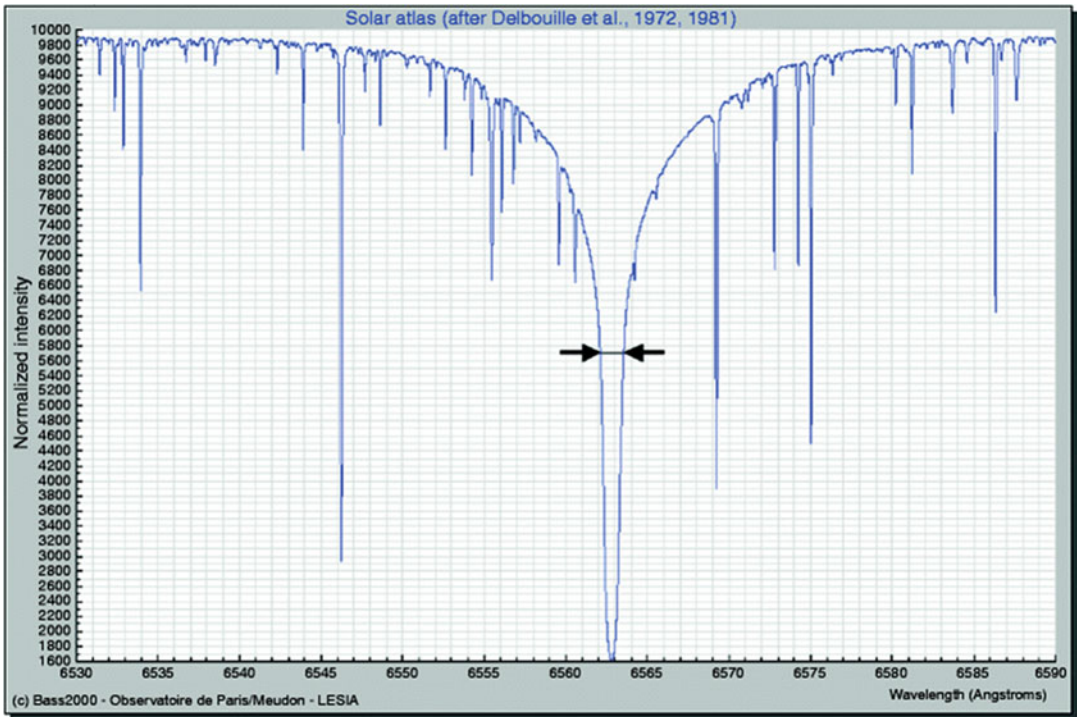
Linewidth

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The expression linewidth designates the intrinsic width of a ► [spectral line](#) expressed in units of ► [wavelength](#) (Å, nm, μm, etc.) or frequency (Hz). Generally, it is the full width at half maximum (FWHM) that is used. The linewidth can refer to a line in absorption or emission. The width of a line results in general from the contributions of several phenomena: for instance, the natural linewidth is linked to the lifetime of the transition, while the Doppler broadening is due to chaotic movements (turbulence, thermal motion)



Linewidth, Fig. 1 The linewidth of the hydrogen H α line seen in absorption in the spectrum of the Sun at $\lambda = 656.6$ nm. The arrows mark the width adopted here (FWHM).

One notes here that the pedestal of the line (top, or bottom in the case of an emission line) can be much larger than the linewidth

in the emitting medium. Note that the spectrograph used to measure a spectral line must have a spectral resolution better than the linewidth to derive a proper value. Figure 1 illustrates the linewidth of a strong hydrogen line ($H\alpha$) seen in the solar spectrum.

Cross-References

- [Electromagnetic Spectrum](#)
- [Line Profile](#)
- [Spectral Line](#)
- [Spectrometer](#)
- [Spectroscopy](#)

Lingula, Lingulae

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

A lingula is an extension of a plateau having rounded lobate or tongue-like boundaries (definition by the International Astronomical Union; <http://planetarynames.wr.usgs.gov/jsp/append5.jsp>). Lingula is used as a descriptor term for naming surface features on ► [Mars](#).

Cross-References

- [Mars](#)

Linkage Map

- [Genetic Map](#)

Lipid

- [Amphiphile](#)

Lipid Bilayer

David Deamer
Department of Chemistry, University of
California, Santa Cruz, Santa Cruz, CA, USA

Keywords

Hydrophobic effect · Permeability barrier ·
Self-assembly

Synonyms

[Membrane](#)

Definition

Lipid bilayers are the primary structural components of all biological membranes, serving as a boundary between the cytoplasm and the external environment.

Overview

Self-assembled structures of amphiphilic molecules occur as ► [micelles](#), monolayers, and bilayers. Monolayers form when amphiphilic molecules accumulate as a monomolecular film at the air-water interface. In contrast, lipid bilayers assemble in bulk aqueous phases, consisting of two monolayers associated in such a way that the nonpolar hydrocarbon chains are directed inward, with hydrophilic polar or ionic groups on the outer surface. Because of their nonpolar interior composed of hydrocarbon chains, lipid bilayers are relatively impermeable to simple ions or ionic compounds in solution. This allows them to act as ► [permeability](#) barriers, which in turn permits ion gradients to be produced and maintained by ion transport enzymes.

Lipid bilayers are surprisingly stable, even though the amphiphilic molecules are not held together by covalent bonds. Instead, the associations between lipid molecules are stabilized by the hydrophobic effect that tends to exclude hydrocarbon chains from bulk water. This stability allows

lipids to assemble into microscopic compartments also called lipid vesicles, or sometimes liposomes. The relevance to the origin of life is that self-assembling amphiphilic molecules were likely to be components of the mixture of organic compounds present in the early Earth environment and could therefore provide membranous compartments required for the first forms of cellular life.

Cross-References

- [Amphiphile](#)
- [Cell Membrane](#)
- [Permeability](#)
- [Self-Assembly](#)

References and Further Reading

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- [55 Cancri](#)

Liquid Chromatography-Mass Spectrometry

Shohei Ohara
Carnegie Institution of Washington, Geophysical
Laboratory, Washington, DC, USA

Keywords

Electrospray ionization · Liquid chromatography · Mass spectrometry

Synonyms

[LC/MS](#)

Definition

Liquid chromatography-mass spectrometry is an analytical technique that combines liquid chromatography (LC) as a separation technique with mass spectrometry (MS) as a detection technique.

Overview

Liquid chromatography (LC) is an analytical technique that exploits the fact that different molecules partition to differing extents between a liquid mobile phase and solid stationary phase. LC is used to separate a very wide range of polar and nonpolar compounds, from low-molecular-weight organic and inorganic compounds to high-molecular-weight proteins and nucleic acids. The use of mass spectrometric detection after a chromatographic separation is a particularly powerful combination in the case of the analysis of complex mixtures in which many compounds co-elute and molecule-specific discrimination is required for unambiguous detection and quantification. Mass spectrometry requires the ionization of the eluting molecules (either positively or negatively charged) followed by the acceleration and separation of the subsequently formed ions according to their dynamic response to either a fixed (magnetic sector) or oscillatory (quadrupole) magnetic field or simply as a function of time (time-of-flight) subject to the ionic mass-to-charge (m/z) ratio. One of the greatest challenges in interfacing LC with MS was how to introduce the liquid chromatographic eluant into the low-vacuum environment required for mass spectrometry. The introduction of the atmospheric pressure ionization (API Huang et al. 1990) technique greatly expanded the number of compounds that can be analyzed by LC/MS. In API, aerosol droplets are ionized at the tip of a nebulizer at atmospheric pressure. The carrier liquid is stripped from the droplets by N_2 gas during their passage from the nebulizer tip to the extraction cone of the MS during which time the charge is transferred to the eluting molecule. Common API techniques include electrospray ionization (ESI Fenn et al. 1989) and atmospheric pressure chemical ionization (APCI Horning et al. 1974). ESI is especially useful for analyzing large biomolecules such as proteins,

peptides, and oligonucleotides, where the use of time-of-flight mass detectors allows for the analysis of high-molecular-weight (MW) molecules. However, if tandem MS is desired (i.e., MS/MS), at least one of the mass detectors has to be a quadrupole. During ESI, large molecules often acquire more than one charge; thus, LC/MS with quadrupole mass analyzers can analyze molecules as large as 150,000 amu even though a quadrupole mass detector typically has an m/z upper limit on the order of 3000 (e.g., 150,000 amu/50 z = 3000 m/z). APCI is applicable to a wide range of polar and nonpolar molecules with MW lower than 1500 amu.

Cross-References

- [Chromatography](#)
- [HPLC](#)
- [Mass Spectrometry](#)

References and Further Reading

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Liquidus

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Liquidus temperature](#)

Definition

In chemistry, the liquidus is the highest temperature at which crystals can exist in a melt at thermodynamic equilibrium. Above the liquidus temperature, the material is homogeneous; below it, two phases exist as crystals begin to form. Below the liquidus temperature, homogeneous glasses may exist via rapid cooling and kinetic inhibition of crystallization.

Cross-References

- [Solidus](#)

Liquidus Temperature

- [Liquidus](#)

LISA

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[Laboratoire Interuniversitaire des Systèmes
Atmosphériques](#)

Definition

LISA is a joint research laboratory involving two universities in Paris, France, and the French National Center for Scientific Research (CNRS). The principal research area is studying how the terrestrial and other planetary atmospheres function, using direct observation, laboratory simulations, and numerical modeling. In terms of astrobiology, LISA research includes studies of the reactivity and evolution of organic matter in

extraterrestrial environments and the search for organic matter in these environments. LISA uses laboratory experiments to simulate extraterrestrial conditions and participates in the designing and construction of instrumentation for chemical analysis, to be used on space missions (principally for ESA and NASA).

Cross-References

- [Astrobiology](#)
- [ESA](#)
- [NASA](#)

Lithium Absorption

Steven W. Stahler
Department of Astronomy, University of California, Berkeley, CA, USA

Definition

The presence of the element lithium acts as a chronometer for stars and brown dwarfs. Objects of solar mass and below which have lithium in their atmospheres must be relatively young, since the element is eventually destroyed by fusing with protons. The presence of the lithium absorption line at 6,708 Å has often been used to confirm the youth of suspected pre-main-sequence stars. Very low-mass stars and brown dwarfs evolve so slowly and are cold enough that their lithium may be intact even at a substantial age. Thus, the appearance of lithium below a certain mass has yielded the ages of ► [stellar clusters](#) such as the Pleiades.

Cross-References

- [Brown Dwarf](#)
- [Pre-Main-Sequence Star](#)
- [Stellar Cluster](#)
- [T Association](#)
- [T Tauri Star](#)

Lithopanspermia

Gerda Horneck
DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Definition

The term Lithopanspermia describes a scenario of interplanetary transport of microorganism by use of ► [meteorites](#). It involves three basic steps: (i) the escape process, that is, removal to space of biological material, which has survived being lifted from surface to high altitudes by impact ejection; (ii) interim state in space, that is, ► [survival](#) of the biological material over timescales comparable with interplanetary or interstellar passage; (iii) the entry process, that is, nondestructive deposition of the biological material on another planet. All three steps of lithopanspermia are now accessible to experimental testing in ground simulation facilities as well as in exposure experiments in space.

History

The possibility of meteorite-mediated interplanetary transport of life was already considered in the 1870s by von Helmholtz and Thomson (Lord Kelvin), who favored a version of ► [Panspermia](#) in which fragments of extraterrestrial rocks carrying microbes as blind passengers within their cracks may transport life from one planet to the other. However, during their lifetime, no mechanism was known to accelerate rocks to escape velocities in order to leave their planet of origin; as a result Kelvin's idea was discarded. After the discovery in 1983 that a certain group of meteorites (SNC meteorites) has originated from ► [Mars](#), evidence was provided that rocks can naturally be transferred between ► [terrestrial planets](#) in conditions that could maintain trapped viable life systems, and as a consequence, Kelvin's idea, now called Lithopanspermia, has been revisited.

Cross-References

- [Crater, Impact](#)
- [Ejecta](#)
- [Exposure Facilities](#)
- [Mars](#)
- [Meteorites](#)
- [Panspermia](#)
- [Planetary and Space Simulation Facilities](#)
- [Spallation Zone](#)
- [STONE](#)
- [Survival](#)
- [Terrestrial Planet](#)

Lithophile Elements

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

In the Berzelius-Goldschmidt classification, lithophile elements are those concentrated in the rocky part (lithos) of the terrestrial planets. They bond with oxygen in tetrahedral sites (Si, Al, P) or in octahedral and dodecahedral sites. These elements form either silicates and oxides (Ca, Mg, Fe, Al, Ti, Na, K) or solid solutions in these minerals. Among the metals, the alkali (Li, Na, K, Rb, Cs) and alkali-earth elements (Mg, Ca, Sr, Ba), the rare-earth elements and the actinides (U, Th), and the high field-strength elements (Ti, Zr, Hf, V, Nb, Ta) are broadly used in geochemistry. Halogens (F, Cl, Br, I) also have a lithophile behavior.

Cross-References

- [Chalcophile Elements](#)
- [Siderophile Elements](#)

Lithosphere, Planetary

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

The *lithosphere* is the comparatively cold, rigid outermost layer of the Earth and of other rocky planets. It is thus defined by a thermal, not a compositional change. Earth has two types of lithospheres: *Oceanic lithosphere* comprises an upper layer of mainly basaltic crust and a lower layer of mantle peridotite whose thickness increases from a few kilometers at mid-ocean ridges to about 100 km beneath the oldest parts of the oceanic crust. *Continental lithosphere* comprises the continental crust and a section of the mantle whose thickness varies from tens of kilometers beneath active rifts to over 200 km beneath old Archean age cratons such as beneath the Kaapvaal, South Africa. Heat transfer is conductive through the lithosphere but convective in the underlying asthenosphere. Martian lithosphere is around 83 km thick beneath ► [Olympus Mons](#) and other volcanic complexes. The shallow lithosphere of ► [Venus](#) consists of a region of brittle flow in the crust to a depth of 2–4 km, underlain by a weak lower crust and brittle to ductile upper mantle.

Cross-References

- [Asthenosphere](#)
- [Continental Crust](#)
- [Craton](#)
- [Crust](#)
- [Mantle](#)
- [Oceanic Crust](#)
- [Peridotite](#)
- [Plate Tectonics](#)

Lithotroph

Charles S. Cockell

Geomicrobiology Research Group, PSSRI, Open University, Milton Keynes, UK

Keywords

Inorganic compounds · Electron donor ·
Extreme environments · Lithic habitats

Definition

Lithotrophs are microorganisms that use inorganic compounds as electron donors to conserve energy for growth.

Overview

A lithotroph is a microorganism that uses inorganic substrates as a source of electron donors to drive energy acquisition, using either organic carbon or carbon dioxide as a source of carbon for constructing cellular materials (Ehrlich and Newman 2008). Microorganisms oxidize the electron donors to generate electrons that are channeled into electron respiratory chains to produce the energy-storing molecule, ► [ATP](#). These organisms can use a variety of electron acceptors to complete the respiratory process, including oxygen, sulfate, and other compounds. Lithotroph means rock (lithos) eater (troph) and representatives are found in both the bacterial and archaeal domains. No multicellular organisms are currently known that are able to use inorganic compounds as an ► [energy source](#), although they can gain energy from symbioses with lithotrophs. Examples of lithotrophs include iron-oxidizing ► [bacteria](#) that metabolize reduced iron to oxidized iron, purple sulfur bacteria that transform sulfide into sulfur, nitrifying bacteria that use ammonia and convert it into nitrite or use nitrite to produce

nitrate, hydrogen bacteria that oxidize hydrogen to water, and a range of sulfur bacteria that use oxidized sulfur compounds to produce sulfide (Widdel et al. 1993; Raven 2009). ► [Methanogens](#) are also lithotrophs and use hydrogen to reduce carbon dioxide to methane. The use of inorganic compounds in this way makes lithotrophs important in a wide variety of geological processes including the biogeochemical cycling of carbon, nitrogen, and sulfur, and the weathering of rocks both on the surface of the Earth and in the deep ocean crust, which releases nutrients into the ► [biosphere](#) and is responsible for drawing down carbon dioxide from the atmosphere (influencing long-term climate control) (Bach and Edwards 2003). Lithotrophs are not exclusively associated with extreme environments, but in physical and chemical extremes they tend to dominate. For example, *Thiobacillus* species, which are iron-oxidizing bacteria, are found in highly acidic environments where reduced iron is stable. Their activity in the environment contributes to the well-known phenomenon of acid mine drainage (AMD) (Baker and Banfield 2003), whereby oxidation of iron in ► [pyrite](#) and its further catalytic effect on pyrite oxidation produces sulfuric acid, generating extremely acidic environments in which the organisms thrive. Methanogens are found in the deep subsurface, where hydrogen that is generated by water-rock reactions in ultramafic settings is used as the electron donor (Lollar et al. 2006). On account of their ability to grow in extreme environments, lithotrophs are of great interest to astrobiologists since their ability to use inorganic compounds from rocks, or the products of chemical reactions involving rocks, makes their metabolisms potential analogues for metabolic processes that could sustain life in other planetary crusts (Onstott et al. 2006) and they provide insights into potential lithotrophic conversions on the early Earth (Canfield et al. 2006; Sleep and Bird 2007; Cockell 2010). Lithotrophs can be divided into a number of subgroups. Photo-lithotrophs use light to gain energy, the inorganic

electron donors being used only in biological synthesis reactions. Photolithotrophs are common in anaerobic environments and include the green bacteria (e.g., Chlorobiaceae) and purple bacteria (e.g., Chromatiaceae), which use sulfide, sulfur, hydrogen, and iron as electron donors. The oxygenic cyanobacteria are also photolithotrophs. Lithoheterotrophs gain their energy from inorganic compounds but use organic matter or other organisms as a source of carbon. Lithoautotrophs use carbon dioxide as a source of carbon and mixotrophs are capable of gaining carbon either from carbon dioxide or from organic carbon.

Cross-References

- [Chemolithoautotroph](#)
- [Chemolithotroph](#)
- [Energy Sources](#)
- [Iron Cycle](#)

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Living Stromatolites

- [Microbial Mats](#)
- [Stromatolites](#)

LMT

- [Large Millimeter Telescope](#)

Local Restframe

- [Local Standard of Rest](#)

Local Standard of Rest

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Local restframe](#)

Definition

In astronomy, the local standard of rest designates the coordinate frame of reference linked to the center of mass of stars belonging to the neighborhood of the Sun. This frame revolves around the ► [Milky Way](#) at about 220 km/s with respect to the Galactic Center.

Lomagundi Carbon Isotope Excursion

Andrey Bekker

Department of Earth Sciences, University of California, Riverside, CA, USA

Department of Geology, University of Johannesburg, Johannesburg, South Africa

Keywords

Paleoproterozoic · Lomagundi Carbon Isotope Excursion · Rise of atmospheric oxygen

Synonyms

Lomagundi–Jatuli Carbon Isotope Excursion;
Paleoproterozoic Carbon Isotope Excursion

Definition

The Lomagundi carbon isotope excursion (LCIE), *sensu stricto* (s.s.), refers to highly positive carbon isotope values (on the average +8‰, but values as high as +16‰ are not uncommon with the highest values observed at +28‰) in Paleoproterozoic sedimentary carbonates deposited between ~2.22 and 2.06 Ga (Karhu and Holland 1996; Bekker et al. 2003), likely reflecting open-marine seawater composition. The beginning and the end of the excursion have not so far been observed in the sedimentary record, and there is also uncertainty about the exact age of these transitions. Positive (at ~2.32 Ga and between ~2.45 and ~2.32 Ga; Bekker et al. 2001; Rasmussen et al. 2013) and negative (between ~2.45 and 2.32 Ga; Bekker et al. 2005) carbon isotope excursions have been found leading to the LCIE s.s. The older positive carbon isotope excursions, in particular the ~2.32 Ga one, are considered to be an early expression of the LCIE *sensu lato* (s.l.). Furthermore, a short-lived, large-amplitude ~2.03 Ga carbon isotope excursion after the LCIE has recently been documented in the Woolly Dolomite of

Western Australia that was deposited in the rift basin connected to the ocean (Bekker et al. 2016). Although originally considered to be a plausible cause for the Great Oxidation Event (GOE) (e.g., Karhu and Holland 1996), it is now widely agreed that the LCIE s.s. followed the GOE and potentially occurred in response to it (e.g., Konhauser et al. 2011; Bekker and Holland 2012). The LCIE s.l. is associated with the Huronian ice ages and the final stage in the assembly of the supercraton Superia (Gumsley et al. 2017), while the LCIE s.s. followed them and ended during the sea level rise associated with the supercontinent breakup and submarine hydrothermal activity (Ossa Ossa et al. 2018). The excursion ended up with the ocean deoxygenation event and in association with deposition of Mn- and P-rich sediments (Bekker et al. 2003). This is by far the longest-lived and largest perturbation to the biogeochemical carbon cycle in the Earth's history, and yet, in contrast to Neoproterozoic events, it followed rather than led to the first series of global-scale ice ages.

History

Paleoproterozoic sedimentary carbonates with highly positive carbon isotope values were first discovered by Galimov et al. (1968) on the Fennoscandian Shield (Kola Peninsula and Karelia, Russia). At that time, authors did not recognize global significance of this phenomenon nor related it to a high relative burial rate of organic carbon. Seven years later, Galimov et al. (1975) reproduced earlier observations on a larger set of samples from Karelia and Kola Peninsula and Schidlowski et al. (1975) found similar values in correlative units of the Peräpohja Schist Belt in Finland near Gulf of Bothnia and in carbonates of the Lomagundi Group, Zimbabwe. The following year, Schidlowski et al. (1976) analyzed 67 carbonate samples from the Lomagundi Group, Zimbabwe, establishing for the first-time basin-scale extent of this anomaly and its name. Poor age constraints prevented them from recognizing the global nature of this anomaly, and they opted for

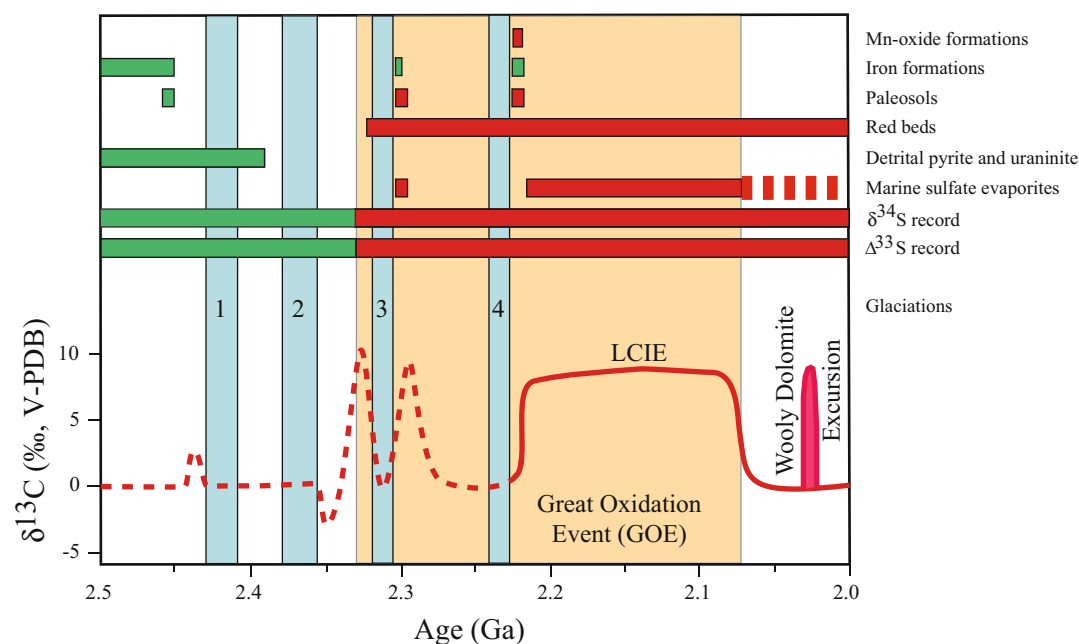
deposition in a closed lake with high productivity. Discovery of the similar-magnitude carbon isotope excursion in roughly correlative, high metamorphic grade carbonates of the Loch Maree Group (Scotland) and Lofoten Vesterålen (Norway) led Baker and Fallick (1989a, b) to propose global extent of this anomaly. Subsequent detailed work on the scale of the Fennoscandian Shield and a comprehensive review of geochronologic and chemostratigraphic data for carbonates bearing the LCIE confirmed the global nature of this signal and bracketed it between ~2.22 and 2.06 Ga (Karhu 1993; Karhu and Holland 1996). The LCIE s.s. has now been discovered on all continents except Antarctica. The older part of the secular carbon isotope curve for the Paleoproterozoic is still poorly constrained since precise ages for carbonates and carbonates themselves are rare for this time interval. Recent work established older than and leading to the LCIE s.s. positive and negative carbon isotope excursions and focused on relationships with other environmental and tectonic changes during the early Paleoproterozoic (e.g., Bekker et al. 2001, 2005, 2006; Rasmussen et al. 2013).

The global nature and sedimentary facies dependence of the LCIE has been discussed numerous times (e.g., Kheiskanen and Rychanchik 1999; Frauenstein et al. 2009; Bakakas Mayika et al. 2020; Prave et al. 2022; see Bekker et al. 2021 for a different view). Specifically, coupling between sedimentary facies and carbon isotope composition of carbonates has been used to argue for heterogeneity in carbon isotope composition of dissolved inorganic carbon in the middle Proterozoic ocean, although opposite trends from shallow- to deep-water settings have been postulated by Kheiskanen and Rychanchik 1999 and Prave et al. 2022. It is difficult to establish synchronicity of shallow- and deep-water facies in Paleoproterozoic sedimentary successions that do not outcrop well. Therefore, Bakakas Mayika et al. 2020 and Prave et al. 2022 relied on the Golovkinsky-Walther's Law, which states that "in a vertical succession of strata unbroken by significant hiatal surfaces, rocks layered one on top of the other were deposited in coeval, laterally adjacent

environments." While this law works well under steady-state sedimentary conditions, it would not work if the surface conditions were perturbed by global or widespread change in redox or chemistry. For example, deposition of black shales during the Cretaceous anoxic events above oxygenated sediments by no means implies that they represent coeval, laterally adjacent environments. Prave et al. (2022) used 100 Ma binning for carbonate carbon isotope data to infer that shallow-marine successions were marked by highly positive carbon isotope values, while deep-water successions were not during the ~2.22–2.06 Ga LCIE. The binning size is, however, too long to make this inference since pre- or post-LCIE successions can be erroneously assumed to be deposited during the LCIE. Presently, there is no known precisely dated LCIE-aged carbonate succession that does not carry positive carbon isotope excursion. It thus seems unlikely that the LCIE is a record of unprecedented seawater heterogeneity in carbon isotope composition of dissolved inorganic carbon, but further work is needed to precisely constrain ages of middle Paleoproterozoic sedimentary carbonate successions that record and do not record the LCIE.

Overview

The rise of atmospheric oxygen in association with the Huronian ice ages led to dramatic fluctuations with escalating magnitude in biogeochemical carbon cycle following the long-term stability of the Archean carbon cycle (Fig. 1). Although these fluctuations are only recognized in single sections, making this part of the secular carbon isotope variation curve less certain, their development before and during the Huronian ice ages argues for a dynamic state of carbon cycle at that time. The negative carbon isotope excursion in cap carbonates overlying glacial diamictites of the second Huronian ice age was recognized in multiple successions in North America and South Africa (Bekker et al. 2001, 2005). However, the subsequent positive carbon isotope excursion, bracketed between two glacial



Lomagundi Carbon Isotope Excursion, Fig. 1 Secular carbon isotope variations in seawater and redox indicators for the oxidation state of the early Paleoproterozoic atmosphere–ocean system (Modified from Bekker and Holland 2012). Four blue vertical bars mark Paleoproterozoic glacial events; the dashed secular carbon isotope curve between 2.5 and 2.22 Ga emphasizes the uncertainty in this part of the curve; red filled shape is the Woolly Dolomite excursion (Bekker et al. 2016); the dashed bar for

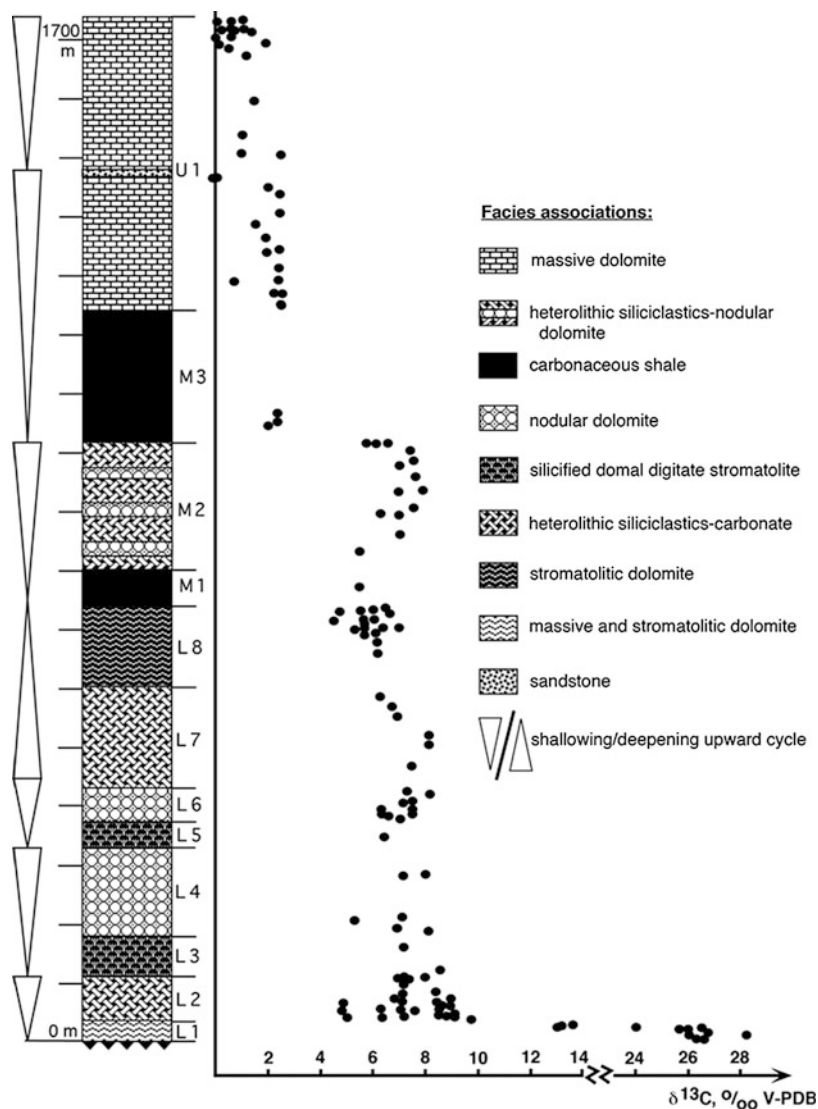
marine sulfate evaporites after ~2.06 Ga indicates that sulfate evaporites again became rare in the Paleoproterozoic and Mesoproterozoic records after that time. Deposition of iron formations and Mn-rich deposits indicates anoxic conditions in deep waters. While deposition of iron formations does not necessary require atmospheric oxygen and can be mediated by anoxygenic photosynthetic bacteria, Mn oxidation requires significant levels of atmospheric oxygen

diamictites, so far was only found in the Deutschland Formation of South Africa (Bekker et al. 2001). The 2.32 Ga Gordon Lake Formation of the Huronian Supergroup, Canada, provides a record of the positive carbon isotope excursion preceding the last (fourth) Paleoproterozoic glaciation before the LCIE s.s. (Bekker et al. 2005; Rasmussen et al. 2013). The LCIE s.s. started some time before the 2.22 Ga mantle plume event, but the stratigraphic record of rising carbon isotope values was not yet found. It is thus unclear whether the 2.32 Ga Gordon Lake Formation records the initial stage of the LCIE s.s. or is a separate event, although considering that they are separated by an ice age, it is likely that they represent separate events. The carbon isotope values mostly stayed at around +8‰ for the duration of the LCIE s.s., but it seems there is a rise to higher (~+15‰) values in the middle part of the

excursion with the highest values found at +28‰ (Bekker et al. 2003; Fig. 2). Since the positive C-isotope values are likely to reflect high relative burial rate of organic carbon, large amounts of oxygen must have been released to the surface environments during the LCIE s.s. (cf. Karhu and Holland 1996) with iron and sulfur in the continental crust consuming most of it. Indeed, red beds, sulfate evaporites, and high concentrations of redox-sensitive trace metals such as U, Mo, and Re in organic matter-rich shales appear at that time (but not reaching anywhere close to the Phanerozoic levels; Scott et al. 2008; Partin et al. 2013; Sheen et al. 2018), indicating expansion of oxidized environments in the ocean. Despite high burial rates of organic carbon, coeval Al-rich shales and clean, mature quartz sandstones indicate intense chemical weathering and likely CO₂-rich atmosphere during the LCIE s.s. The fall of

Lomagundi Carbon Isotope Excursion,

Fig. 2 Stratigraphic column, inferred shallowing/deepening upward cycles, and variations of $\delta^{13}\text{C}_{\text{carb}}$ values in the Nash Fork Formation, Snowy Pass Supergroup of Wyoming (Modified from Bekker et al. 2003). Labels to the right of the stratigraphic column refer to members. Note the total thickness and extreme ^{13}C enrichment at the base of the unit



carbonate carbon isotope values at the end of the LCIE s.s. and its stratigraphic expression in the rock record are not yet documented in detail, but the best sedimentary succession for this work might be the Zaonega Formation of Karelia, Russia (Črne et al. 2014). The transition to normal (close to 0‰) carbon isotope values is associated with the sea level rise linked to the supercontinent breakup (cf. Bekker et al. 2003) and therefore marked by a change from carbonate to siliciclastic, organic matter-rich lithologies. Geochronologically, the end of the LCIE is bracketed between 2.11 and 2.06 Ga (Karhu and Holland

1996; Melezhik et al. 2007; Martin et al. 2013); however, the data suggest that it happened closer to 2.11 Ga than to 2.06 Ga. The end of the LCIE is marked by deposition of organic matter-rich shales with highly ^{13}C -depleted isotope values and Mn- and P-rich sediments, whereas sulfate evaporites became again scarce and proxies for ocean oxidation state indicate expansion of anoxia (e.g., Scott et al. 2014). Although Kump et al. (2011) inferred large negative carbonate carbon isotope excursion in the aftermath of the LCIE, the subsequent detailed studies (Črne et al. 2014; Kreitsmann et al. 2019) and the global record

(e.g., Bekker et al. 2003) do not support seawater signal for the reported negative values. At least one younger than the LCIE positive carbon isotope excursions have been demonstrated with the ~2.03 Ga Woolly Dolomite of West Australia (Bekker et al. 2016).

The beginning of the LCIE s.l. has been related to high continental nutrient (e.g., phosphorus) flux linked to acidic groundwaters during the GOE (Konhauser et al. 2011; Bekker and Holland 2012). The highly acidic conditions in terrestrial waters were inferred to be related to extensive oxidation of continental sulfides for the first time during weathering. Acidic conditions in continental runoff promoted dissolution of phosphates and higher P delivery to the ocean resulting in higher relative burial rate of organic carbon and associated oxygen release. The duration of the LCIE s.s. is comparable to the half-life of sedimentary rocks in the continental crust suggesting that groundwater acidity was largely titrated by the end of the LCIE. This, by itself, could have resulted in decreased nutrient (e.g., phosphorus) flux to the ocean bringing the LCIE to the end (cf. Bekker and Holland 2012). Alternatively, weathering of organic matter-rich shales deposited during the LCIE and uplifted during the ~2.1 Ga accretional and orogenic events could have contributed carbon with highly negative carbon isotope values to the atmosphere–ocean system and resulted in expansion of anoxic settings in the oceans (cf. Kump et al. 2011; Bekker and Holland 2012). It remains unclear which of these two scenarios (or both) led to the end of the LCIE. Deoxygenation of the atmosphere–ocean system and collapse of the seawater sulfate reservoir have been indeed inferred (e.g., Planavsky et al. 2012; Partin et al. 2013; Scott et al. 2014; Ossa Ossa et al. 2018). Ocean with a shallow-water redoxcline would harbor secondary productivity, and highly negative carbon isotope values of organic matter deposited in the aftermath of the LCIE suggest methane production and biological recycling. Considering large fractionations between organic and carbonate carbon, evidence for warm climate and moderate levels of pCO₂ during the Middle Proterozoic (Sheldon 2013), it is likely that some of the methane produced in the

ocean escaped into the low-oxygen atmosphere, where it functioned as a short-lived greenhouse gas (cf. Pavlov et al. 2003). In summary, the largest and longest-lived carbon isotope excursion in the Earth's history ended up with the return to low-oxygen levels in the atmosphere–ocean system, intermediate between those during the Archean and GOE.

Cross-References

- [Cap Carbonates](#)
- [Carbon Cycle, Biological](#)
- [Diamictite/Diamicton](#)
- [Glaciation](#)
- [Great Oxidation Event](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Paleosols](#)
- [Precambrian](#)
- [Proterozoic Eon](#)
- [Pyrite](#)
- [Red Beds](#)
- [Sedimentary Rock](#)
- [Snowball Earth](#)
- [Stable Isotopes](#)
- [Stratigraphy](#)
- [Sulfur](#)
- [Sulfur Cycle](#)
- [Transvaal Supergroup, South Africa](#)
- [Weathering](#)

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Lomagundi–Jatuli Carbon Isotope Excursion

► Lomagundi Carbon Isotope Excursion

Long Duration Exposure Facility

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Keywords

Cosmic rays · Long-term survival in space ·
Material testing · Space parameters

Synonyms

LDEF

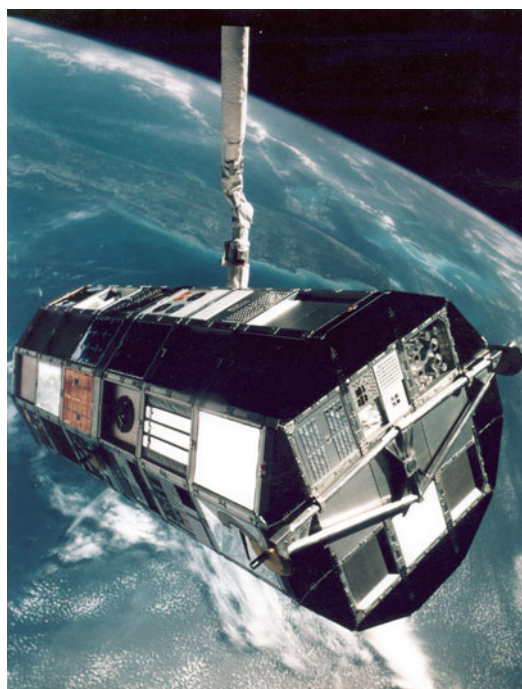
Definition

The Long Duration Exposure Facility (LDEF) was a large nearly cylindrical structure designed to provide long-term data on the space environment and its effects on space systems and operations. It was transported to space by the Space Shuttle in 1984 and remained in Earth orbit for nearly 6 years until it was retrieved by the Space Shuttle in 1990.

Overview

The Long Duration Exposure Facility (LDEF) was a large open-grid cylindrical structure, on which a series of rectangular trays used for mounting experiment hardware were attached. LDEF was launched and deployed in Earth orbit by the Shuttle Challenger on April 7, 1984, where it stayed in a nearly circular orbit at an altitude of about 500 km and an inclination of 28.4° (Fig. 1). LDEF was attitude controlled, i.e., oriented with respect to a defined frame of reference, with one end always facing Earth and the other one always facing space. This was achieved by gravity gradient and inertial distribution to maintain three-axis stability in orbit. Propulsion or other attitude control systems were not required, and LDEF was free of acceleration forces and contaminants from jet firings. LDEF was retrieved by the Shuttle Columbia on January 11, 1990.

LDEF accommodated 57 experiments, including the following three biological experiments:



Long Duration Exposure Facility, Fig. 1 LDEF structure before release from the arm of the Space Shuttle. Biostack units are accommodated on the space pointing end (upper right corner) of LDEF

- Space Expose Experiment Developed for Students (SEEDS), which carried 12.5-million tomato seeds that after retrieval were offered to students to evaluate their survivability after storage in the space environment and to determine possible mutants and changes in the mutation rate (Hammond et al. 1996).
- Free Flyer Biostack experiment (Fig. 1), which consisted of several ► [Biostack](#) units to study the biological effectiveness of HZE particles (particles of high atomic number Z and high energy) of cosmic rays (Wiegel et al. 1995; Mei et al. 1994; Horneck 1994; Zimmermann et al. 1996).
- Exostack experiment accommodated in two Biostack units facing space, which were open to space (covered by a perforated dome only) to study the long-term ► [survival](#) of ► [spores](#) of *Bacillus subtilis* in outer space. If shielded from the influx of solar extraterrestrial ► [UV radiation](#) and embedded in 5% sugar as a chemical protecting substance, 70–90% of the spores survived the nearly 6-year exposure to outer space on board LDEF (Horneck et al. 1994; Horneck 1998). With LDEF, the longest exposure of microorganisms to space has been achieved so far.

Cross-References

- [Biostack](#)
- [Cosmic Rays in the Heliosphere](#)
- [Exposure Facilities](#)
- [HZE Particle](#)
- [Space Vacuum Effects](#)
- [Spore](#)
- [Survival](#)

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Long Wavelength Astronomy

- [Radio Astronomy](#)

Lorenz-Mie-Debye Scattering

- [Mie Scattering](#)

Lorenz-Mie-Debye Solution

- [Mie Scattering](#)

Louis Pasteur

Stephane Tirard
Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes University, Nantes, France

Keywords

Molecular dissymmetry · Pouchet · Spontaneous generation

History

Louis Pasteur (1822–1895) was a student at the École Normale Supérieure in Paris where he studied physics and chemistry. His scientific work led to important transformations in biology and medicine.

From 1847, Pasteur worked on crystallography. By studying how tartaric acid salts deflect polarized light, he showed that the paratartrate does not have this property because it is made up of a mixture of two symmetrical tartaric acid crystals that can be separated manually under the microscope. In 1854, Pasteur was working at the Faculty of Sciences of Lille. Distillers of the north of France asked him to work on the irregularities of alcoholic fermentation. He showed that a given mold consumed only the right tartaric acid. Pasteur then asserted that living beings are characterized by molecular dissymmetry, because they contain only one of the two forms of asymmetric molecules, for example, left albumin and left quinine. He thus posed a distinction between the living and the nonliving, and he affirms: “I even feel that all living species are primordially, in their structure, in their external forms, functions of the cosmic dissymmetry” (Pasteur 1994).

He also engaged in a scientific debate on the cause of fermentation and claimed that it is necessarily microorganisms. Fermentation is not, according to him, an action by contact, as Berzelius thought, or a spontaneous decomposition of the substance, as Justus von Liebig thought. He developed a process for eliminating the “ferments” by heating. This process called pasteurization will be widely applied to the manufacture of food.

In 1857, Pasteur was professor in the École Normale Supérieure in Paris. At the instigation of the Academy of Sciences of Paris, which launched a prize concerning the existence or not of spontaneous generation, a debate took place in the early 1860s that had a strong impact. Pasteur opposed the biologist from Rouen, Félix Pouchet (1800–1872), who had published a book on heterogenesis in 1859. This debate lasted about 6 years. The two opposing groups criticized their respective experiments. They studied the

possibility of the development of microorganisms in glass balloons containing previously heated organic mixtures. Pasteur used artificial mixtures, and Pouchet used decoctions of heated hay. The first observed the absence of spontaneous generation, whereas the second noted the formation of microorganisms. Pasteur’s conclusion was that the germs observed by Pouchet were either pre-existing in the medium or resulted from contamination by air germs. During the debate, the experimental instruments were modified to answer the arguments of the opposite group. Thus, Pasteur invented his balloons with thin and curved necks to prevent the entry of germs, and the protagonists moved to the mountains to submit the contents of their balloons to air that, according to Pasteur, would contain fewer germs in altitude. As for Pouchet’s hay decoctions, it would later turn out that they contained heat-resistant *Bacillus subtilis* spores, which he could not know, but which finally explains his results and his apparent spontaneous generation.

This scientific debate had an important impact in France. It opposed two communities, Pasteur’s camp being in fact the most conservative, and his opposition to spontaneous generation was not without a certain rejection of evolutionism.

In addition to these fundamental aspects, Pasteur’s demonstration of the contamination of environments by airborne germs contributed to the development of the concept of sterilization. In 1865, Joseph Lister (1827–1912), inspired by Pasteur’s results, developed the methods of antiseptics, which allowed him to eliminate germs by killing them with a disinfectant.

From the end of the 1860s, Pasteur devoted his work to contagious diseases. Between 1865 and 1870, he confirmed that the silkworm disease, pebrine, which was rampant in France, was correlated with the presence of particular corpuscles in the worm’s tissues. It will be shown that they were in fact spores of a sporozoan. Pasteur succeeded in eliminating the disease locally, by examining the crushed tissues of females with a microscope and by eliminating the eggs of those in which corpuscles were found.

After 1870, he conceived contagious diseases as being due to microbial germs that had entered

the organism. In this, he opposed certain authors, notably Prussian, such as Rudolph Virchow (1821–1902), who considered Pasteur’s position as vitalist and wanted to explain these diseases by physicochemical factors.

In 1877, Pasteur carried out cultures of the bacteria contained in the blood of sheep suffering from anthrax and showed that these were the agents. He recommended burning the carcasses of dead sheep to eliminate the germs.

Finally, during the last years of his life, he was particularly interested in vaccination and thus continued the work started by Edward Jenner in 1796. In 1880, he discovered that hens inoculated with ancient cultures of hen cholera germs suffered only a moderate illness from which they recovered when exposed to the germ again. And so, by attenuating germs by heating, he developed a vaccination process that protected sheep against anthrax. Pasteur’s work on rabies remains the most emblematic in this field. Knowing that the symptoms of this disease mobilize the nervous system, Pasteur used the brain of a trepanned dog as a culture medium and, from the substance of the spinal cord of a rabid animal, obtained the attenuation of the virus by letting the spinal cord dry out in the air. He succeeded in immunizing dogs and tried a first application on humans in July 1885.

On the strength of these successes, Pasteur created the Pasteur Institute, which was inaugurated in October 1888.

During his career, Pasteur tackled fundamental problems of biology in a very concrete way. Two of his main results have particularly marked the history of studies on the origins of life. The dissymmetry of the molecules of living organisms (chirality) that he demonstrated remains one of the characteristics of living organisms in which exobiologists are particularly interested. Moreover, his refutation of spontaneous generation also marked the biology of the end of the nineteenth century and has remained a reference for biologists.

Cross-References

- [Chirality](#)
- [Spontaneous Generation, History of](#)

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Low Mass Star

Nikos Prantzos

Institut d’Astrophysique de Paris, Paris, France

Definition

► [Stars](#) with an initial mass on the ► [Zero Age Main Sequence](#) lower than $\sim 1. M_{\odot}$ (spectral types later than G) are called low mass stars. They evolve on timescales of $\sim$ several Gyr, fusing H through the p-p chains and going through the Asymptotic Giant Branch (AGB) phase of double shell (H- and He-) burning (fusion). After the ► [Planetary nebula](#) phase, they finally leave behind a ► [white dwarf](#). They play a limited role in galactic chemical evolution, mainly by “astrating” (i.e., destroying) fragile nuclides like deuterium. Because of their long lifetimes, which would facilitate the development of complex life, they are major targets for extrasolar planet research.

Cross-References

- [Asymptotic Giant Branch Star](#)
- [Planetary Nebula](#)
- [Stars](#)
- [Stellar Evolution](#)
- [White Dwarf](#)
- [Zero Age Main Sequence](#)

Lowell, Percival

Kevin Schindler

Lowell Observatory, Flagstaff, AZ, USA

History

American astronomer Percival Lowell (1855–1916) established Lowell Observatory in 1894 primarily to study Mars and the possibility of life on that planet. He popularized the theory that intelligent life on Mars built a series of canals to direct water from the polar ice caps to the rest of the planet.

Percival Lowell earned his bachelor's degree in mathematics at Harvard University in 1876, studying under the eminent professor Benjamin Peirce (1809–1880). After splitting the next 17 years between overseeing the finances of his uncle's textile mills and traveling to the Far East, Lowell built his astronomical observatory in 1894 in Flagstaff, Arizona. His primary observing instrument was the 24-in. Clark Telescope, the sixth largest refracting telescope ever operated in the United States.

Lowell believed that the solar system developed through a process of planetary evolution that he later termed “planetology.” This theory suggested that Mars had reached a stage of development at which plant and, ultimately, animal life existed. This theory, coupled with the apparent network of waterways crisscrossing the planet that Lowell and other astronomers had observed through telescopes, served as proof to Lowell of intelligent life on Mars. Lowell never speculated about the exact nature of this Martian life except that it was intelligent. He did, however, admit that such Martian life would have adapted to the unique atmospheric conditions of Mars and thus likely appear much different than life on Earth.

Lowell published his observations and theories in various scientific publications. Some astronomers embraced Lowell's controversial ideas while others denounced them. In both cases, Lowell inspired further Martian studies from peers intending to either prove or disprove Lowell's pronouncements. Lowell also took his theories to

the public, popularizing the concept of intelligent Martian life by giving spellbinding public lectures and summarizing his ideas in books, newspapers, and magazines.

Lowell died in 1916, still believing in intelligent Martian life even though the mainstream scientific community had by then generally abandoned the idea. Still, some scientists continued to depict the alleged canals on maps up into the 1960s, when Mariner 4 and later spacecraft failed to detect the features.

In retrospect, Lowell profoundly impacted both scientific and literary thought, from the late nineteenth century into the twenty-first century and undoubtedly beyond. In astronomical circles, his compelling theories inspired comprehensive studies of the red planet, from Earth-based observations to up-close examinations by rovers, made possible by spacecraft landing on the Martian surface. Moreover, Lowell almost singlehandedly built a consciousness in the minds of the lay public that mysterious Mars may be home to intelligent life. Writers of fiction, such as H.G. Wells and Edgar Rice Burroughs, quite naturally picked up on this phenomena and incorporated Martian life scenarios into their works, significantly adding to the genre now recognized as science fiction.

Cross-References

- [Life](#)
- [Life in the Solar System \(History\)](#)
- [Mars](#)
- [Telescope](#)

Lowest Taxonomic Category

- [Species](#)

LUCA

- [Last Universal Common Ancestor](#)

Lucretius

Richard Hutchins

University of Miami, Miami, FL, USA

Keywords

Atomism · Astrobiology · Cosmology · Evolutions

Definition

Lucretius was a Roman philosopher, poet, and scientist. His poem, *De rerum natura*, or *On the Nature of Things*, is our fullest source of Epicureanism and ancient atomism. Lucretius presents ingenious arguments about the eternity of the universe, the infinity of space, the plurality of worlds, and the origin of life and humankind, the latter of which includes proto-evolutionary views about the origins of human thought, language, and society. His thinking had a major impact on early modern science.

Overview

Titus Lucretius Carus, and his epic poem *De rerum natura* (or *On the Nature of Things*), is our fullest source for Epicurean philosophy, science, and cosmology. It is also the only detailed account of ancient atomism to come down to us. Living over 2000 years ago, Lucretius was a poet, philosopher, and scientist. He wrote in Latin verses and synthesized the thoughts of the Greek philosopher Epicurus (341–270 BCE), who himself wrote in prose and was the founder of the Epicurean school of philosophy in Athens, two hundred years before Lucretius. About Lucretius himself, we know less than about any other major Latin poet. He lived in the waning days of the Roman Republic, from roughly 99–55 BCE. He was a contemporary of Cicero, who mentions the genius (*ingenium*) and artistry (*ars*) of Lucretius' poem (Cicero, *Cicero: Letters to Quintus and Brutus*, 2.10). It is possible that Lucretius lived

near the bay of Naples, but nothing certain is known of his birth, residence, or social status. The *gens Lucretia* was an aristocratic Roman family and Lucretius likely belonged to it (Don and Peta Fowler, xi–xiv).

The title of Lucretius' poem, *De rerum natura*, has been variously rendered into English. The most common translation is *On the Nature of Things*, but it might be better entitled *On the Nature of the Universe*, since it represents an attempt, in six “books” of roughly 1200 lines each, to explain the entire universe, from the motion of atoms to the origins of life and civilization to the existence of an infinite universe with multiple worlds. *De rerum natura* is a theory of everything. Unfortunately, Lucretius probably did not live to finish it. It is possible, however, that the gaps in the poem are the results of the historical vagaries of textual transmission, and not the failure of Lucretius to finish his *magnum opus*.

Book One of *De rerum natura* presents an outline of atomism and its philosophical rivals. Book Two delves more deeply into atomic motion and shows how atoms combine to produce the world we experience. Book Three uses the theory of atoms to argue that the soul is a physical thing, that it is not immortal, and that “we” no longer exist once the atoms of our soul and body have dispersed. On Lucretius' view, we have no need to fear death or what happens after death, since once our soul has dispersed, we experience no more sensation. Book Four discusses mental operations, acoustic and optical illusions, and ends with an aggressive critique of romantic love as just another harmful illusion. Book Five explains the creation of the world by atoms, the origins of animal life, the origins of human life and society, as well as the rise of civilization and its eventual collapse under empire. Book Six presents naturalistic explanations of potentially frightening meteorological and terrestrial phenomena that, in Lucretius' time, were used as evidence of divine intervention in the world, such as earthquakes, floods, lightning, and clouds. Lucretius shows that these phenomena can be fully accounted for by his theory of atoms, with no need to invoke gods. Book Six, the final book of *De rerum natura*, ends grimly, with humans trapped in a

plague-ridden Athens fighting over space on funeral pyres to cremate dead bodies.

There has long been debate about whether Lucretius meant to end *De rerum natura* on such a menacing note, or whether he intended to write a further, more serene, book about the lives of the gods as models of *ataraxia*, or “tranquility” – the ethical goal of Epicureanism (Giussani, xi–xxvi). The strongest evidence that Lucretius intended to write a further book about the gods comes from *De rerum natura* 5.155, where Lucretius promises to discuss the life of the gods as models of tranquility – a promise which he does not fulfill in the poem as we have it. Most scholars today believe that Lucretius meant to end *De rerum natura* with Book Six, and the plague (Cf. *De rerum natura* 6.92–5). A popular view sees the plague as a test of the reader’s ability to maintain *ataraxia*, or “tranquility,” in the face of the death and atrocity that Lucretius presents in his account of the great plague at Athens (Clay, 157–60). On this view, the goal of Lucretius’ extended discussions of atomism, cosmology, and natural causes throughout *De rerum natura* is to liberate the reader from the fear of death and from religious superstition.

Lucretius did not invent atomism. It was an inheritance from Leucippus (fifth century BCE) and Democritus (c. 460 – c. 370 BCE), both of whom were Greek Presocratic thinkers. Their atomism was later picked up and modified by Epicurus. Leucippus and Democritus were the first to argue that the ultimate constituents of the universe are maximally small bodies that cannot be seen with the naked eye. Lucretius believes, like Leucippus and Democritus, that atoms are infinite in number, but unlike Leucippus and Democritus, he does not believe that the atoms are infinite in shape. The fact that atoms have shape forces Lucretius to reckon with the problem of atomic minima, or “minimal parts” (*minimae partes*) as he calls them, of the atom. Lucretius describes a *minima pars* as the minimum of extension in an atom, essentially a point. Minimal parts, in Lucretius’ theory, are the smallest points in an atom, that when combined make up the shape of the atom, but that themselves cannot be separated from the atom (1.599–634). The word *atomos* (ἄτομος) comes from ancient Greek and means

“un-cuttable” (*a-tomos*). So, even though atoms, for Lucretius, have minimal parts, the atom as whole cannot be cut, because its minimal parts are too closely packed, and the atom is too solid and singular to be divided (Bailey 1947, 700–708).

The Greek atomists Leucippus and Democritus were not only atomist but also determinists. They believed that free will cannot exist in an atomic universe in which everything is reducible to physical cause and effect (Laks & Most, pp. 138–9 = D73). Epicurus took up Leucippus’ and Democritus’ atomism, but rejected their determinism (Long, 75). Epicurus simply asserted that there is free will, and late in his life seems to have hypothesized a physical “swerve” (*parenklisis*) of atoms to explain how free will is possible in an atomic universe. Epicurus, thus, seems to locate the possibility of free will in unpredictable swerves of atoms (Sextus Empiricus, *Against the Professors*, 11.96). Lucretius’ account of the swerve picks up from Epicurus, and is the only detailed surviving account of the swerve that we have. It can be found in Book Two of *De rerum natura* (2.216–24), where Lucretius says that originally, before any worlds existed, atoms were falling eternally through the void like rain, straight down, until one swerved “at an indefinite time” (*incerto tempore*, 2.218) and “in indefinite places” (*incertisque locis*, 2.219). After this swerve, atoms began to collide, hook together, and amass worlds.

The Epicurean theory of the swerve was mocked in antiquity (Usener, §281, 199–202). Recently, however, it has regained some respectability as a forerunner to the idea of indeterminacy in quantum physics. There has been much debate in scholarship about how often Lucretius thought swerves occur in the universe. One interpretation has it that swerves occur before every free action (Giussani, 135–41; Bailey 1928, 319–23). Another theory has it that swerves occur as little as once in a person’s lifetime. On this latter view, the swerve is a deviation in the person’s atomic makeup, or character, sufficient to allow that person’s subsequent actions to be free in the sense that, after the swerve has occurred, the ultimate source of that person’s actions cannot be traced to anything outside the person (Furley, 232). In

Lucretius' poetic phrase, "it bursts the bonds of fate" (*fati foedera rumpat*, 2.254). In her masterful overview of this issue, Elizabeth Asmis suggests that swerves happen at the beginning of each free act, but that they are the result of a "striving," or *voluntas*, on the part of the agent. Asmis also notes that when Lucretius describes the swerve in Book Two of *De rerum natura*, he uses the subjunctive mood. This suggests that the swerve was a hypothesis or theory rather than a committed doctrine among Epicureans (Asmis 1990, 275–91). As can be seen from the example of the swerve, Lucretius does not deviate substantially from Epicurus' atomic theory, and is often our fullest source for it. The principles of Lucretius' atomism are the following.

The universe – what Lucretius calls *natura* – is ultimately atoms and void. All other objects in the universe are compounds of atoms and void. Atoms, void, and the sum of the universe that atoms and void together make up, are the only indisputably everlasting things. Universes and worlds may form and collapse, but there will always be atoms moving in the void (5.351–62). Lucretius, therefore, does not believe in the creation of the universe as a whole, in the sense of something coming from nothing. Lucretius does, however, believe in the creation of individual worlds by the chance collision and compounding of atoms, with no gods guiding the process. In arguing for the eternity of the world, Lucretius seems to have applied something like "the principle of sufficient reason," often said to be the discovery of Spinoza or Leibniz in the seventeenth century (Cp. Melamed and Lin 2018).

Lucretius was not original in using the principle of sufficient reason to argue for the uncreated status of the world (for the "principle of indifference" in Epicureanism, cf. Taub 115–16; Asmis 1984, 265, 310–11, 319, 335). The Greek Presocratic philosophers Anaximander, Parmenides, and the atomists Leucippus and Democritus had already used the principle of sufficient reason to this end. In Lucretius' version of this argument against creationism, he says, "The first principle of our study we will derive from this fact: that nothing can come from nothing by divine power (*divinitus*)" (1.149–50). Lucretius goes on to

demand of the creationist that he or she give a sufficient reason as to why we should be persuaded that the universe came from nothing rather than from something already existing, and why creation happened at one specific time rather than another, or why we do not still observe things being created out of nothing now. Lucretius mocks *ex nihilo* creation as a view in which, if true, "men could arise from the sea, scaly tribes from the earth, and birds burst from the sky" (1.161–2). Lucretius' main line of attack is that the theory of *ex nihilo* creation, relying as it does on the impulsiveness of creator gods, cannot account for the regularity we observe in the world.

Only the concept of "seed," Lucretius thinks, can explain the regularity, or "reason" (*ratio*), of nature, that is, the idea that each atomic compound has a structure the reproduces itself with no need of outside or divine intervention: "For if things came out of nothing, all kind of things could be produced from all things, nothing would need seed" (1.159–60). Lucretius' argument that "nothing comes from nothing" (*nullam rem e nihilo gigni*, 1.150) implies both that the sum of atoms in the universe cannot be increased or decreased and that each thing in a world has "seeds" (*semina*) that guarantee the regularity of its growth, development, and ultimately the regularity of the world itself (Leonard and Smith, 220). Anthony Long has argued that by "seeds" of a world, Lucretius does not mean so much individual atoms as "atomic nuclei," that is, atomic compounds suitable for building a world that contains regularity (Long, 78).

Lucretius also seems to believe that the gods themselves are atomic compounds, and that they live in the spaces between worlds (*intermundia* in Latin; *μετακόσμια* in ancient Greek). The spaces between worlds make it less likely that the gods will be struck by stray objects moving through space. On this view, while the gods are by definition beings that do not die, they could in principle be destroyed if an atomic body were to hit them. Other Epicureans, however, thought that the gods were only ideal images, or thought constructs. The gods, on this view, are not physical and do nothing more than present an image of the life of *ataraxia*, or tranquility, to the human mind that humans

should strive for. Epicureans believe that humans in the state of nature naturally saw true images of the gods, images that were later corrupted by society and institutional religion (Cicero, *On the Nature of the Gods*, 1.49; Sextus Empiricus, *Against the Professors*, 9.43–7).

Lucretius also made famous an ingenious argument by the Greek Pythagorean philosopher Archytas about the infinity of space, against predecessors who believed that the universe as a whole has an outer limit (Taub, 112–13). Lucretius uses a thought experiment in which a person runs to the edge of the universe and throws a spear. Where would the spear go, Lucretius asks: “If all space (*omne quod est spatium*) is finite (*finitum*), suppose someone were to run to the outermost edge and cast a flying spear, would the spear, thrown with force, go where it was sent and fly far away, or do you think something would be able to hinder (*prohibere*) it and stand in its way (*obstare*)?” (1.968–73). From this, Lucretius believes that he has forced the reader to conclude that there can be no limit to the universe, and that the universe is infinite.

Because the atoms and the universe are infinite, Lucretius thinks that there must be infinite worlds. He follows Epicurus in this claim (Epicurus, *Letter to Herodotus*, §49; *Letter to Pythocles*, §89; in Gerson & Inwood). As Lucretius puts it: “If the same force of nature stands ready to throw the seeds of things together into a place in the same way as they have been thrown together here, then of necessity you must confess that other earths (*terrarum...orbis*) exist in other places (*aliis...partibus*), with varied tribes of men and generations of beasts” (2.1072–6). Consonant with his idea that the sum of atoms in the universe is constant, Lucretius also believes that the distribution of kinds of plants, animals, and humans on infinite worlds will be consistent across the universe. For instance, while one world may have more elephants than another or no elephants at all, the number of elephants in the entire universe, Lucretius believes, will be constant. Lucretius even considers the possibility of extinction on our world, but nonetheless believes that if an animal kind goes extinct on this world, there will be others on other worlds to maintain the balance

of animal kinds in the cosmos. This is the doctrine of *isonomia* (ἰσονομία), or “equality of distribution,” and Lucretius inherited it from Epicurus.

Worlds form when atoms happen to collide in space and hook onto each other. As this proceeds and a world takes in atoms from outside it, that world grows. Lucretius compares the growth, maturity, and decay of worlds to the life cycle of the human body, describing the increase of atoms in a world during its growth phase in terms of a human body increasing in power as it takes food into its veins (*venas*, 2.1119; 2.1125; 2.1148). At a certain point, however, a world reaches a tipping point and begins to lose more atoms into the void than it gains from it. Such a world grows old and dies, becoming gradually less fertile and producing ever smaller plants and animals. This dying world becomes increasingly harder for humans to cultivate and for animals to feed themselves on, until, finally, it collapses back into the void (2.1145.74). Lucretius’ idea that worlds are mortal is in stark contrast to Aristotle’s view that worlds are immortal and unchanging, and that animal kinds are fixed (Solmsen 1953, 50; Schijvers 2007, 272–3).

After describing the creation of our world by atoms at the beginning of Book Five, Lucretius turns to the origins of life and of the human race (5.772–1011). The first forms of life, Lucretius believes, were grasses and trees. Then birds and other animals sprang up by spontaneous generation: “formed by the rain and the warm heat of the sun” (5.798). Lucretius then tells us that these original creatures were nourished by wombs (*uteri*, 5.808) growing from roots in the earth, presumably to explain how the first animals, whom Lucretius imagines as “infants” (*infantum*, 5.810), were fed and protected until they broke out of the wombs of mother earth (*terra mater*, 5.796–7) to fend for themselves, in an explanation of the origins of life similar to the one described by the Greek Presocratic philosopher Anaximander. Lucretius then says that many of these first animals were born with the wrong mouths or genitals, and were therefore unable to feed or reproduce their kind. About these early “monsters and portents” (*monstra ac portenta*, 845), Lucretius says: “For we see that living beings need

many things in conjunction to be able to forge out the chain of generations by procreation: first there must be food, then there must be a way for the life-giving seeds (*genitalia...semina*) throughout the limbs and members of the body to flow out of the slackened body; and that male and female be able to join, they must have the means to exchange mutual pleasures” (5.849–54). Lucretius here explains how all the animal kinds that exist today are simply those “monsters and portents” who were able successfully to feed and reproduce themselves in the survival-of-the-fittest atmosphere of the youthful earth. As Gordon Campbell puts it: “We are all descendants of *portenta*, but of ones successful in competition” (Campbell, 115–6).

Lucretius then describes the origin of the human race (*humanum genus*, 5.925–1010). Because Lucretius does not believe that the world was divinely created, he thinks that it was neither purpose-built for human flourishing nor to be hostile to it. Like any other animal, humans exist today because we outlasted the struggle for life in the state of nature. Lucretius describes early humans as bigger than humans now, and more like animals. They lacked reason and language, and lived a semi-nomadic existence, passing their lives “in the wide-wandering fashion of wild beasts” (*volgivago vitam tractabant more ferarum*, 5.932). The early human mind, as Lucretius describes it, was a *tabula rasa*, devoid of any innate ideas. Humans gradually developed intelligence, Lucretius thinks, by learning from their environment. Through repeated interactions with things in the natural world, the early human mind was slowly populated with concepts, or “*prolepseis*” (προλήψεις), until humans began to have clear mental images of things and thereby develop rationality. Lucretius ends his description of early human life by recounting how they ultimately survived and escaped the state of nature by forging a social contract with one another for mutual protection. The protection afforded by the social contract allowed humans to settle down into communities and families, which in turn provided the social context for the emergence of language, which Lucretius describes as arising through social need (*utilitas*, 5.1029). And

language, as Lucretius tells the story, is only a short step away from the beginnings of civilization (5.1011–1090).

Lucretius’ *De rerum natura* represents a stunning attempt by a poet-scientist to account for the entire nature of the universe through the physical theory of atoms. The poem is rich with details of atomic, natural, meteorological, astronomical, and astrobiological phenomena, as well as imaginative thought experiments and logical proofs. While the majority of the poem focuses on detailed points about the working of the natural world and cosmology, its aim is ultimately ethical: to rid the human soul of fear of the gods and fear of death through the knowledge of nature and its causes. It is a work of liberation, in which the knowledge of nature is the ultimate source of freedom. As Lucretius put it: “If you know these things well, you will see at once that nature is free, free from proud masters – that nature by herself performs all things with her own resources without the aid of the gods” (2.1090–93).

Basic Methodology

The basic methodology of this entry is Classics and the History of Science. Lucretius is our fullest source of Epicureanism and atomism in classical antiquity.

Key Research Findings

Lucretius’ epic Latin nature poem not only anticipates many early modern discoveries in physics, biology, and cosmology, but is at heart a poem of liberation. Lucretius believes that understanding the causes of things in nature will eliminate fear of the gods, religion, and human mortality.

Future Directions

Scholarship on Lucretius has tended to focus on “source criticism,” that is, uncovering the earlier atomistic and Epicurean sources that Lucretius read before putting down his ideas in the epic

Latin nature poem *De rerum natura*. Future directions for the study of Lucretius might include comparing and connecting Lucretius' atomism, biology, and cosmology to later developments in these fields.

Cross-References

- [Anaximander](#)
- [Astrobiology](#)
- [Autopoiesis](#)
- [Biodiversity](#)
- [Cosmogony](#)
- [Cosmogony: Greece](#)
- [Ecology, History of](#)
- [Intelligence, Evolution of](#)
- [Life](#)
- [Life in the Solar System \(History\)](#)
- [Life, Concept of \(from Antiquity to the Eighteenth Century\)](#)
- [Plurality of Worlds](#)
- [Space Biology](#)
- [Species](#)
- [Survival](#)

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Luminosity

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The luminosity of a celestial object is the total electromagnetic power it emits; this depends in most cases on the object's surface temperature and surface area. Symbol: L ; unit: W, or in terms of the Solar Luminosity (3.839×10^{26} W). The

luminosity can sometimes be defined for a restricted spectral domain: For x-rays, visible, infrared, radio, etc., one uses then the symbols L_X , L_{vis} , L_{IR} , L_{radio} , respectively.

Cross-References

- [Bolometric Magnitude](#)
- [Effective Temperature](#)

Luminosity-Temperature Diagram

- [Hertzsprung-Russell Diagram](#)

Lunar Cataclysm

- [Late Heavy Bombardment](#)

Lunar Geology

- [Selenology](#)

Lutetia

Stefano Mottola
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

(21) Lutetia is a Main Belt asteroid discovered in 1852 by Hermann Goldschmidt from Paris, France, and named after the Latin name of the city. With an equivalent spherical diameter of about 100 km Lutetia is a comparatively large asteroid and could represent a surviving member of the population of original planetesimals that contributed to the formation of the inner planets. In 2010 Lutetia was visited by the Rosetta spacecraft on its tour to comet 67P Churyumov-

Gerasimenko. The close flyby enabled its bulk density to be determined to about 3.4 g cm^{-3} , among the highest densities of asteroids measured so far. The images returned by the spacecraft revealed a body that experienced a complex collisional evolution, with multiple local resurfacing events and a thick regolith layer.

Ly α

- [Lyman Alpha](#)

Lyman Alpha

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[Ly \$\alpha\$](#)

Definition

In the hydrogen atom, the Lyman series of lines is emitted or absorbed during transitions between an excited state and the fundamental (ground) state. Lyman alpha (noted $L\alpha$) is the first and the less energetic of these lines and connects the electronic levels $n = 2$ and $n = 1$, where n is the principal quantum number. Most of stellar matter is hydrogen; hence Lyman alpha is a very prominent line in stellar spectra. At a wavelength of 121.5 nm, Lyman alpha photons are in the VUV (vacuum ultraviolet) domain and play an important role in the dissociation of interstellar or cometary molecules.

History

These lines were discovered in 1906 by the American physicist Theodore Lyman.

Cross-References

- ▶ [Comet](#)
- ▶ [Interstellar Medium](#)

Lys

- ▶ [Lysine](#)

Lysine

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Synonyms

[Lys](#)

Definition

Lysine is one of the 20 coded protein amino acids; its structure is $\text{NH}_2\text{CH}(\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{NH}_2)\text{COOH}$. Its molecular weight is 146.19. Its three-letter symbol is Lys, and the one-letter symbol is K. Lysine is a basic ▶ [amino acid](#) (pI is 9.74), as are ▶ [histidine](#) and ▶ [arginine](#), but only lysine is a diamino acid (amino acid with two amino groups and one carboxylic group). Diaminoacids have been suggested to be key molecules for the abiotic construction of peptide ▶ [nucleic acids](#) (PNAs). Lysine (side-chain $-\text{CH}_2\text{CH}_2\text{CH}_2\text{NH}_2$) and ▶ [ornithine](#) (side-chain $-\text{CH}_2\text{CH}_2\text{NH}_2$) have not been detected in carbonaceous chondrites, though diaminobutyric acid ($-\text{CH}_2\text{CH}_2\text{NH}_2$) and diaminopropionic acid ($-\text{CH}_2\text{NH}_2$) have.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [PNA](#)
- ▶ [Protein](#)

M

Ma

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Synonyms

[Mega-annum](#); [Megayear](#)

Acronyms

Myr

Definition

Ma is a common scientific abbreviation for Megayears = one million (10^6) years derived from the Latin *Mega-annum*. Note that the Latin accusative, *annum*, expresses an absolute age (e.g., the Earth is 4560 Ma old), while the English accusative, *years*, expresses a period of time (e.g., the Archean eon lasted for 1500 Myr). Ma is the most common unit of time used to describe events through most of the history of the Earth, the other planets, and meteorites.

Cross-References

- ▶ [Absolute and Relative Ages](#)
- ▶ [Earth, Age of](#)
- ▶ [Extinct Radionuclides](#)
- ▶ [Ga](#)
- ▶ [Geochronology](#)
- ▶ [Geological Timescale](#)

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Macro Monte Carlo Models

Eric Herbst
University of Virginia, Charlottesville, VA, USA

Definition

Rate equation models for the simulation of the chemistry occurring in interstellar clouds or extended stellar atmospheres are perfectly adequate for gas-phase chemistry but have several failings for the chemistry that occurs on and in

core-mantle dust particles. The major problem arises because dust particles are discrete entities, and reactions between species on one granular particle and another must be ruled out. If one considers grains separately, the often small number of important reactive species per grain is not treated well by rate equations, which are only useful for large concentrations of reactant species. One solution to this problem is the use of the master equation model in which rate equations are replaced with differential equations with time derivatives of the probabilities of finding selected numbers of species on a grain, and the coupled differential equations are integrated. Another approach to the problem, which has been utilized more extensively in the astrochemical literature, is the Monte Carlo method, which can be run for both macroscopic and microscopic models. The exact positions of each species are not calculated in the macroscopic method, which should yield the same probabilities as the master equation technique (Stantcheva et al. 2002). In both Monte Carlo approaches, solution of differential equations is replaced by the calling of pseudorandom numbers. In the macroscopic method, the chemical species are contained in a given region, such as the surface of an interstellar grain, or the gas in a bubble containing an interstellar grain. One starts with given concentrations for each species. The first event – a chemical reaction or a physical event such as the adsorption of a gas-phase species – can be obtained from a Markovian exponential distribution of time involving the sum of all processes between collisions and other events that change the concentrations. This is done by suitable choice of a pseudorandom number to determine the specific time at which the average sum of events occurs and another random number to determine what the event is, be it a desorption, an accretion, or a specific reaction. The relative probability of each event can occupy a range in the random number space between 0 and 1, with the range related to the probability of the event. The probabilities are obtained using the same rate expressions used

in the rate equation approach. After the necessary concentrations are updated, the time of the next average sum of events and a particular event is found. Eventually a whole Markovian chain of abundances at given times is obtained up to the maximum time desired. It must be noted that this chain represents just one evolution of the system, so that many more such chains must be investigated using a different random number to start the procedure. The macroscopic approach can be used for both gas-phase and grain-surface chemistry and can even couple the two together. Once a Monte Carlo approach is utilized for the granular chemistry, it must also be used for the gas-phase chemistry, because rate equations follow a very different clock. Recently, Monte Carlo models that are partially microscopic in nature have been developed (Vasyunin and Herbst 2013).

Cross-References

- ▶ [Cosmic Ray, Ionization Rate](#)
- ▶ [Cosmic-Ray-Induced Desorption](#)
- ▶ [Dense Core](#)
- ▶ [Desorption](#)
- ▶ [Diffusion](#)
- ▶ [Gas-Grain Chemistry](#)
- ▶ [Interstellar Chemical Processes](#)
- ▶ [Interstellar Ices](#)
- ▶ [Master Equation Models](#)
- ▶ [Micro-Monte-Carlo Models](#)
- ▶ [Physisorption](#)
- ▶ [Rate Equation Models](#)
- ▶ [Reaction Rate Coefficient](#)

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Macronutrient

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Culture media](#); [Nutrients](#)

Definition

Macronutrients are nutrients required in large amounts for cell growth. All cells require carbon. On a dry basis, a typical cell is about 50% carbon, and this element is the major element in all classes of macromolecules. Some organisms are autotrophs and use CO_2 as the source of carbon. The rest are heterotrophs and they use reduced organic compounds as a carbon source. Heterotrophs require autotrophs for their carbon source. The next abundant element is nitrogen. A typical nitrogen content in a prokaryotic cell is about 12%. Nitrogen is found mainly in ► [proteins](#) and ► [nucleic acids](#). Nitrogen is available in both organic or inorganic forms. However, the bulk of available nitrogen is in inorganic form, either as ammonia (NH_4), nitrate (NO_3^-), or diatomic nitrogen (N_2). Most organisms can use ammonia or nitrate as a nitrogen source but only a few are able to fix atmospheric N_2 because of the strong triple bond. Other macronutrients are phosphorus, sulfur, potassium, magnesium, calcium, sodium, and ► [iron](#). Phosphorus occurs in nature in the form of organic and inorganic phosphate and is required by the cell primarily for synthesis of nucleic acids and phospholipids. Sulfur is needed for the synthesis of two aminoacids, cysteine and methionine, and is also present in vitamins and coenzyme A, an important biosynthetic cofactor. Most cellular sulfur originates from reduced (S^{2-}) or oxidized sources (SO_4^{2-}). All organisms require potassium. Different enzymatic activities require this cation specifically. Magnesium

stabilizes different cellular structures such as membranes, ribosomes, and nucleic acids. Calcium, which is not essential for cell growth, helps to stabilize cell walls, and is also fundamental for endospore heat stability. Sodium requirements are related to the ionic strength of the environment in which the organisms grow. Iron plays a fundamental role in important cellular functions including respiration.

Cross-References

- [Alkaliphile](#)
- [Compatible Solute](#)
- [Endospore](#)
- [Halophile](#)
- [Iron](#)
- [Nucleic Acids](#)
- [Protein](#)

Macula, Maculae

Roland J. Wagner

German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

A macula is a dark spot or dark area on the icy satellites ► [Europa](#) (► [Jupiter](#)), ► [Titan](#) (► [Saturn](#)), and ► [Triton](#) (► [Neptune](#)). Maculae have circular, elliptical, elongate, or irregular shapes. Various processes that can create these features are in discussion, for example, ► [cryovolcanism](#) (e.g., Ganesa Macula on Titan).

Cross-References

- [Albedo Feature](#)
- [Cryovolcanism](#)
- [Europa](#)

- [Facula, Faculae](#)
- [Jupiter](#)
- [Neptune](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Titan](#)
- [Triton](#)

Mafic and Felsic

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, QC, Canada

Synonyms

[Basic and acid](#)

Definition

An igneous rock is mafic when its SiO₂ content is low, typically 50%, and felsic when this content is high, typically above 60%. The adjective mafic refers to a silicate mineral or rock (magmatic, either intrusive or extrusive) enriched in compatible elements (i.e., easily incorporated into a crystal structure and refractory) magnesium and iron (old term, *basic*). Typical mafic igneous rocks such as ► [basalts](#) contain ferromagnesium minerals such as olivine and pyroxene, and calcium-rich-plagioclase. Upon crystallization of the residual magma, the residual magmatic rocks concentrate incompatible elements (i.e., not compatible with a crystal structure, or fusible) such as silicon, aluminum, potassium, and sodium. Typical felsic (old term, *acid*) rocks such as [granite](#) contain quartz, potassium feldspar, and sodium-rich plagioclase.

Cross-References

- [Basalt](#)
- [Granite](#)

MAG

- [Venus Express](#)

Magma

Nicholas Arndt

ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Magma is the molten or partially molten rock from which ► [igneous rocks](#) are derived through crystallization. It forms through melting of parts of the ► [mantle](#) (partial melting) or of the crust, either oceanic or continental (process of *anatexis*). On eruption, it forms volcanic rocks; when it solidifies in the crust, it produces intrusive or plutonic rocks. Its composition ranges from ultramafic (► [komatiite](#)) through mafic (► [basalt](#)) to felsic (► [granite](#)) and rarely to carbonatitic (carbonatite). Its temperature ranges from ca. 1600 °C in erupted komatiite to less than 700 °C in water-rich intrusive granitic magma. The viscosity ranges from about 1 Pa s (pascal-second) in carbonatite (that of water) through 10–100 Pa s in basalt (roughly equivalent to the viscosity of motor oil) to 10⁹ in rhyolitic magmas.

Cross-References

- [Archean Mantle](#)
- [Asthenosphere](#)
- [Basalt](#)
- [Continental Crust](#)
- [Craton](#)
- [Crust](#)
- [Granite](#)
- [Igneous Rock](#)
- [Komatiite](#)
- [Lithosphere, Planetary](#)

- [Mafic and Felsic](#)
- [Mantle](#)
- [Mantle, Oxidation of](#)
- [Plate Tectonics](#)

Magma Oceans

Sabrina Schwinger and Nicola Tosi
German Aerospace Center (DLR) Institute for
Planetary Research, Berlin, Germany

Keywords

Terrestrial planets · Magma · Planetary
interiors · Planetary differentiation · Giant
impacts

Synonyms

[Magma sphere](#)

Definition

A magma ocean is a layer of molten rocks of approximately uniform depth that behaves rheologically as a liquid, is globally distributed, and makes up a substantial volume fraction of a planetary body (e.g., Taylor and Norman 1992; Tonks and Melosh 1993). Smaller, more localized magma bodies may also be referred to as magma ponds. Magma ocean formation and its subsequent solidification are crucial mechanisms for the differentiation of terrestrial bodies into a metallic core, a rocky mantle and a rocky crust. Hence they play a fundamental role in shaping the evolution of rocky bodies.

Magma oceans are sometimes also referred to as magmaspheres. The term magma “ocean” is intended to describe the extent and the liquid-like rheological behavior of a magma volume, which, like all magmas, is generally a mixture of liquid, solid and gaseous phases. The term magmasphere is intended to avoid the term

magma “ocean,” which in analogy to water oceans, might be misinterpreted as describing a body that is completely liquid.

History

The term “magma ocean” has been established in the context of the early evolution of the Moon. Shortly after the identification of globally distributed anorthosite on the lunar surface in the early 1970s, the flotation of light plagioclase crystals in a global magma ocean was recognized as the most plausible mechanism to explain this peculiar characteristic of the surface of the Moon (e.g., Wood et al. 1970; Smith et al. 1970). Magma ocean formation was generally considered even more likely on planetary bodies larger than the Moon. Slower cooling associated with a lower area/mass ratio, the potential presence of an insulating atmosphere, a stronger heating by accretionary impacts, and the release of gravitational heat during core formation all concur to facilitate heating and melting of silicate rocks so that magma oceans were proposed also for the terrestrial planets (e.g., Warren 1985). In later studies, the term “magma ocean” was also adopted to describe global melting on asteroids (e.g., Righter and Drake 1997).

Overview

Formation of Magma Oceans

During the early stages of the evolution of planets, multiple energy sources concur to raise the temperature of silicates above their liquidus, leading to the formation of magma oceans (Warren 1985; Elkins-Tanton 2012; Solomatov 2015). Heat sources include radiogenic heating, accretion heating, impact heating following giant collisions, and gravitational heating due to metal-silicate separation upon core formation. The availability of these heat sources depends on the size of a planetary body and its actual formation time.

On the one hand, early formed small planetesimals (e.g., the parent bodies of differentiated meteorites) contained a sufficient amount of the

short-lived radioactive isotopes ^{26}Al and ^{60}Fe (with half-lives of ~ 0.7 and 2.6 Myr, respectively) to provide heat for their complete melting (e.g., Urey 1955). On the other hand, the terrestrial planets and parent bodies of undifferentiated meteorites formed at a later stage, when the short-lived radioactive isotopes had already decayed.

The heat produced by impacts depends on the size of the planetary body since the energy of the collisions increases with the size of the colliding bodies and larger bodies tend to cool more slowly (e.g., Tonks and Melosh 1993). For planet-sized rocky bodies, giant impacts, such as the one that may have led to the formation of the Moon (e.g., Barr 2016), are the dominant heat source for the formation of magma oceans. All rocky planets likely experienced giant collisions at some stage of their evolution that led to the formation of magma oceans (Quintana et al. 2016).

Although difficult to constrain due to the multi-stage nature of the process, the release of gravitational potential energy upon formation of the iron-rich core can also contribute decisively to large-scale silicate melting, in particular of the lower parts of the mantle (e.g., Rubie et al. 2015).

In the context of exoplanets, bodies orbiting close around their host star may also experience sufficiently intense radiative heating (e.g., Demory et al. 2016) or, because of high orbital eccentricities, tidal heating (e.g., Driscoll and Barnes 2015) to produce magma oceans.

Evidence for Magma Oceans

The Moon is the body for which the magma ocean phase is best documented. As revealed by samples and remote-sensing measurements, the ancient lunar highlands largely consist of anorthosites, mostly composed of plagioclase feldspar, which build a 30–40 km thick crust (Wieczorek et al. 2013). In a cooling magma ocean, plagioclase minerals form at conditions for which the crystals are lighter than the residual liquid. They tend to float to the top of the magma ocean forming the anorthositic crust. Such differentiation processes during magma ocean solidification explain the observed negative Eu-anomaly in the mantle

sources of mare basalts (by separation of Eu-enriched plagioclase from the rest melt) and the strong enrichment of crustal rocks in the Procellarum KREEP terrane in incompatible trace elements, that accumulated in the rest melt during the latest stages of magma ocean solidification (see Shearer et al. 2006).

For the terrestrial planets, an early magma ocean stage has been proposed as a likely explanation for their differentiated structure. Spectral measurements suggest that the dark character of Mercury's surface is due to graphite (Peplowski et al. 2016). Similar to anorthosites on the Moon, graphite is thought to have formed a flotation crust in a crystallizing magma ocean (Vander Kaaden and McCubbin 2015). The Earth's surface does not present direct evidence for an early magma ocean because of its continuous recycling due to plate tectonics. However, simulations of the Moon-forming impact indicate that the mantle of the proto-Earth underwent nearly total melting (e.g., Nakajima and Stevenson 2015). In addition, the budget of siderophile elements of the mantle is thought to be set by metal-silicate equilibration at the base of a deep magma ocean (e.g., Walter et al. 2000). Isotopic measurements of Martian meteorites suggest that the planet differentiated into mantle and core within the first few million years of the Solar System and that the mantle differentiated into distinct source reservoirs within a few tens million years of the Solar System (e.g., Elkins-Tanton 2012). Both findings contain strong indications that also Mars underwent an early magma ocean phase.

For early formed planetesimals like the asteroid Vesta, a magma ocean phase is inferred from the occurrence of differentiated meteorites originating from the asteroid belt (e.g., Neumann et al. 2014).

Properties and Evolution of Magma Oceans

Due to large uncertainties in current accretion models, the initial thermal state of planets and the extent of their magma oceans are not well known. The siderophile element content of the mantle provides some constraints on the depth of core-mantle equilibration, which have been used

to infer possible depths of magma oceans on Earth and Mars (e.g., Elkins-Tanton 2012). The depth of the lunar magma ocean is further constrained by the thickness of its primordial crust, the crystallization depth of crust-forming plagioclase, and the source depth of lunar volcanic glasses (Longhi 2006).

The duration of the magma ocean phase depends strongly on the presence or absence of insulating crusts or atmospheres. On the Moon, the formation of an insulating anorthositic crust on the surface of the magma ocean may have prolonged its solidification to up to 200 Ma (Maurice et al. 2020). In absence of an atmosphere, on planets like Venus, the Earth, and Mars, a magma ocean radiating heat to space is expected to solidify within a few thousand years (e.g., Lebrun et al. 2013). However, the large amount of greenhouse gases that are likely released upon magma ocean solidification can lead to the formation of a thick insulating atmosphere that can prolong the magma ocean lifetime to a few million years for a planet at Earth's orbit, or even to ~100 million years for a planet at Venus' orbit receiving a higher stellar radiation (e.g., Hamano et al. 2013).

Cross-References

- [Accretion](#)
- [Achondrite](#)
- [Anorthosite](#)
- [Asteroid](#)
- [Basalt](#)
- [Core, Planetary](#)
- [Crust](#)
- [Dichotomy, Planetary](#)
- [Differentiation, Planetary](#)
- [Earth](#)
- [Earth, Formation, and Early Evolution](#)
- [Exoplanets, Discovery](#)
- [Extinct Radionuclides](#)
- [Extrasolar Planets](#)
- [Giant Impact](#)
- [Graphite](#)
- [Heat Transfer, Planetary](#)

- [KREEP](#)
- [Magma](#)
- [Mantle](#)
- [Mare Plains](#)
- [Mars](#)
- [Mercury](#)
- [Meteorites](#)
- [Mineral](#)
- [Moon, Origin of](#)
- [Moon, The](#)
- [Parent Body](#)
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- [Planet Formation](#)
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- [Planetesimals](#)
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- [Rock](#)
- [Rocky Planet](#)
- [Siderophile Elements](#)
- [Terrestrial Planet](#)
- [Tides, Planetary](#)
- [Trace Elements](#)
- [Venus](#)
- [Vesta](#)

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Magmasphere

- [Magma Oceans](#)

Magmatic Rock

- [Igneous Rock](#)

Magnetic Anomaly

Nicholas Arndt

ISterre, University Grenoble Alpes, Grenoble, France

Definition

A *magnetic anomaly* is the local departure in orientation or strength from the large-scale pattern of a planetary magnetic field. Stripes of alternating positive and negative polarity parallel to isochrons in the Earth's oceanic crust record reversals of the magnetic field; they provided the first evidence of seafloor spreading. The pattern of variation of field direction and intensity is recorded in volcanic or stratigraphic sequences and provides the basis of the magneto stratigraphy. More localized anomalies provide information about the subsurface structure and composition of the Earth's crust and are an important index for the presence of certain metallic (generally ferruginous) ore deposits.

Cross-References

- [Magnetic Field](#)
- [Magnetic Field, Planetary](#)
- [Magnetic Pole](#)
- [Oceanic Crust](#)
- [Plate Tectonics](#)

Magnetic Field

Claude Catala

LESIA, Observatoire de Paris – PSL, Meudon,
France

Keywords

Magnetic field · Magnetism · Stellar magnetism · Planetary magnetism · Dynamo · Star formation · Planet formation · Stellar evolution · Planetary evolution

Synonyms

[Magnetism](#)

Definition

A magnetic field is a physical field that arises from an electric charge in motion, producing a force on another moving electric charge. Magnetic fields play a major role in star and planet formation, as well as at most stages of planetary system evolution.

Overview

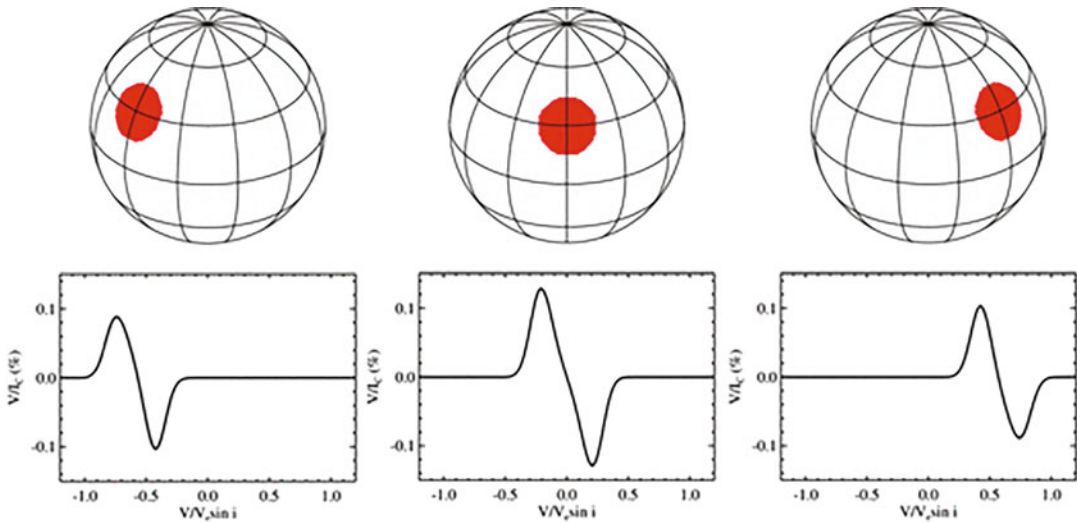
Magnetic fields are present everywhere in the Universe, with intensities ranging from a fraction of a micro-Gauss (10^{-6} Gauss) in the intergalactic medium, to about 1 Gauss for the Earth magnetic field, and up to several peta-Gauss (10^{15} Gauss) in some highly magnetized compact objects, such as

neutron stars. They play an important role in most physical processes at work in the Universe, and are believed to be responsible for some spectacular behaviors, such as energetic collimated jets escaping from galactic nuclei or from protostars and young stars. They also constitute an essential ingredient of star and planet formation and their subsequent evolution. The Earth magnetic field has played and continues to play a major role in protecting our planet from impinging hard solar radiation, and therefore has had a crucial impact on the emergence and evolution of life.

Basic Methodology

Stellar magnetic fields can be measured thanks to the Zeeman effect on spectral lines: in presence of a magnetic field, spectral lines are split into multiple, closely spaced components, the so-called π and σ Zeeman components. There exist several ways of exploiting this property, the most efficient being the analysis of the light polarization induced by the Zeeman effect. Each one of the Zeeman components indeed is polarized in a particular way, linearly for the π components or linearly and circularly for the σ components. Circular polarization is sensitive to the line-of-sight (longitudinal) component of the magnetic field, while linear polarization is sensitive to the component of the magnetic field perpendicular to the line-of-sight (transverse). The strength and orientation of the star's magnetic field can thus be determined by a careful examination of the Zeeman polarization of spectral lines.

The instrument used for this purpose is called a spectropolarimeter, and consists of a high-resolution spectrograph combined with a polarimeter. Very powerful such instruments were developed in the last two decades, in particular ESPaDOnS on the 3.6 m Canada-France-Hawaii telescope (CFHT) on Mauna Kea, HARSPol on the 3.6 m telescope at ESO-La Silla, and NARVAL/NeoNARVAL on the 2 m Bernard Lyot telescope (TBL) at Pic du Midi in the French Pyrénées. The remarkable efficiency of these instruments allowed astronomers to measure



Magnetic Field, Fig. 1 The principle of Zeeman-Doppler imaging. In the upper row of the figure, a magnetic region is depicted at three different phases of the rotation,

while its corresponding circular polarization signature is shown in the lower row. Credit O. Kochukhov.

the magnetic fields of hundreds of stars of all types, providing valuable information on stellar magnetism. More recently, as described in section “[Future Directions](#)” below, an extension of spectropolarimetric techniques toward the infrared was developed, providing for instance the possibility to study magnetic fields in very cool stars.

The Zeeman polarization measurement described above provides the longitudinal or transverse component of the magnetic field (depending on the type of polarization, linear or circular, which is measured), averaged on all the visible hemisphere of the star at the moment of the observation. In order to reconstruct the magnetic field vector at all locations at the stellar surface, astronomers have developed the so-called Zeeman-Doppler imaging technique, which consists of monitoring the star during its rotation. A magnetic region appearing at the limb on the side of the star which is approaching the observer will produce a polarimetric signature at the blue edge of a spectral line, due to the Doppler effect. As the star rotates, the magnetic region will continue to approach the observer but with a decreasing velocity, and therefore its signature will move toward the center of the line. At some point, the meridian plane of the magnetic region will cross

the line of sight and the polarimetric signature will have a zero velocity in the observer’s direction, then it will start moving toward the red wing of the line, until eventually the magnetic region disappears at the opposite limb. The excursion of the polarimetric signal across the line and the speed at which it evolves from blue to red depend on the latitude of the magnetic region and on the inclination of the star’s rotation axis with respect to the line of sight.

Based on this principle, astronomers have developed powerful tools to reconstruct the topology and intensity of the magnetic field at the surface of a star, although it cannot be resolved directly.

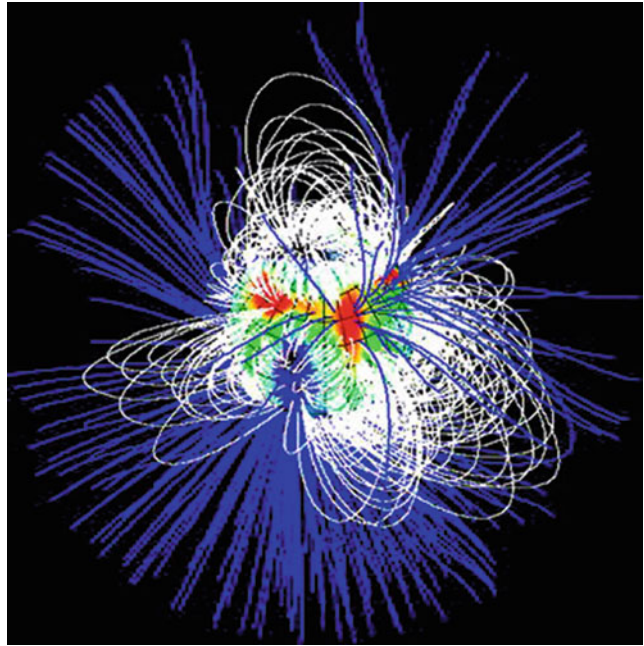
Key Research Findings

Importance of Magnetic Fields for Planet Formation, Evolution, and their Habitability

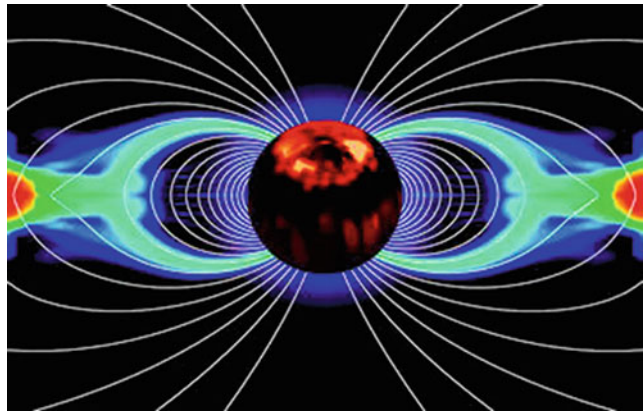
Magnetic fields are believed to play a crucial role in the formation and evolution of stars and planetary systems. Stars are formed from molecular clouds in the interstellar medium, which are threaded by magnetic fields. The gas and the magnetic field are intimately coupled during star

Magnetic Field,

Fig. 2 The magnetic topology of SU Aur (a young star of T Tauri type located at 150 pc from the Sun), reconstructed by means of Zeeman-Doppler imaging. Credit JF Donati

**Magnetic Field, Fig. 3**

A model of a pre-main sequence star, magnetically coupled to its circumstellar accretion disc. Credit Klaus Strassmeier



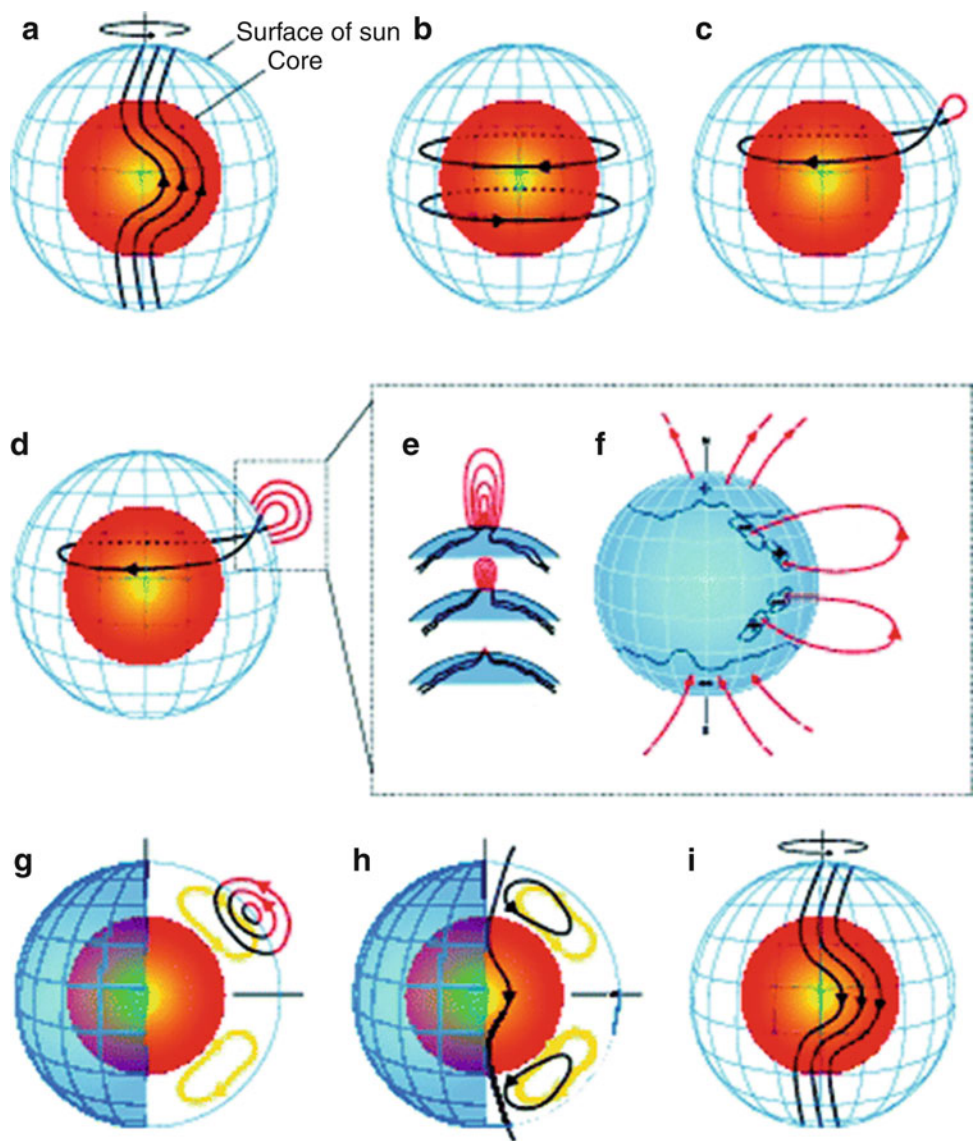
M

formation, the collapsing gas dragging in the magnetic field lines, while the magnetic field tends to slow down the collapse. This has a significant impact on the distribution of matter which is left behind in the nebula after the collapse, out of which planets form.

Magnetic fields are also an essential ingredient of the coupling between protostars or young pre-main sequence stars with their surrounding accretion discs. In these early phases of stellar evolution, this coupling is responsible for the transfer of angular momentum from the star to

the disc, and prevents the contracting star from spinning up to breakup velocity. It can be concluded that stars could not be formed in the absence of magnetic fields, hence that magnetic fields are crucial for the emergence of life, which definitely requires the energy provided by stars.

Moreover, stellar magnetic fields are coupled to stellar rotation throughout the evolution of a star. For solar-type stars, they are generated by dynamo action inside the star, whose efficiency is a strong function of rotation. Additionally,



Magnetic Field, Fig. 4 Dynamo generation of magnetic field in the Sun. Credit M. Dikpati

stellar magnetic fields, through their coupling with the stellar wind, enhance and control the angular momentum loss during the star's evolution. As a result, due to its magnetic field, a star will keep spinning down during its entire life, with a related decrease of its level of activity. Because the level of stellar activity and its accompanying particle bombardment can have a major impact on the appearance and evolution of life on a planet, stellar magnetic fields can definitely not be

ignored in this process. This relationship between stellar activity and life on a planet is further impacted by the eventual presence of a magnetic field on the planet itself, which can act as a shield against stellar particle bombardment.

Magnetic fields, both stellar and planetary, therefore play an essential role in stellar and planetary evolution, participate to the control of planet habitability, and may significantly impact the appearance and evolution of life on a planet.

Magnetic Field,

Fig. 5 This artist view shows the earth magnetosphere, protecting us from solar charged particles, compressed on the day side and extended on the night side. The image is not to scale

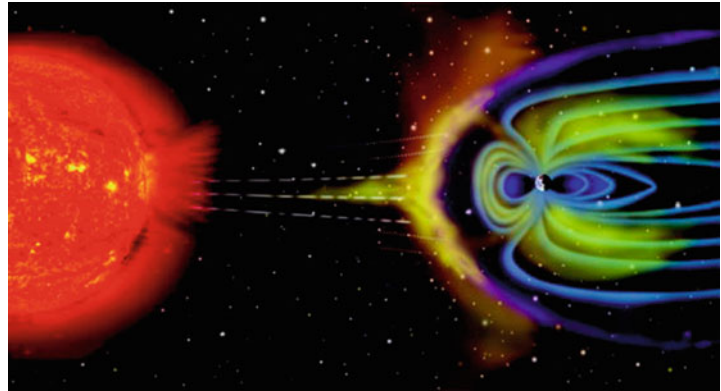
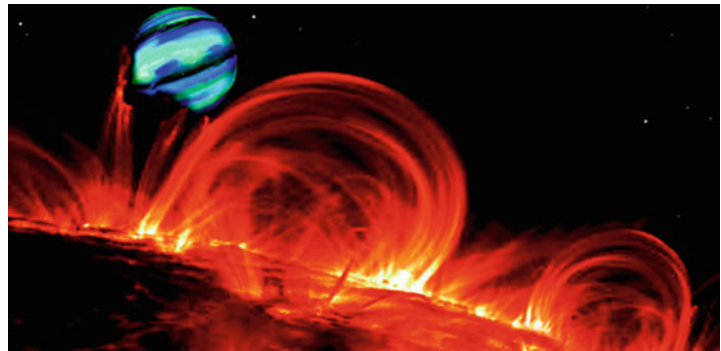
**Magnetic Field,**

Fig. 6 An artist view of the hot giant exoplanet orbiting τ Boo, within the star's magnetosphere. The planet is 4.4 times more massive than Jupiter and its separation with the star is only 0.049 AU. Credit David Aguilar



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Solar and Stellar Magnetic Fields

The first stellar magnetic field, that of the Sun, was discovered in 1908 by George Hale, who measured the field inside solar dark spots using the Zeeman effect on spectral lines. Since then, our understanding of the solar magnetic field has considerably progressed. The solar magnetic field can be approximated at first order by a dipole, and controls most of the active phenomena that it displays: solar spots, chromospheric plagues, filaments, corona, wind, flares, etc. However, the dynamo mechanism by which the solar magnetic field is generated and sustained is far from being fully understood.

Understanding the solar magnetic field is one of the motivations for studying the magnetic field of other stars, offering a wide range of physical conditions (rotation, convection, temperature, etc.), and which can therefore be used as cosmic laboratories to study stellar magnetism. It is also very important to understand stellar magnetic

fields because of their strong impact on stellar formation and evolution, as described earlier.

The Magnetism of Cool Stars

Magnetic fields of cool stars, such as the Sun, are believed to be produced within the convective zone, as the result of convection coupled with rotation. Differential rotation inside the star wraps and amplifies the magnetic field around the star, changing the seed poloidal field into an intense toroidal one. Convection and meridional circulation then regenerate the poloidal field from the toroidal one. Although the details of this mechanism still need to be worked out, it seems well established that this type of dynamo, which is responsible for the magnetic field of most cool stars, including the Sun, is predominantly located at the base of the convection zone, near its interface with the underlying radiative zone, where the differential rotation is maximum.

However, spectropolarimetric observations of various classes of cool stars, with various rotation rates and depths of the convective envelopes, have revealed the existence of several regimes of dynamo generation of magnetic fields. In particular, red dwarfs, which are entirely convective, and hence do not have any radiative-convective interface where dynamo action is supposed to be most effective, still exhibit intense, predominantly dipolar magnetic fields, in contradiction with predictions of the above simplified model. Stellar magnetism therefore still preserves some of its mysteries.

As a consequence of the dynamo regeneration of magnetic fields in cool stars, the major magnetic component reverses direction periodically. The cadence of these reversals is of the order of once every 11 years for the Sun, but can be considerably shorter or longer for other stars, depending on various parameters, in particular the amount of differential rotation.

The Magnetism of Massive Stars

In addition to cool stars with masses similar to that of the Sun, about 10% of the massive stars (more than twice the mass of the Sun) also exhibit intense, well-ordered, dipolar magnetic fields. These fields are believed to be fossil in origin, remnants of the weak magnetic field present in the molecular cloud out of which the star was formed. During the contraction of the star toward the main sequence, the magnetic field lines are frozen in the contracting plasma, and are therefore pinched, resulting in a gradual enhancement of the magnetic field intensity and the evolution of its topology toward a dipole.

The magnetic fields of these massive stars are thought to be responsible for a variety of properties, such as the presence of patches of chemical abundance anomalies seen at the surface of some of them.

The Magnetic Field of the Earth

Like the solar magnetic field, the magnetic field of the Earth is approximately a dipole, more or less similar to that of a bar magnet. The Earth magnetic axis is tilted by about 11 degrees with respect to its rotation axis. The magnetic poles are therefore

near (but not at) the geographic poles. The magnetic field is generated and sustained in the liquid outer core by a dynamo process involving convection of molten iron and rotation. The strength of the field at the surface of the Earth is approximately 0.5 gauss in average, but varies over the surface in the range 0.3 Gauss (in the area including South America and South Africa) to 0.6 Gauss (around the magnetic poles in northern Canada and southern Australia, and in Siberia).

The direction of the Earth magnetic axis is not constant in time. The geographic location of the magnetic poles has considerably varied over the centuries. Rock specimens of different ages found at the same location have different directions of permanent magnetization, indicating this long-term variation of the Earth magnetic field orientation. Evidence is found for 171 magnetic field reversals during the past 71 million years. The locations of the magnetic poles move as much as 15 km every year.

The magnetic field extends to thousands of kilometers above the Earth into a gigantic magnetosphere which shields us against solar high energy charged particles, which otherwise would have prevented life on Earth. The Earth's magnetosphere deflects most of the solar particles. Some of them are trapped in the so-called Van Allen radiation belt. Frequently, the Earth's magnetosphere is hit by energetic solar flares causing geomagnetic storms, giving rise to boreal and austral aurorae. During these events, a small number of solar charged particles reach the Earth's upper atmosphere and ionosphere in the polar zones, channeled along the magnetic field lines.

Star-Planet Interactions: The Role of Magnetic Fields

Special attention is being paid presently to the interaction of close-in Jupiter-sized exoplanets with their host stars. Evidence has been accumulated in recent years that large size planets orbiting very close to their star can have a significant influence, through tidal effects, on the activity behavior of their star. If the planet is itself magnetic and orbits a magnetic star, we can expect a complex interaction between the planet magnetosphere and that of the star, comparable to some extent to the

well-known Io-Jupiter system interaction. It has been recently conjectured that the magnetic interaction between close-in giant planets and their host star could play a dominant role in the migration and evolution of these planets.

One example of this kind of star-planet magnetic interaction is provided by the τ Bootis system, in which a $4.4 M_{\text{Jup}}$ planet orbits a solar-type star at the distance of 0.049 AU. The star τ Bootis has been shown to be magnetic, with a magnetic field intensity of the order of a few gauss, and to have a strong surface differential rotation. The planet orbital motion is synchronized with the star's rotation at intermediate latitudes. The magnetic field reverses its polarity approximately every 2 years, that is, much more often than the Sun. The potential magnetic interaction between this star and its planet has triggered a major interest in recent years.

Future Directions

Most of the results obtained so far in the field of stellar spectropolarimetry, and briefly summarized in the previous chapters, were obtained in visible light. The foreseen future of this field consists mostly in an extension of this technique to the infrared and ultraviolet domains.

These developments are already well underway toward the infrared with instruments such as the SPIRou spectropolarimeter installed at CFHT, soon to be complemented by a twin instrument (SPIP) at TBL. Extending spectropolarimetric techniques toward the infrared provides an easier access to the measurement of magnetic fields in stars cooler than the sun, such as M dwarfs and brown dwarfs, as well as access to objects in heavily obscured environments, such as protostars, and to magnetospheres around hot stars.

In parallel, projects for the development of spectropolarimeters in the ultraviolet are currently under study, with the additional difficulty of the need to go to space because ultraviolet radiation is blocked by the earth atmosphere. Several space mission projects for ultraviolet spectropolarimetry exist, ranging from nanosatellites, such as the

CASSTOR project under study in France, to medium size missions, like the Polstar satellite proposed to NASA or the Arago project proposed to ESA, or large size missions such as LUVOIR (Large UV/Optical/Infrared Surveyor), an 8 m space telescope recently recommended by the US Astronomy decadal survey, for which a UV spectropolarimetric instrument (Pollux) is planned. Spectropolarimetry in the ultraviolet will open a new discovery space, from the environment of magnetic hot stars to the interactions between cool stars and their planets.

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Magnetic Field Generation

► [Dynamo, Planetary](#)

Magnetic Field, Planetary

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Keywords

Core · Dipole field · Dynamo · Induced magnetic field · Magnetometer · Remnant magnetic field

Definition

The magnetic field of a ► [planet](#) or satellite can be measured by magnetometers onboard orbiting space craft or – more locally – onboard landers and rovers. The magnetic field at any given point has a strength and a direction and thus is a vector field. On a global scale and measured at some distance from the planet or satellite, planetary magnetic fields resemble dipole fields. On or close to the surface the field is typically of more complicated topology. Planetary magnetic fields are generated by a ► [dynamo](#) mechanism in the iron-rich liquid core shells of ► [terrestrial planets](#) and satellites, in metallic ► [hydrogen](#) shells in ► [Jupiter](#) and ► [Saturn](#), and in ionic oceans in ► [Uranus](#) and ► [Neptune](#). Magnetic fields may be also induced in electrically conducting oceans in icy moons such as the Jovian moon ► [Europa](#). Local magnetic fields may be caused by remnantly magnetized ► [rock](#).

Overview

Magnetic fields are – in general – detected by the force they exert on magnetic materials and electrical charges. This principle is used in magnetometers onboard spacecraft with which magnetic fields around planets are detected and measured. The magnetic field strength is a vector quantity and is measured in the SI unit tesla [T]. In geophysics and planetary physics, the *cgs* units Gauss [G] and gamma [γ] are still widely used with 1 γ equaling 10^{-3} G and 1 G equaling 10^{-4} T. The terrestrial planets ► [Earth](#) and ► [Mercury](#) are known to have global magnetic fields. The Earth’s field is known to vary in time, with short period and secular changes and polar wander (motion of

the North and South Poles with respect to the solid ► [crust](#)). The polarity of the field has changed over geological history on time scales of 10^5 a. The Earth’s magnetic field strength varies between 25,000 and 65,000 nT with the maxima near the poles and the minimum near the equator.

The magnetometer onboard the ► [Mars Global Surveyor](#) Mission discovered local magnetic fields on ► [Mars](#), mostly in the southern hemisphere, that have been interpreted to be due to magnetized crustal rock provinces with varying strength and direction of magnetization. This observation indicates that Mars once had a global magnetic field, the polarity of which may have varied in time similar to the Earth’s field. Magnetized crustal rock units have also been discovered on the Moon.

The planets of the outer Solar System Jupiter, Saturn, Uranus, and Neptune all have global magnetic fields. Periodically varying magnetic fields have been discovered around ► [Europa](#), ► [Ganymede](#), and ► [Callisto](#), the icy satellites of Jupiter. These fields vary in time with the orbital periods of the satellites, which are on the order of days. In addition, Ganymede has a steady global magnetic field. This satellite is the only satellite known to posses such a field.

Global magnetic fields of planets largely resemble dipole fields (the field of an ideal bar magnet). A simple representation of the global magnetic field is the offset tilted dipole. This dipole is characterized by a moment (a vector quantity) $\vec{M}$ and an offset vector $\vec{r_0}$ measured from the figure center of the planet. The dipole moment is measured in Tm^{-3} , and the tilt is measured relative to the rotation axis. Table 1 collects dipole moments and tilts for the planets with known global magnetic fields. More detailed representations of global magnetic fields use spherical harmonic functions.

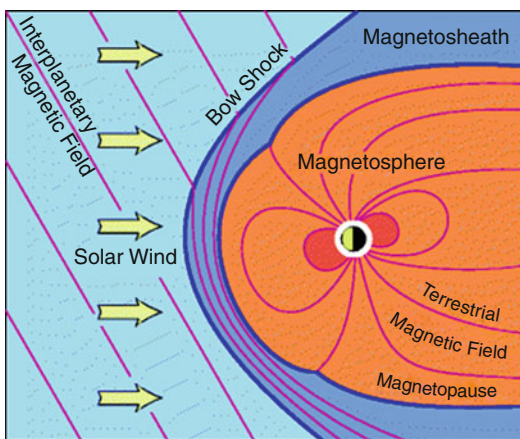
Magnetic Field, Planetary, Table 1 Dipole moment and tilt of planets and satellites with known active magnetic fields

	Mercury	Earth	Jupiter	Ganymede	Saturn	Uranus	Neptune
Dipole moment [$10^4 \text{nT} \cdot \text{R}^3_{\text{p}}$]	0.019	2.58	42.8	0.07219	2.11	2.28	1.42
Tilt [°]	4.5	11	9.5	176	1	60	47

The offset in terms of the planetary radius is usually small, suggesting that the magnetic field is generated deep in the interior. Exceptions are Jupiter with $0.11 R_p$ and even more so Uranus and Neptune with 0.33 and $0.55 R_p$, respectively (e.g., Connerney 2015). It is held that in these planets the dynamo is closer to the surface.

A planet with an intrinsic magnetic field stands as an obstacle to the solar wind with an interaction region that resembles a set of nested conic sections (Fig. 1). The outer section is called the bow shock. It marks the shock-wave front that is created by the impingement of the supersonic solar wind on the planetary field. The slowed solar wind mostly flows around the obstacle within a region called the magnetosheath. The latter is bounded on the one side by the bow shock and on the other by the magnetopause. Within the magnetopause is a region called the ► [magnetosphere](#) that is mostly filled by the planetary field. The magnetosphere extends downstream into the magnetotail.

In terrestrial planets and in Ganymede, the global field is agreed to be produced in their fluid iron cores or core shells by a ► [dynamo](#). In the ► [giant planets](#) Jupiter and Saturn, the field is generated by dynamo action in their metallic hydrogen shells. In Uranus and Neptune, the field is held to be produced in ionic oceans.



Magnetic Field, Planetary, Fig. 1 Solar wind interaction with the terrestrial magnetic field. (Adapted from Baumjohann and Nakamura 2015)

Rock that contains sufficient amounts of ferri- and ferromagnetic materials can be magnetized in a planetary magnetic field. Part of the magnetization can be permanent or remnant at temperatures below the Curie temperature. The value of the Curie temperature varies between ► [minerals](#) but is typically between 500 and 1000 K. The remnant and the induced magnetizations are vector quantities. The direction of the remnant magnetization reflects the direction of the magnetizing field at the time of the cooling below the Curie temperature. Therefore, remnant magnetization data can be used to reconstruct the evolution of the global magnetic field and the movement of crustal units relative to, for example, the poles of the magnetic field. Remnantly magnetized crustal units are known from the Earth, Mars, and the Moon. For the Earth, remnant magnetizations have been used to date the spreading of the oceans and to determine its rates, continental drift, and polar wander as well as the evolution of the magnetic field and its polarity. For Mars, the magnetization patterns have been interpreted as indicating a global magnetic field in the first 500–1000 Ma that may have experienced polarity reversals. This field would have been similar in strength to the present global field of the Earth. For the Moon, an early field has been suggested, but it has also been proposed that the magnetizing field may have been due to plasma that emanated from large impacts (Hood and Vickery 1984).

The periodically varying fields of the icy moons of Jupiter have been interpreted as induced fields (Kivelson et al. 1999). If the satellites contain an electrically conducting layer of sufficient conductivity then their moving through the magnetic field of Jupiter along their orbits will induce a time-varying current. That current by the laws of induction will induce a magnetic field. Salty ► [water](#) will have a sufficiently strong conductivity. The geometry of the field also suggests that the conductor cannot lie deep in the satellite. The induced fields thus have been taken to suggest the existence of (ice-covered) oceans.

The presently available data for Mercury interpreted together suggest a dipole tilted by

5° with a moment of $190 \text{ nT} \cdot R_M^3$, but non-dipolar terms are found to be significant (Uno et al. 2009; Johnson et al. 2012). These could indicate crustal fields or significant dynamo action close to the core/mantle boundary, which should be close to $0.8 R_M$. Missions to Venus have failed to detect a magnetic field of the planet. An upper limit for its dipole moment is 10^{-5} times the moment of the Earth or $0.35 \text{ nT} \cdot R_V^3$. The first unambiguous detection of an intrinsic field at Mars was achieved by the Mars Global Surveyor (MGS) mission (Acuna et al. 1999). The field strength varies between $\pm 200 \text{ nT}$ along the mapping orbit at 400 km height above the surface. These values suggest magnetizations of approximately 10^3 nT at the surface. It has been concluded that the Martian crust must be about ten times more intensely magnetized than the Earth's crust. The Moon does not have a dipole field at present, but large parts of the crust show remnant magnetization. The magnitude of the magnetization reaches values of up to 250 nT , much smaller than the magnetization of the Martian and the Earth's crust.

Cross-References

- Callisto
- Core, Planetary
- Crust
- Dynamo, Planetary
- Earth
- Europa
- Ganymede
- Giant Planets
- Hydrogen
- Jupiter
- Magnetic Field
- Magnetosphere
- Mantle
- Mars Global Surveyor
- Mars
- Mercury
- Mineral

- Moon, The
- Neptune
- Planet
- Rock
- Satellite or Moon
- Saturn
- Terrestrial Planet
- Uranus
- Venus
- Water

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Magnetic Fields and Planetary Systems Formation

Wayne G. Roberge and Glenn E. Ciolek
New York Center for Astrobiology, Rensselaer
Polytechnic Institute, Troy, NY, USA

Keywords

Habitability · Magnetic fields · Planet formation

Definition

The magnetic field of a protostellar disk is a field that permeates the rotating disk of gas and dust about a protostar from which planets may form. Magnetic field lines rotate with the ionized component of the disk material and are subject to an instability that is the likely source of turbulence and viscous drag within a disk. This makes possible the inward accretion of mass from a disk onto its central protostar. It has also been suggested that magnetic forces are responsible for the observed ejection of high-velocity bipolar outflows from protostellar disks.

Overview

Interstellar and Planetary Magnetic Fields

Electrical currents flowing in conductors produce magnetic fields (“B fields”). Conductors in the cosmos include the metallic cores present in some planets and asteroids as well as the ionized gases, called plasmas, which pervade star- and planet-forming regions of interstellar space. Thus, Earth’s B field is attributed to currents in its iron-rich core. However, planetary magnetism is not universal: Mercury, Jupiter, Saturn, Neptune, and Uranus all have large-scale B fields, but Venus and Mars do not. Moreover, planetary magnetic fields vary widely, from ~ 1 mG (Mercury) to ~ 1 G (Earth, Jupiter) (Stevenson 2010). (1 G = 1 Gauss is a

standard unit of magnetic induction.) Within interstellar clouds, where star and planet formation takes place, field strengths ~ 10 – 100 μ G have been detected (Heiles and Crutcher 2005).

Magnetic fields tend to decay via the dissipation of currents by electrical resistance (“Ohmic dissipation”). In a material with electrical conductivity σ , the decay time is $t_{\text{decay}} = 4\pi\sigma L^2/c^2$, where L is a characteristic size or length scale for variations in B, and c is the speed of light. Setting σ to the conductivity of molten iron and L to the radius of Earth’s core gives $t_{\text{decay}} \sim 10^5$ years. Hence, persistent planetary B fields require some process to counteract Ohmic dissipation; this “dynamo mechanism” must be driven by convective motions in planetary cores, but the physics is complex and poorly understood. In contrast, the enormous scale of B fields in star- and planet-forming clouds makes them much longer lived: setting σ to a typical conductivity for interstellar cloud plasma and $L = 100$ AU (1 AU is the radius of the orbit of the Earth) yields $t_{\text{decay}} \sim 10^{11}$ year, which is almost ten times greater than the age of the universe.

Magnetohydrodynamics

Magnetic fields are mapped by magnetic field lines. At each point on a magnetic field line, the direction of the line indicates the direction of B and the spacing between adjacent field lines is inversely proportional to the magnitude of B. The motions of conducting liquids and plasmas (Cowling 1957; Parker 1979) can be described by the equations of magnetohydrodynamics (“MHD”). The motions of the conducting fluid dictate electrical currents and thus the B field. Magnetic forces feedback and affect the fluid motions, which makes the resulting dynamics generally complex. However, under conditions where Ohmic dissipation can be neglected, corresponding to large length scales and/or electrical conductivities, a much simpler picture arises. In this circumstance (“ideal MHD”), the magnetic field lines are frozen into and move with the plasma. The frozen-in field exerts tension and pressure forces on the fluid that are correlated with the curvature and spacing of the field lines.

Magnetic Fields and Planet Formation

Angular momentum conservation prohibits the direct formation of a star by gravitational collapse. A protostellar core (i.e., the part of an interstellar molecular cloud that gravitationally fragments and will ultimately form a star and planetary system) contracts first into a rotating protoplanetary disk or protoplanetary disk (Vicente and Alves 2005; Williams et al. 2005). The central star is built up later via the migration of disk material inward, a process which requires friction (viscosity) between matter in adjacent orbits with slightly different speeds. It is now generally accepted that magnetic fields are required to produce this friction, via a mechanism called the *magnetic rotational instability* (“MRI”) (Balbus 2010). Because field lines are dragged inward by collapsing core material, the B fields required by the MRI are plausible. The presence of dynamically significant B fields in protoplanetary disks is also indicated by observations of *bipolar outflows*, extended and highly collimated jets of material ejected parallel and antiparallel to the disk rotation axis (Reipurth and Bally 2001). According to *magnetocentrifugal outflow* models of bipolar outflows (Blandford and Payne 1982; Königl and Pudritz 2000), centrifugal forces fling plasma outward along magnetic field lines, which direct and collimate the flow. Bipolar outflows are extremely supersonic, producing *multifluid MHD shock waves* wherever they impact ambient material. Magnetic forces on the charged particles cause large differential velocities between ions and neutral molecules. Friction associated with the differential motions heats the plasma to $\sim 10^3$ K over an extended region (Draine et al. 1983). Shock heating opens chemical pathways which are closed in cold clouds, with unknown but potentially important consequences for prebiotic chemistry.

Magnetic Fields and Habitability

It is interesting that the only planet known to be inhabited also has a large magnetic field. However, it is well known that Earth’s B field ameliorates or eliminates effects that would be harmful to life. For example, the Sun emits a high-velocity stream of charged particles, the solar wind, which

flows through the solar system at hundreds of kilometers per second. A planetary atmosphere directly exposed to the solar wind would be partially or completely eroded. However, Earth is protected from solar wind erosion by its magnetic field, which fills a region (the magnetosphere) that largely excludes the solar wind (Lammer et al. 2010). The frozen-in magnetic field of the solar wind also protects the Earth, by sweeping galactic cosmic rays out of the solar system (Parker 1963).

Cross-References

- [Magnetic Field](#)
- [Magnetic Field, Planetary](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)
- [Star Formation, Observations](#)

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Magnetic Fields and Star Formation

Wayne G. Roberge and Glenn E. Ciolek
New York Center for Astrobiology, Rensselaer
Polytechnic Institute, Troy, NY, USA

Keywords

Magnetic fields · Star formation

Definition

Interstellar magnetic fields are fields that thread the massive clouds of gas and dust in which stars are born. They exert magnetic forces on charged particles and can influence the large-scale stability of a cloud. Because magnetic forces do not act on neutral particles, self-gravity of the mostly neutral molecular gas in a cloud becomes greatly enhanced due to small-scale drift of neutrals with respect to charged particles. This creates dense localized regions known as protostellar cores, wherein self-gravity of the gas and dust exceeds restoring magnetic forces. Star formation is initiated by the subsequent gravitational collapse of a protostellar core.

Overview

Magnetic Fields in Space

Magnetic fields (“B fields”) are produced by electrical currents flowing in conductors. Conductors in space include ionized gases, called plasmas, which comprise stars and pervade interstellar clouds. Magnetism is universal in interstellar plasmas with field strengths $\sim 10\text{--}100\ \mu\text{G}$ in star-forming clouds (Heiles and Crutcher 2005).

Here $1\ \text{G} = 1\ \text{gauss}$ is a commonly used unit of magnetic induction B ; a typical value of B at the surface of the Earth is $0.5\ \text{G}$ (Stevenson 2010). Magnetic field lines map magnetic fields: at each point on a magnetic field line, the orientation of the line indicates the direction of B , and the spacing between adjacent lines is inversely proportional to the magnitude of B .

Magnetic fields tend to decay via the dissipation of currents by electrical resistance (“Ohmic dissipation”). In a material with electrical conductivity σ , the decay time is $t_{\text{decay}} = 4\pi\sigma L^2/c^2$, where c is the speed of light and L is a characteristic length scale for variations in B . The enormous scale of interstellar B fields makes them virtually immortal: setting σ to a typical conductivity for interstellar cloud plasma and representative $L = 1\ \text{pc}$ ($1\ \text{pc} = 3.26\ \text{light-years}$) gives $t_{\text{decay}} \sim 10^{18}$ years, about a hundred million times the age of the universe.

Magnetohydrodynamics

Magnetohydrodynamics (“MHD”) describes the motions of conducting plasmas (Cowling 1957; Parker 1979). The fluid motions dictate electrical currents and hence the B field. Since magnetic forces also affect the fluid motions, the dynamics are generally complex. However, under conditions where Ohmic dissipation is negligible, corresponding to large length scales and/or conductivities (such as in interstellar clouds), a simple picture emerges. In this regime (“ideal MHD”), the magnetic field lines are frozen into and move with the plasma. This frozen-in field exerts tension and pressure forces correlated with the curvature and spacing of the field lines.

Magnetic Fields and Star Formation

Magnetic fields play a crucial role in the support of interstellar [molecular clouds](#) against gravitational collapse. These clouds consist primarily of gaseous H_2 molecules and He atoms, along with much smaller relative abundances of other molecular species (such as CO and NH_3). They also contain interstellar dust grains, with $\sim 1\%$ of the cloud mass. Clouds are extremely cold ($\sim 10\ \text{K}$), having sizes from $\sim 1\ \text{pc}$ to $100\ \text{pc}$, mean particle densities $\sim 10^3\ \text{cm}^{-3}$, and masses $\sim 1\ M_{\odot}$ to

$10^5 M_{\odot}$ ($1 M_{\odot} = 1$ solar mass). Because the temperatures are so low, thermal pressure stresses are negligible compared to magnetic forces in clouds. Star formation in molecular clouds is observed to be very inefficient: less than 10% of a cloud's mass is converted by gravitational collapse into stars (Zuckerman and Palmer 1974). This inefficiency is due to internal B fields, whose supporting forces prevent wholesale cloud collapse; consequently, B fields regulate the rate of star formation (Mouschovias 1978; Shu et al. 1987). This is quantified by a cloud's *mass-to-magnetic flux ratio* (MtMFR), which is the ratio of its gravitational binding energy (proportional to the cloud mass squared) relative to its internal supporting magnetic energy (proportional to the square of the cloud's mean magnetic field strength). If the MtMFR is less than a critical value ("subcritical"), magnetic forces can support a cloud against its self-gravity. Conversely, if a cloud's MtMFR is greater than the critical value ("supercritical"), gravitational forces overwhelm magnetic forces and collapse can take place (Mouschovias and Ciolek 1999). Observations of Zeeman splitting of molecular OH lines, as well as polarimetric observations of the fluctuations in the direction of magnetic field lines in clouds (due to transverse MHD Alfvén waves that propagate along field lines), yield field strengths and MtMFRs in molecular clouds that are closely clustered around the critical value (Crutcher 2004), confirming large-scale magnetic support of clouds.

Even though molecular clouds are supported by internal B fields, star formation can still occur within them on small scales because clouds are weakly ionized. As stated above, a plasma can have a *frozen-in* magnetic field. But how effectively magnetic forces, which act only on charged particles, are transmitted to the bulk neutral matter (through charged-neutral particle collisions) depends on the abundance x_{cp} of charged particles relative to neutral particles (the plasma in molecular clouds is made up of cations such as Na^+ , Mg^+ , HCO^+ , electrons, and charged dust grains, which capture electrons on their surfaces). The outer layers of a cloud have $x_{cp} \sim 10^{-4}$, a value sufficient to ensure that collisions are frequent enough so that

supporting magnetic forces on the plasma are readily transferred to the neutrals, counterbalancing the compressing gravitational forces exerted on the neutrals. But $x_{cp} < 10^{-8}$ deep within a cloud, where matter is shielded from ionizing external UV photons. For x_{cp} values this low, neutral particles slip through the plasma and magnetic field lines (a process known as ► [ambipolar diffusion](#) (Mestel and Spitzer 1956)), increasing the mass in cloud interiors, but not the B field strength, as the field lines are "left behind" by the inwardly drifting neutrals. Hence, dense compact regions (mean densities $\sim 10^4 \text{ cm}^{-3}$, radii $\sim 0.1 \text{ pc}$) having MtMFRs greater than the critical value form inside globally supported clouds. These supercritical regions are *protostellar cores*, which dynamically collapse as a result of self-gravity. They are the localized sites within clouds where stars are born (Mouschovias and Ciolek 1999). MHD simulations of the formation and collapse of protostellar cores by ambipolar diffusion have been constructed for model molecular clouds, and their predicted magnetic field strengths and density and infall velocity profiles are consistent with multiwavelength observations of collapsing cores (Mouschovias and Ciolek 1999; Ciolek and Basu 2001). An alternative theory of star formation is that molecular clouds are short-lived objects formed by interstellar MHD turbulence. In this scenario, supercritical cores form randomly, via turbulent fluctuations, and collapse gravitationally to form stars (Mac Low and Klessen 2004).

Cross-References

- [Fragmentation of Interstellar Clouds](#)
- [Interstellar Medium](#)
- [Magnetic Field](#)
- [Protostars](#)
- [Star Formation, Observations](#)
- [Star Formation, Theory](#)

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the lines of magnetic flux enter and get out, and where the magnetic intensity is the highest. Due to the presence of a convecting liquid metal core, the interior of the Earth behaves as a giant dynamo, giving the Earth a magnetic field. This later is dipolar with an axis at a small angle to the Earth rotational axis, making the magnetic poles slightly offset from the geographic poles.

The magnetic polarity has changed with highly variable frequency through geological history. At times, the reversals are frequent, every few hundred thousand years or less, but in the mid-Cretaceous, the polarity remained constant for nearly 40 Ma. As the magnetic field is global, a reversal is strictly contemporaneous on any point on the planet. Consequently, it is used as a reliable chronometer, which led to the establishment of a *Geomagnetic Polarity Time Scale*.

The inclination of the magnetic field vector depends on the latitude; therefore, when recorded by magnetic minerals in rocks, it provides information about the latitude at the time the rock formed (paleomagnetism). Apparent polar wander curves are compilations of the positions of the magnetic poles as reconstructed from the minerals in strata of different ages from a single ► [continent](#) or smaller terranes; they trace the position of that tectonic element with reference to the position of the pole, assumed to be fixed. Such information provides evidence of relative plate movement from as early as the Archean.

M

Magnetic Iron Ore

► [Magnetite](#)

Magnetic Pole

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

Magnetic poles are the two regions on the opposite ends of a magnet; they are the places where

Cross-References

- [Magnetic Anomaly](#)
- [Magnetic Field](#)
- [Magnetic Field, Planetary](#)
- [Paleomagnetism](#)
- [Plate Tectonics](#)

Magnetism

- [Magnetic Field](#)

Magnetite

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Magnetic iron ore](#)

Chemical Formula

Fe_3O_4

Definition

Magnetite is a black, cubic iron oxide belonging to the spinel group. It is one of the most common magnetic minerals on Earth. The occurrence of two iron ions having different valences (2^+ and 3^+) occupying specific sites in the crystal structure causes a transfer of electrons generating the magnetic field. Magnetite occurs in almost all igneous and metamorphic rocks and in several types of sedimentary rocks, including banded iron formations. Crystals of magnetite are found in magnetotactic bacteria (e.g., *Magnetospirillum magnetotacticum*). Magnetic minerals were found in the Martian meteorite ALH 84001 and interpreted as the best evidence of indigenous bacterial activity (controversial) (e.g., McKay et al. [2003](#)).

Cross-References

- ▶ [ALH 84001](#)
- ▶ [Banded Iron Formation](#)
- ▶ [Hematite](#)
- ▶ [Igneous Rock](#)
- ▶ [Iron](#)
- ▶ [Iron Cycle](#)
- ▶ [Iron Oxidation](#)

- ▶ [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- ▶ [Iron Reduction](#)
- ▶ [Magnetosome](#)
- ▶ [Magnetotactic Bacteria](#)
- ▶ [Metamorphic Rock](#)
- ▶ [Sedimentary Rock](#)

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Magneto-fluid Dynamics

- ▶ [Magnetohydrodynamics](#)

Magnetohydrodynamics

Etienne Pariat

Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris-PSL, CNRS, Laboratoire de Physique des Plasmas (LPP), Paris, France

LESIA, Observatoire de Paris, Université PSL, Sorbonne Université, Université Paris Cité, CNRS, Meudon, France

Keywords

Magnetic field · Magnetohydrodynamics

Synonyms

[Hydromagnetics](#); [Magneto-fluid dynamics](#)

Acronyms

MHD Magnetohydrodynamics

Definition

Magnetohydrodynamics (MHD) is a physical paradigm pertinent to describe the dynamics of electrically conducting fluids, such as plasmas, electrolytes, and liquid metals. MHD couples fluids dynamics with electromagnetism.

History

The first recorded use of the word *magnetohydrodynamics* (MHD) can be found in Alfvén (1942), who initiated this field. Hannes Alfvén received the Nobel Prize in Physics in 1970 for his work on MHD

Overview

Magnetohydrodynamics (MHD) is a set of postulates and theories that enables a synthetic description of the behavior of electrically conducting fluids subject to electromagnetic fields. Plasmas, liquid metals, electrolytes are example of electrofluids. Since plasma is by far the most abundant form of ordinary matter, MHD is a key paradigm in astrophysics, applying to stars and the Sun (formation, dynamo mechanism, atmospheric dynamics, eruptions, jets), star-planet interactions and in particular the stellar/solar winds, planetary magnetospheres, as well as protoplanetary disks, interstellar and intracluster media, active galactic nuclei, and possibly to the intergalactic regions.

The standard MHD description relies on several core hypothesis. First, MHD assumes a fluid description of matter, focusing on the macroscopic scales and relying on the continuous assumption, i.e., neglecting the specific behavior and properties of the particles that constitutes the fluid. Under the continuum assumption, macroscopic properties such as density, pressure, temperature, and bulk velocity are taken to be well-defined at “infinitesimal” volume elements – small in comparison to the characteristic length scale of the system, but large in comparison to the particles length scales. As a fluid theory, MHD also relies on the conservation of mass,

momentum, and energy. A second key hypothesis of MHD is the electric neutrality. At valid MHD scales, there shall be no free electric charge. MHD thus applies at a length scale that significantly exceeds the Debye length of the medium as well as at a temporal scale that is markedly larger than any specific particular timescale (e.g., frequency smaller than the plasma frequency).

The set of equations that describe MHD is a combination of the Navier–Stokes equations of fluid dynamics and Maxwell’s equations of electromagnetism. A key concept behind MHD is that the magnetic field that permeates the medium induces electric currents in the moving conductive fluid, currents that in turn affect the dynamic of the fluid, which retroactively modify the magnetic field itself. The Ohm’s law for conductive fluid links the electric field, with the magnetic field and the fluid velocity. The interplay between the magnetic field and the fluid dynamics is marked by the central role of the Lorentz force, through which the magnetic field affects the dynamics of the conductive fluid.

Several models of MHD can be used depending on the degree of complexity necessary to describe the studied system. One can cite: ideal MHD, resistive MHD, incompressible MHD, Hall MHD, multi-fluid MHD, Hartmann MHD, collisionless MHD, electron MHD, relativistic MHD, etc.

In ideal MHD, the fluid is treated as a perfect conductor (e.g., the electric resistivity is infinitely small). In such conditions, the Alfvén’s theorem states the fluid and the magnetic field are tied together, and have to move altogether: the so-called “frozen-in” condition. The magnetic flux through a co-moving surface is conserved in ideal MHD. Magnetic linkage is thus preserved which makes it possible to store magnetic energy by moving the fluid or the magnetic field. The stored energy can become available if the ideal condition breaks down, e.g., during magnetic reconnection: the magnetic field can then be rearranged and magnetic energy is converted to kinetic energy, thermal energy, and particle acceleration. While magnetic reconnection is by essence an MHD concept, its complete description lies beyond the MHD approximation

MHD waves are another major concept that derives from MHD. There are three main MHD wave modes: pure Alfvén wave, slow (shear) and fast (compressional) MHD waves. Alfvén waves are incompressible waves and do not appear in pure hydrodynamics. All the MHD waves have constant phase velocities for all frequencies and are thus dispersionless. Their role is heavily discussed in link with the heating of stellar corona and the acceleration mechanisms of stellar winds.

Cross-References

- [Activity, Magnetic](#)
- [Magnetic Field](#)
- [Magnetic Field, Planetary](#)
- [Magnetic Fields and Planetary Systems Formation](#)
- [Magnetic Fields and Star Formation](#)

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Magnetosome

Alfonso F. Davila
SETI Institute – NASA Ames Research Center
MS 245-3, Moffett Field, CA, USA

Keywords

Bacteria · Biomineralization · Magnetism · Magnetofossil · Magnetotaxis · Magnetite · Greigite · Biomarker

Definition

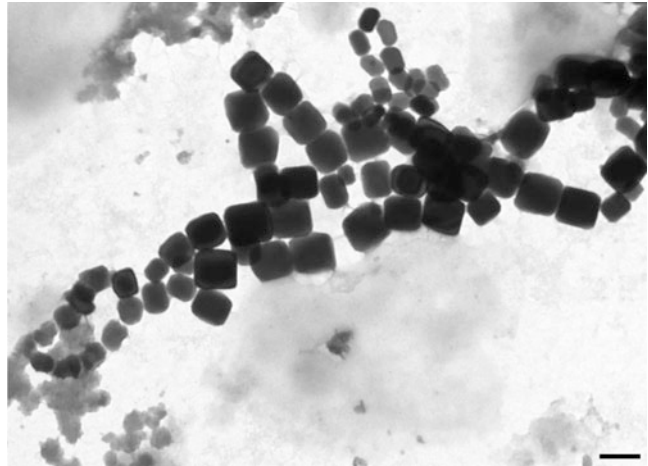
Intracellular magnetic crystal typically surrounded by a lipid membrane synthesized by magnetotactic organisms. Magnetosomes are chemically pure, have a narrow size range with species-specific crystal morphologies, and are arranged in chains (Bazylinski 1995; Spring and Bazylinski 2000). Magnetosomes are usually composed of the iron oxide ► [magnetite](#) (Fe_3O_4) or the iron sulfide greigite (Fe_3S_4). Membrane-bound magnetosomes form from invaginations of the inner membrane, and their position in the ► [cytoplasm](#) is supported by cytoskeletal filaments (Komeili et al. 2006), which suggests that magnetosome synthesis is a biomineralization process with strict biological control. Chains of magnetosomes are responsible for the passive orientation of ► [magnetotactic bacteria](#) along ► [magnetic field](#) lines (Blakemore 1975) (Fig. 1).

Overview

Bacterial magnetosomes have been a subject of intense research due to their relevance in such diverse fields as biomineralization, paleomicrobiology, technology, medicine, or astrobiology. Due to their small size and strong magnetic remanence, magnetosomes have also been used in nano- and biotechnological applications. Iron biomineralization is likely an ancient trait of terrestrial life, and iron minerals are common among organisms in the ► [Bacteria](#) and ► [Eukarya](#) domains. In particular, magnetosomes are often found in the fossil record (magnetofossils) in marine and lake sediments. The traits that characterize magnetosomes: chemical purity, size, morphology, and chain arrangement, all contribute to maximize the magnetic moment of the crystals, and the capacity of magnetotactic organisms to swim along magnetic field lines, and search efficiently for chemical gradients. These properties also confer magnetosomes a strong potential as ► [biomarkers](#), since non-biogenic magnetite and greigite crystals often fail to possess one or several of these traits. Biogenic minerals are also more resistant to chemical and physical weathering than

Magnetosome,

Fig. 1 Chains of magnetosomes extracted from lake sediments. The size, shape, morphology, and composition of the crystals reflect the biogenic origin. Crystals of different sizes are likely related to different species of magnetotactic bacteria. Scale bar represents 100 μm



organic biomarkers. For those reasons, magnetosomes have been proposed as a potential target in the search for life beyond Earth. Putative magnetite magnetosomes have been identified in the Martian meteorite ALH84001 and presented as evidence for relic biological activity on [Mars](#) (McKay et al. 1996), although these claims have been disputed.

Cross-References

- [ALH 84001](#)
- [Biomarkers](#)
- [Biominalization](#)
- [Cytoplasm](#)
- [Magnetic Field](#)
- [Magnetite](#)
- [Magnetotactic Bacteria](#)

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Magnetosphere

Philippe Zarka

LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France

Keywords

Aurora · Currents · Atmosphere · Magnetic fields · Magnetospheric dynamics · Plasma · Sun

Definition

The solar wind (SW) which flows across the solar system interacts with obstacles possessing a ► [magnetic field](#), an atmosphere, or a high internal conductivity. In the first case, generally concerning planetary obstacles, the magnetic pressure creates a cavity in the SW, where ► [plasma](#) motions are dominated by the planetary field; this region is called the “magnetosphere.” This magnetic bubble acts as a shield preventing the bombardment and escape of the planetary atmosphere. It also generates an intense electrical

activity, behaving as a natural charged particle accelerator. Planetary magnetospheres are contained in the Sun's sphere of influence (heliosphere), and in turn contain the magnetospheres of some of their satellites.

History

Auroras have been known since ancient times. In the nineteenth century, statistical measurements allowed localization of the northern auroral oval at 65–80° latitude, but its origin was not understood. Shortly after, Thomson discovered the electrons. This gave Birkeland the idea to use them to bombard a magnetized sphere in a rarefied atmosphere (vacuum chamber). He could then create and observe polar auroral lights as early as 1895–1910. He proposed that “polar magnetic storms” exist in the auroral zone, due to electron beams from the Sun. In the 1930s, Chapman and Ferraro proposed that “magnetic storms” are caused by solar plasma clouds interacting with the Earth's magnetic field. They proposed the existence of the dayside magnetopause (the outer boundary of the magnetosphere) at a few Earth radii based on the use of a reversed “image” of the terrestrial magnetic dipole to represent the compressed dayside terrestrial field. Thomas Gold proposed the name “magnetosphere” for the cavity, above the ionosphere, where the planetary magnetic field has dominant control over the motions of gas and fast charged particles.

The concept of solar plasma clouds remained vague until the suggestion by Biermann in 1951 of the existence of a permanent solar “wind” (flow of electrons, protons, and heavier ions escaping permanently from the solar atmosphere), in order to explain the second cometary tail, blueish, straight, and always antisolar (now known to be a plasma tail). In 1958, Parker proposed the first theory of the SW, which not only escapes the solar atmosphere but is accelerated up to supersonic speed into the interplanetary space. The first observational confirmation came with spacecraft observations in 1960.

Two years earlier, the Explorer 1 spacecraft discovered the Earth's radiation belts (of highly

energetic charged particles). In 1961, Dungey proposed the model of an open magnetosphere, still valid to describe the terrestrial magnetospheric dynamics, and involving elusive magnetic reconnection at the magnetopause. The magnetopause was actually observed as an abrupt magnetic field discontinuity in 1967. The auroral oval was first imaged from space in the 1980s.

In parallel, the discovery in 1955 of Jupiter's decimeter radio emission gave the first indications on the existence and intensity of the Jovian magnetic field, further refined by the discovery in 1958 of the synchrotron emission from Jupiter's radiation belts. In 1964, the statistical influence of Io on Jupiter's decimeter radio emission unveiled the first satellite-magnetosphere interaction.

Overview

Solar Wind Flow and Planetary Magnetic Fields

A central concept to the following discussion is that magnetic field (B) and plasma are “frozen” together, due to high plasma conductivity. Thus, in a frame where the magnetized plasma moves at velocity V , Maxwell's equations show that an electric field $E = -V \times B$ appears. It is equal to zero in the plasma frame, consistent with quasi-neutrality. Also, the fact the E and B are orthogonal implies that magnetic field lines are electric equipotentials. Potential drops between field lines are thus conserved along these field lines.

Being dominated by its bulk kinetic energy density, the SW carries away the solar magnetic field rooted in the Sun, generating the undulated surface (“ballerina skirt”) which separates the two magnetic hemispheres of the interplanetary medium. At Earth orbit, the SW has a speed $V \sim 400$ km/s (largely supersonic), a density of protons and electrons $N \sim 5$ cm⁻³, a temperature $T \sim 200,000$ K, and a weak magnetic field $B \sim 3$ nT.

Its interaction with a planetary obstacle depends on the existence of an intrinsic large-scale magnetic field, an ionosphere, and/or a high internal conductivity of the obstacle. In the first case, an abrupt boundary limits the region of

influence of the planetary magnetic field: the magnetopause.

There are six magnetized planets in the Solar System: Mercury, Earth, and the four giants. Their magnetic fields have a strong dipolar component as well as multipolar ones (of order $n = 2, 3, \dots$). These components are known up to $n \sim 14$ at Earth versus $n \leq 4$ for the other planets. Especially remarkable are the very weak dipolar field of Mercury (compared to the very large field of Jupiter), the largely tilted dipoles of Uranus and Neptune, and the purely axisymmetric Saturnian field (Table 1).

Magnetospheric Regions and Boundaries

The magnetosphere is the cavity bounded by the magnetopause, where the external SW pressure balances the internal planetary magnetic field pressure (Fig. 1). Electric currents circulate on the magnetopause, preventing magnetic field lines from crossing it (the field is tangential on the magnetopause). As a first approximation, there is no plasma exchange across the magnetopause. The dayside magnetopause radius lies

between a fraction to several tens of planetary radii from the planetary obstacle (Table 1). This “standoff” distance fluctuates with variations of the SW strength. Planetary magnetospheres are the largest structures in the solar system. If Jupiter’s with its 10^7 km radius was visible, it would appear larger than the full moon.

Because the SW flow is supersonic, a stationary bow shock develops ahead of the magnetopause. The intermediate region is the magnetosheath, whose thickness is 15–40% of the standoff distance, and where the flow is slowed down, heated and deflected around the obstacle, and the SW magnetic field lines “pile up” and are draped around it. Due to the flow and draping, the nightside magnetosphere is stretched and forms a magnetospheric tail up to several AU long. A singular region, the polar cusp, separates closed planetary field lines anchored to both hemispheres on the dayside from open lines swept back to the tail. A small fraction of the SW plasma penetrating the outer magnetosphere across the magnetopause may directly reach the polar ionosphere via the cusp. The cusp does not exist for

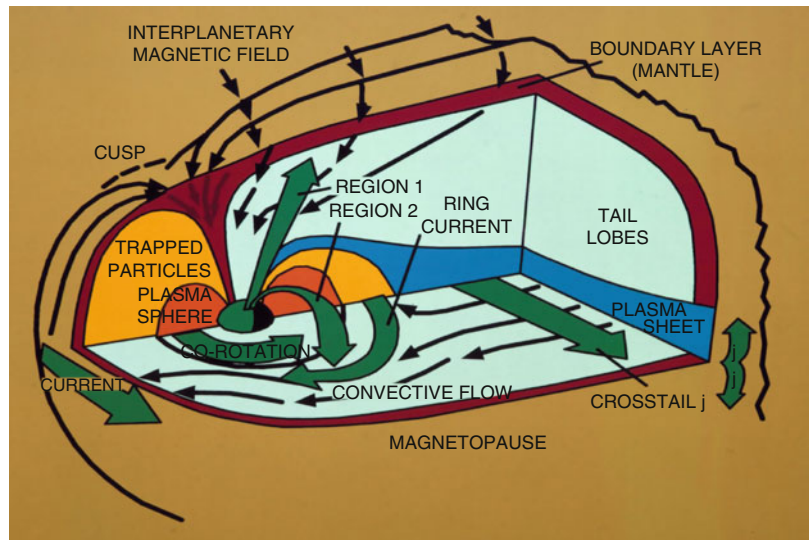
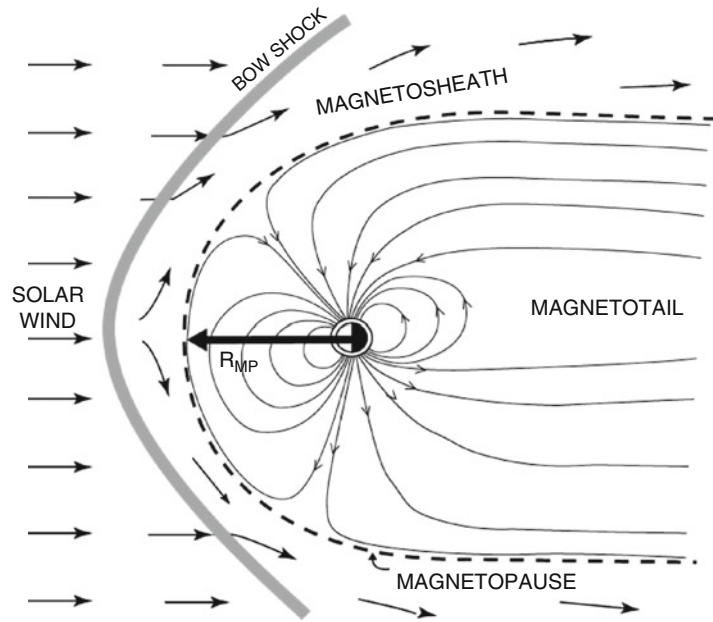
Magnetosphere, Table 1 Typical parameters of planetary magnetospheres. Comparison of the convection and corotation potential drops, as well as the ratio between

plasmasphere radius and magnetopause standoff distance tells which type of plasma circulation dominates magnetospheric dynamics

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
Planetary radius R_P (km)	2439	6378	71,492	60,268	25,559	24,764
Orbital radius (AU)	0.39	1	5.2	9.5	19.2	30.1
Rotation period, P_{rotation} (h, min)	1407 h 30 min	24 h	9 h 55.5 min	10 h 39.4 min	17 h 14.4 min	16 h 6.6 min
Dipolar magnetic moment M_{dip} ($G \cdot \text{km}^3$)	5.5×10^7	7.9×10^{10}	1.6×10^{15}	4.7×10^{13}	3.8×10^{12}	2.2×10^{12}
Equatorial magnetic field B_e (G)	0.003	0.31	4.3	0.21	0.23	0.14
Dipole tilt (B, Ω) ($^\circ$)	+14	+11.7	−9.6	−0.	−58.6	−46.9
Solar wind magnetic field B_{SW} (nT)	10 (20)	4	0.8	0.4	0.2	0.13
Magnetopause radius R_{MP} (R_P) [calculated]	1.4	9	40	17	22	21
Magnetopause radius R_{MP} (R_P) [measured]	[~1.5]	[~10]	[~90]	[~20]	[~18]	[~23]
Convection potential drop $\Delta\phi_{\text{conv}}$ (kV)	7	46	900	90	17	14
Corotation potential drop $\Delta\phi_{\text{corot}}$ (kV)	0.002	90	400,000	12,000	1500	1000
Plasmasphere/magnetopause Radius R_P/R_{MP}	0.01–0.02	0.3–0.8	~4	2–4	0.9–4	1–3

Magnetosphere,

Fig. 1 2D and 3D views of the terrestrial magnetosphere



obstacles not possessing an intrinsic magnetic field, although an induced magnetosphere and a tail form due to magnetic draping.

Plasma Sources and Sinks

Although more rarefied than the surrounding SW, a magnetosphere contains plasma that may have various origins: the SW itself (via the cusp and diffusion/reconnection across the magnetopause), planetary ionospheres (through vertical diffusive

equilibrium), satellite exospheres (atmospheric escape from Titan, Io's volcanism, Enceladus' geyser plumes), surfaces of Mercury or icy satellites (through sputtering by SW of magnetospheric energetic particles), rings (sputtering, photo-dissociation, and ionization). These sources represent between a few hundred g/s to 1000 kg/s of H, He, and heavy (N, O, S, H₂O, ...) ions of temperatures between ~ 0.1 eV (ionospheric source) and ~ 100 eV (SW source).

The magnetospheric plasma is stored in various reservoirs including “boundary layers” (low-latitude on the dayside and tail mantle), plasma tori along satellite orbits, an equatorial plasma/current sheet at the center of the tail, and radiation belts. The total mass stored ranges from $\sim 10^7$ kg at Earth to $\sim 10^{10}$ kg at Jupiter.

Plasma sinks include absorption by the rings, satellites and auroral ionosphere, and interaction with neutrals atoms. At Saturn, the neutral nebula is 100 times denser than the magnetospheric plasma (dominated by H_2O ions), while the neutrals/ions ratio at Jupiter is only ~ 0.003 .

Plasma Circulation and Role of Ionosphere

If the magnetosphere was electro-magnetically insulated from external conditions, its plasma would simply be dragged by friction of the SW flow along the magnetopause flanks (over a thickness of few ion Larmor radii), generating two convection cells with antisolar plasma motion on the edges and solarward plasma return inside the magnetosphere. Such a circulation pattern is indeed observed at Earth, together with other phenomena inconsistent with the above “closed” magnetosphere model:

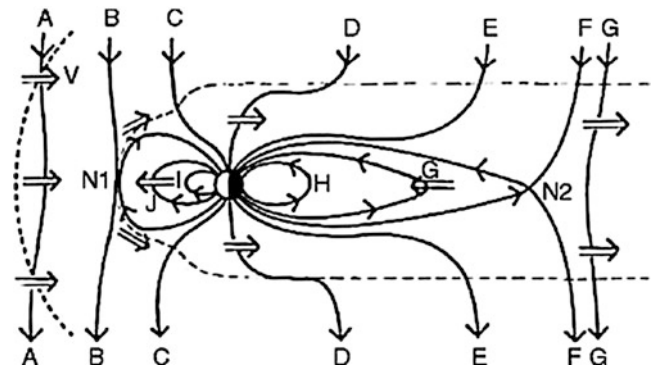
- Presence of energetic plasma inside the magnetosphere.
- Existence of a large-scale (dawn $\rightarrow$ dusk) electric field.
- Quasi-permanent circumpolar aurora at $65\text{--}80^\circ$ latitude, brighter on the nightside.
- Magnetospheric “activity” correlated with the direction of the interplanetary magnetic field (IMF) perpendicular to the ecliptic (B_z).

Hence the concept of an “open” magnetosphere, in which reconnection of the IMF with the planetary field at the magnetopause allows plasma entry. Dayside reconnection occurs at the magnetopause nose when B_z is oriented in opposition to the planetary magnetic field, so that their sum cancels out. This causes magnetospheric field lines to “open,” and then be transported to the tail above the poles, where they close after a new reconnection. Closed field lines then “redipolarize” (retract) toward Earth while a “plasmoid” is ejected tailward. In this cycle, proposed by Dungey (Fig. 2), the circulation pattern is similar as above, but it is associated with the observed dawn $\rightarrow$ dusk “convection” electric field ($E_{\text{conv}} \propto V_{\text{VS}} \times B_{\text{VS}}$) whose equipotentials are the solar-antisolar circulation lines. The second reconnection corresponds to a magnetic “substorm” during which energy is dissipated through charged particles heating and acceleration. Planetary rotation generates another large-scale, radial electric field ($E_{\text{corot}} \propto R\Omega \times B$), whose equipotentials are circles centered on the planet. Corresponding plasma circulation is “corotation.” Global magnetospheric circulation results from the superposition of convection and corotation, with a different relative importance at the various planets (Table 1).

The internal, corotation-dominated region is the dense plasmasphere fed by the ionosphere, where planetary field lines never open. Its radius is compared to that of the magnetopause in Table 1. At Jupiter and Saturn, the dominant centrifugal force drives outward plasma transport and forms a plasma disk where million-Ampere current flows and stretches the equatorial magnetic

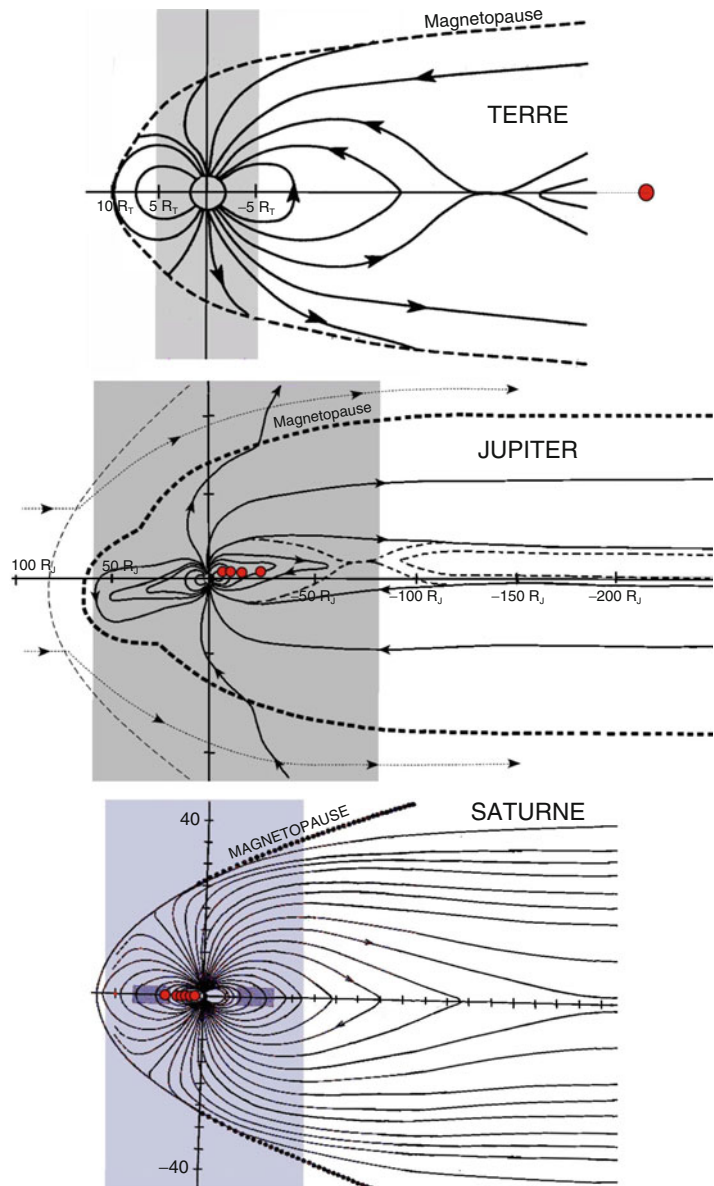
Magnetosphere,

Fig. 2 Meridian sketch of the Dungey cycle of magnetospheric convection driven by the solar wind. Magnetic reconnection occurs in N1 and N2. The motion of a field line is followed from A to G along arrows ($\Rightarrow$)



Magnetosphere,

Fig. 3 Corotation-dominated plasmasphere (gray-shaded) and moons positions (red dots) in the magnetospheres of the Earth, Jupiter, and Saturn. Plasma corotation generates the equatorial current disk that stretches magnetic field lines. The tail X-line (where magnetic reconnection occurs) is located in the convection-dominated region at Earth, and in the corotation region at Jupiter, explaining why substorm-like events are related to the SW-magnetosphere interaction at Earth and to internal plasma mass-loading effects at Jupiter



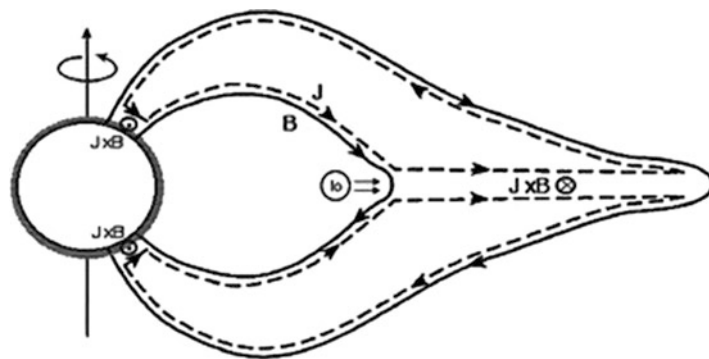
field (Fig. 3). Corotation dominates so much at Jupiter that it modulates many magnetospheric phenomena (including radio emissions from which the planetary rotation period has been measured with 10^{-6} accuracy); a modified Dungey cycle exists, entirely driven by corotation (so-called “Vasyliunas cycle”). The magnetospheres of Earth and Mercury are convection-dominated, while Saturn is an intermediate case (Fig. 3). Interestingly, plasma circulation and the

degree of corotational control are – at first order – independent of the planetary magnetic dipole tilt (except at Uranus and Neptune where this tilt is extremely large).

Ionosphere-magnetosphere coupling ensures the closure of magnetospheric currents in a conducting spherical layer around the planet. Because magnetic field lines are electric equipotentials, the potential drops originating in the magnetosphere (with respect to the SW) are

Magnetosphere,

Fig. 4 Current generator associated with outward transport of the plasma produced by Io



mapped to the ionosphere along field lines. The magnetospheric circulation thus causes the existence of high-latitude ionospheric convection cells. Due to converging field line geometry, ionospheric electric fields are larger than their magnetospheric counterparts, while plasma velocities are smaller. At Mercury, the nature of the process(es) ensuring magnetospheric current closure is still a puzzle.

Current Generators

Large-scale closed current circuits exist in planetary magnetospheres, each related to a specific generator:

- SW-driven convection drives high-latitude currents at the boundary between open and closed field lines that close into the polar ionosphere.
- In the Jovian system, outward transport of the plasma from Io generates a radial current (J), which closes into the ionosphere via magnetic-field-aligned (or “Birkeland”) currents. The Lorentz force ($J \times B$) associated with this radial current accelerates the magnetospheric equatorial plasma to corotation speed, while slowing down the ionospheric plasma.
- Ganymede’s intrinsic magnetic field is in permanent Dungey-like reconnection between with the Jovian field sweeping past the satellite.
- Unmagnetized satellites swept past a fast-rotating magnetosphere “see” part of the corotation electric field in their rest frame. When they have an ionosphere, like Io or Titan, a current is driven by this electric field that

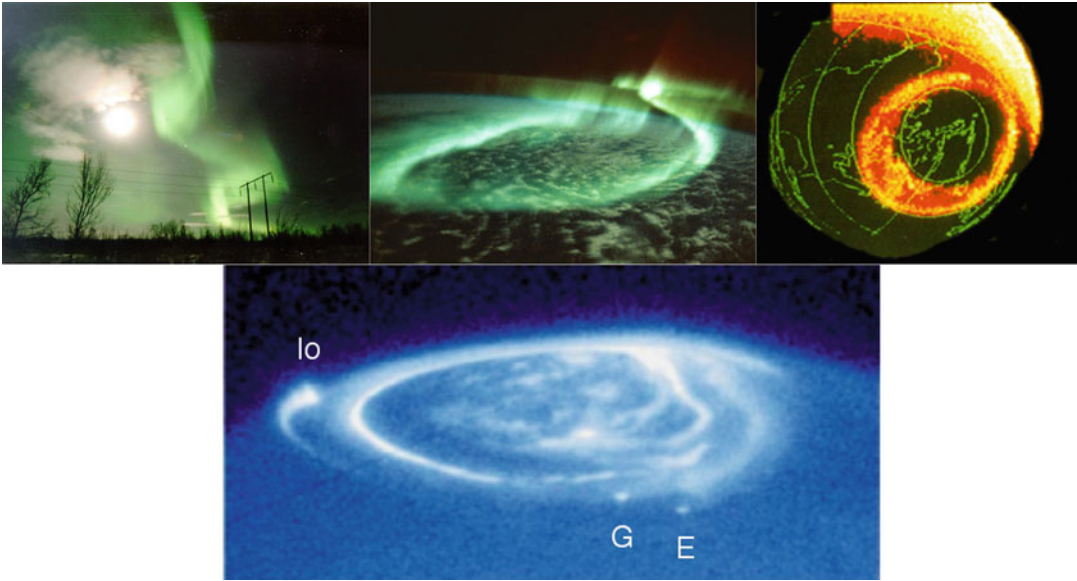
again closes into the planetary ionosphere via field-aligned currents (Fig. 4).

All these currents dissipate energy in the magnetosphere and the ionosphere. Furthermore, when a strong current is forced through a rarefied plasma, it leads to electron acceleration. A fraction of the magnetospheric plasma is thus accelerated to keV/MeV energies through various processes.

Aurora

Polar auroras are the most spectacular sign of magnetospheric activity (Fig. 5). They are produced by the radiative de-excitation of atmospheric atoms and molecules, emitting green and red oxygen lines on Earth, and ultraviolet H and H₂ bands on Jupiter and Saturn. These atmospheric constituents are collisionally excited by energetic electrons ($\sim 1\text{--}10$ keV) accelerated in the magnetosphere by the above processes. Joule heating also produces infrared auroral emissions, while intense radio emissions are produced along magnetic field lines above the auroras.

In a convection-dominated magnetosphere (as Earth’s), auroral ovals are located at the boundary of open and closed field lines. They are the magnetic projection onto the atmosphere of reconnection sites, especially the tail one, where accumulated energy and magnetic flux are suddenly released during substorms (typically several times a day). Note that auroras are by no means related to direct SW entry in the cusps. In a corotation-dominated magnetosphere (as Jupiter’s), auroras map the region where corotation breaks down due



Magnetosphere, Fig. 5 Earth auroras (*top*) seen from the ground (*left*), the space shuttle (*center*), and from a spacecraft (*right*). The auroral oval corresponds to the boundary between open and closed field lines. Jovian

auroras (*bottom*): the oval corresponds to the corotation breakdown, the isolated spots to the magnetic footprints of Io, Ganymede, and Europa

to insufficient momentum transfer from the ionosphere to the magnetosphere, in spite of maximum intensity field-aligned currents.

Auroral-like emissions are also produced at the planetary magnetic footprints of satellites, either magnetized or possessing an ionosphere (Fig. 5). Auroras (visible, UV, IR, radio) are the image of magnetospheric activity projected along magnetic field lines onto the atmosphere as on a TV screen.

Concluding Remarks and Future Directions

Planetary magnetospheres are complex electrodynamic machines, both charged particle accelerators and shields protecting the atmospheres against cosmic rays, solar eruptions, and evaporation. They are also plasma physics laboratories, displaying universal processes operating in very diverse environments (depending on object size, distance to Sun, magnetic field intensity, rotation, plasma sources, etc.). Each solar system magnetosphere has specific characteristics, which makes comparative study essential. Expanding these studies to exoplanet-star plasma interactions is very appealing. Hot Jupiters (close-in orbiting giant exoplanets), enduring high stellar wind pressure, might have compressed magnetospheres.

Alternately, they might be interacting with their parent star, via reconnection if they are magnetized (like Ganymede with Jupiter, or interacting magnetic binaries) or via currents and Alfvén waves (like Io with Jupiter) if they are unmagnetized. They are expected to produce intense electromagnetic emissions, especially in the radio range, which are being actively searched for.

Notations and Acronyms

AU	Astronomical Unit
IMF	Interplanetary Magnetic Field
nT	nanoTesla
SW	Solar Wind

Cross-References

- [Atmosphere, Structure](#)
- [Exoplanets, Discovery](#)
- [Giant Planets](#)
- [Hot Jupiters](#)
- [Magnetic Field](#)
- [Planet](#)
- [Plasma](#)
- [Satellite or Moon](#)
- [Sun \(and Young Sun\)](#)

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magnetic crystals called ► [magnetosomes](#), which can be composed of the iron oxide magnetite or the iron sulfide greigite. Magnetite-producing magnetotactic bacteria are typically microaerophilic, whereas greigite-producing magnetotactic bacteria are usually strict anaerobes. Their magnetotactic response allows this type of bacteria to navigate efficiently along chemical gradients. Magnetotaxis is not a taxonomic trait, and has been described in many phylogenetic groups comprising diverse morphologies, including coccoid, rod-shaped, spirilloid, and even multicellular (Fig. 1).

History

Magnetotactic bacteria were first observed by Salvatore Bellini, from the University of Pavia, in 1963 in samples from drainage water. Richard P. Blakemore described them in marsh sediments and first coined the term “magnetotactic” (Blakemore 1975). Since then, magnetotactic bacteria have been observed in almost every aquatic environment, including polar lakes, and several strains have been grown in pure cultures in the laboratory. This has allowed for comprehensive

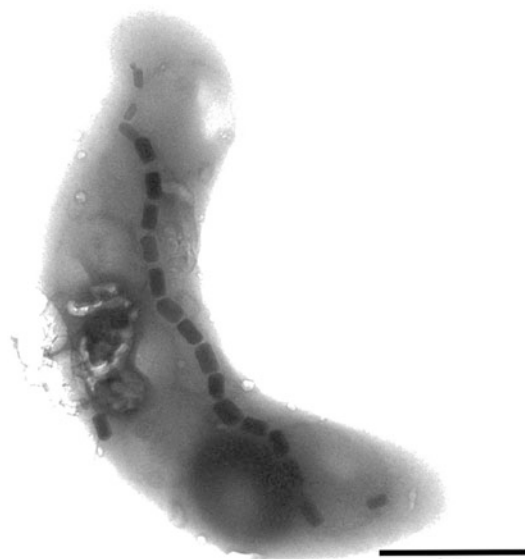
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Magnetotactic Bacteria

Alfonso F. Davila
SETI Institute – NASA Ames Research Center
MS 245-3, Moffett Field, CA, USA

Definition

Magnetotactic bacteria are motile, prokaryotic organisms characterized by their tendency to align with, and move along ► [magnetic field](#) lines. All magnetotactic bacteria synthesize intracellular



Magnetotactic Bacteria, Fig. 1 Magnetotactic bacteria with an intracellular chain of magnetosomes, extracted from lake sediments. Scale bar represents 0.5 μm

genetic studies and the identification of the genes involved in the synthesis of magnetosomes. In 1996, researchers from NASA Johnson Space Center suggested that magnetic crystals in the ► [ALH 84001](#) Martian meteorite resemble those synthesized by magnetotactic bacteria and would therefore constitute relic evidence of biological activity on the planet (McKay et al. [1996](#)). While these claims have been disputed, the origin of the magnetic crystals in the meteorite remains a matter of debate.

Cross-References

- [ALH 84001](#)
- [Magnetic Field](#)
- [Magnetosome](#)
- [Microorganism](#)
- [Prokaryote](#)

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Magnitude

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Brightness · Flux · Photometric system · Star

Definition

In astronomy, the magnitude is a measure of the brightness of a celestial object expressed on a logarithmic scale.

Overview

The magnitude scale, which comes from the visual astronomy, is only defined in the optical to mid-infrared wavelength range (300 nm to 20 μm); in other parts of the electromagnetic spectrum (X, radio, etc.) physical units are used, such as W m^{-2} , Jy, etc. The measure is generally defined for a specific filter, that is, for a given wavelength and a given bandpass. A set of filters corresponds to a photometric system, one of the most widely used being the Johnson system. With no other indication, the term magnitude refers to the magnitude in the V (“visible”) band of the Johnson system ($\lambda = 550 \text{ nm}$; bandpass = 89 nm). The magnitude scale is a relative scale, the reference of brightness being the star Vega. It is thus a quantity with no units. The magnitude of a given object whose measured flux in a given filter X is F_X is given by the expression: $m_X = -2.5 \log 10(F_X/F_X[\text{Vega}])$.

The coefficient -2.5 as a factor in the logarithm of the brightness was chosen by Norman R. Pogson in the nineteenth century, so as to link this scale to the one used by ancient Greek astronomers when estimating qualitatively the star’s brightness.

Note that the lowest magnitudes refer to the brightest objects: for instance, Sirius, the brightest star, has a magnitude $V = -1.46$, while the faintest stars seen by a trained unaided eye is of magnitude 6 and the dimmest objects that very large telescopes are able to catch are typically of magnitude 27.

The magnitude scale has several avatars: the absolute magnitude, the ► [bolometric magnitude](#), and the ► [color index](#). It is also used to measure the dimming by an absorbing medium, for instance, that introduced by the atmosphere or by the interstellar extinction. In this last case, the difference in magnitude is noted as A_V .

Cross-References

- [Bolometric Magnitude](#)
- [Color Excess](#)
- [Color Index](#)
- [Extinction, Interstellar or Atmospheric](#)

- [Flux, Radiative](#)
- [Johnson UBV Bandpasses](#)
- [Magnitude, Absolute](#)

Magnitude, Absolute

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The absolute magnitude of a star or any celestial object is the apparent magnitude that the object would have if it were at a distance of 10 pc or 32.6 light-years from Earth. Within the solar system, the definition differs; it is the magnitude an object would have when put at a distance of one Astronomical Unit from Earth.

Cross-References

- [Magnitude](#)

Main Asteroid Belt

- [Asteroid Belt, Main](#)

Main Sequence, Star

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The region of the ► [Hertzsprung-Russell diagram](#) occupied by stars during their central H-burning phase is called the main sequence. It is a quasi-diagonal band, running from low to high values of stellar luminosities and effective temperatures.

The position of a star in that band is mostly determined by its mass (through the ► [mass-luminosity relation](#)), and to a much smaller degree by its metallicity (where astronomers refer to all elements heavier than helium as “metals”; less metallic stars being hotter) and age (older stars being more luminous). Since H-burning (fusion of hydrogen to helium) is the longest period in a star's life, about 90 % of all stars are on the main sequence. In star clusters, the upper end of the main sequence is truncated since the more massive stars have evolved toward the red giant branch (or already died); the position of this truncation provides a means to infer the cluster's age.

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Mass-Luminosity Relation](#)
- [Stellar Evolution](#)
- [Zero Age Main Sequence](#)

Mainbelt Comet

- [Active Asteroid](#)

Mangalayaan

- [Mars Orbiter Mission](#)

Manganese Oxidation

Colleen M. Hansel
Woods Hole Oceanographic Institution, Woods
Hole, MA, USA

Keywords

Metal · Bacteria · Fungi · Metabolism ·
Oxygen reduction · Desert varnish ·
Ferromanganese crusts · Ferromanganese
nodules · Sediments · Minerals · Redox

Chemical Formula

Mn, MnO₂

Definition

Manganese (Mn) is a transition metal present at trace levels in the modern ocean where it cycles between three oxidation states, +2, +3, and +4. Mn is a cofactor in enzymes critical for life, including the oxygen-evolving complex of photosystem II involved in oxygenic photosynthesis and superoxide dismutase (SOD) that degrades oxygen radicals responsible for oxidative stress. Mn(IV) forms a suite of Mn oxide minerals found within marine ferromanganese crusts and nodules that scavenge trace metals and record paleoredox conditions throughout Earth's history. Mn oxides form within a wide range of environments, including deserts, and on Mars as rock varnish and crusts.

Overview

Manganese (Mn) oxides are widespread on Earth, occurring as particles or grain coatings, rock varnish, cave deposits, and ferromanganese crusts and nodules. Rocks and sediments enriched in Mn oxides have been observed on Mars (Lanza et al. 2014) and in early Earth strata (Crerar et al. 1980; Krinsley et al. 2009); yet, little is known about the modern or paleo-environmental behavior of Mn. Mn oxides are receiving increasing attention as useful paleoredox indicators since oxidation of Mn(II) to Mn(III,IV) oxides requires oxidants with high redox potential. Unlike iron, oxidation of Mn(II) by molecular oxygen (O₂) is thermodynamically prohibited in the absence of (in)organic catalysts (Luther III 2010). Further, the budgets and isotopic fractionation of many trace metals (e.g. vanadium, copper, nickel, molybdenum, and thallium) are partially controlled by their strong adsorption to Mn oxides, rendering Mn oxides a primary driver of the isotope composition of important trace element paleoproxies (Siebert et al. 2003).

The presently known pathways for Mn(II) oxidation to Mn(III,IV) oxides require the presence of O₂ or derivatives of oxygen, specifically reactive oxygen species (ROS). Most cases/examples of Mn(II) oxidation on Earth are also believed to be a consequence of direct or indirect microbial activity. Three general pathways exist for the oxidation of soluble Mn(II) to insoluble Mn(IV) and ultimate precipitation as Mn oxide minerals. First, Mn(II) can be oxidized by O₂ when complexed to mineral surfaces or organic ligands (Duckworth and Sposito 2005). Second, some bacteria directly mediate Mn(II) oxidation using enzymes such as multi-copper oxidases (Butterfield et al. 2013) even in the presence of micromolar levels of O₂ (Clement et al. 2009). Third, Mn(II) oxidation to Mn oxides occurs via reaction with the ROS superoxide of both abiogenic (Learman et al. 2013) and biogenic (fungal, bacterial) origin (Hansel et al. 2012; Learman et al. 2011; Tang et al. 2013). Unlike O₂, oxidation of Mn(II) to Mn(III) by superoxide is rapid even in the presence of low superoxide and Mn levels (pM-nM) (Hansard et al. 2011) and is thermodynamically favored over a broad pH range (Luther III 2010).

At present, evidence is lacking for Mn(II)-based chemolithotrophy and instead Mn(II)-oxidizing bacterial isolates are obligate aerobic heterotrophs that do not gain energy or acquire a known physiological benefit from oxidizing Mn(II). Regardless of the abiotic or biotic pathway the oxidation of Mn(II) to Mn(IV) oxides occurs via a one electron transfer process leading to the formation of a Mn(III) intermediate (Johnson and Tebo 2008; Learman et al. 2011; Webb et al. 2005). The absence of observed Mn-based metabolisms may therefore stem from the energetic constraint imposed by the first electron transfer step from Mn(II) to Mn(III). Mn(III) has historically been regarded as environmentally unimportant due to its instability in solution in the absence of organic complexing ligands. More recently, significant levels of soluble Mn(III) ligand complexes (Mn(III)-L) were measured in marine systems spanning oxic to anoxic (Madison et al. 2013; Oldham et al. 2017). The fate of Mn(III)-L and subsequent reaction pathway from Mn(III) to Mn(IV) is less clear and may involve

further (a)biotic oxidation to Mn(IV) or disproportionation to Mn(II) and Mn(IV). Alternatively but currently unproven, this Mn(III)-L could provide an energetically favorable electron donor for Mn based chemolithotrophy or phototrophy. The ultimate precipitation and stabilization of Mn oxides within environmental systems is nevertheless at odds with Mn(IV)-reducing processes, including photoreduction, reaction with the ROS hydrogen peroxide, and anaerobic respiration by bacteria (Learman et al. 2013; Sunda and Huntsman 1994). Mn oxide formation and preservation may in fact require stabilizing organic templates (Estes et al. 2016). Together, Mn oxides are recorders of the surrounding geochemistry during their formation, and thereby provide a window into the geochemistry of past environments on Earth and elsewhere.

Cross-References

- ▶ Bacteria
- ▶ Biomineralization
- ▶ Chemocline
- ▶ Chromium Isotopes
- ▶ Diagenesis
- ▶ Iron Isotopes
- ▶ Iron Oxidation
- ▶ Iron Reduction
- ▶ Manganese Reduction
- ▶ Microbial Mats
- ▶ Oxic Sediments
- ▶ Oxygenation of the Earth's Atmosphere
- ▶ Redox Zonation
- ▶ Suboxic
- ▶ Suboxic Sediments
- ▶ Trace Metals

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Manganese Reduction

Colleen M. Hansel
Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Keywords

Metal · Bacteria · Metabolism · Carbon oxidation · Mn oxides · Desert varnish · Ferromanganese crusts · Ferromanganese nodules · Sediments · Minerals · Redox · Redox stratification

Chemical Formula

Mn, MnO₂

Definition

Manganese (Mn) is the third most abundant transition metal in the Earth's crust, where it is about 56 times less abundant than iron. Nonetheless, the abundance of Mn is ~60% greater in oceanic compared to continental crust. Thus, Mn is distributed widely throughout the global ocean, where it cycles among three dominant oxidation states – Mn²⁺, Mn³⁺, and Mn⁴⁺ – via reduction, oxidation, and disproportionation reactions. The reduction of Mn(III)-ligand complexes and Mn (III, IV) oxides is mediated by a number of abiotic and biotic processes involving either the direct or indirect activity of microorganisms. The reduction of Mn impacts the distribution of numerous other trace metals within the modern ocean and rock record.

Overview

Manganese (Mn) is distributed broadly throughout the modern global ocean and rock record on the Earth. Weathering of Mn-bearing primary minerals and hydrothermal vent fluids are dominant sources of Mn(II) to the ocean. Despite the fully oxidized Mn(IV) species being thermodynamically favored in oxic seawater, aqueous Mn(II) and Mn(III) are the dominant species in the ocean (Bruland et al. 1994; Oldham et al. 2017). This distribution is due in large part to the rapid photoreduction of Mn oxides in the photic zone (Sunda and Huntsman 1994) and the thermodynamic and kinetic constraints on the first oxidation step (Mn²⁺ to Mn³⁺) via O₂ (Luther III 2010). Deeper in the water column and within marine sediments, oxidation of Mn (II) and Mn(III) via direct and indirect microbial activity leads to the formation of Mn(III,IV). Here, as Mn(IV) is not stable in solution, Mn precipitates as single or mixed valence Mn oxy(hydr)oxides. Manganese oxides are often found as particles below the photic zone (Johnson et al. 1996) and in surface sediments within deep fjords or ocean basins, where geochemical focusing leads to their accumulation (Thamdrup et al. 1994). At the sediment interface

at abyssal depths, a significant portion of Mn is concentrated in ferromanganese concretions (nodules) and crusts (Horn et al. 1972).

A wide diversity of facultative or obligate anaerobic microorganisms couple the oxidation of organic carbon to the reduction of soluble Mn(III) complexes (Kostka et al. 1995) and solid-phase Mn(III,IV) oxides (Myers and Nealson 1988). In fact, microbial Mn reduction can be a dominant control on carbon oxidation within marine sediments (Thamdrup et al. 2000). For instance, microbial Mn reduction has been attributed to 25–99% of carbon oxidation within Mn-rich coastal marine sediments (Canfield et al. 1993a,b; Thamdrup et al. 2000). Despite observations of unique Mn(IV)-reducing communities within marine sediment incubations (Vandieken et al. 2012), at present there are no obligate Mn(IV)-reducing microbial isolates in culture. Instead, organisms capable of Mn reduction typically have the capacity to utilize a broad range of electron acceptors, including other metals, and at times oxygen, nitrate, various sulfur species, and/or organic compounds (e.g., fumarate).

The (a)biotic reduction of Mn(III,IV) oxides is coupled also to other elemental cycles, including nitrogen, trace metals, and sulfur. For instance, the reduction of Mn oxides has been proposed to play a role in the anaerobic oxidation of methane (Beal et al. 2009) and ammonium (Thamdrup and Dalsgaard 2002). However, the exact reaction pathways and organisms involved, and whether these reactions can be coupled to energy gain within one organism or involve a consortia remain unresolved. Further, Mn(III,IV) oxides serve as potent chemical oxidants at oxic-anoxic interfaces reacting rapidly in the absence of O₂, most notably with sulfide (Dellwig et al. 2012), iron(II) (Postma and Appelo 2000), nitrite (Luther and Popp 2002), and iodide (Fox et al. 2009). The reduction of Mn oxides also indirectly influences trace metal cycling through the liberation of a suite of trace metals that are adsorbed on and/or coprecipitated with the oxide. Indeed, Mn oxides, which have been coined the “scavengers of the sea,” sequester disproportionately high levels of trace metals and nutrients in comparison to the surrounding

seawater (Goldberg 1954), making these oxides a dominant control on the concentration and also stable isotope composition of trace metals in the ocean.

Cross-References

- [Bacteria](#)
- [Chemocline](#)
- [Chromium Isotopes](#)
- [Diagenesis](#)
- [Iron Oxidation](#)
- [Iron Reduction](#)
- [Manganese Oxidation](#)
- [Methane Oxidation](#)
- [Redox Zonation](#)
- [Suboxic](#)
- [Suboxic Sediments](#)
- [Trace Metals](#)

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Mantle

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

The *mantle* is the part of the Earth or of other rocky planets which lies between the outermost solid crust and the metallic core. On the icy planets of our Solar system, the mantle is the part that lies between the layered atmosphere and the ice-silicate core. On Jupiter, the mantle is made of two layers: one liquid and one metallic hydrogen. On Earth, it is mainly composed of silicate minerals, whose nature changes depending on the pressure (or depth). In the upper mantle, between the base of the crust and the transition zone at about 660 km, the principal rock type is peridotite composed of olivine, orthopyroxene, clinopyroxene, and an aluminous phase (plagioclase, spinel, or garnet). In the lower mantle, these minerals convert to denser phases such as Mg- or Ca-perovskite and magnesiowüstite. The terrestrial mantle is solid except in shallow zones of partial melting beneath mid-ocean ridges or in hot spots, and perhaps at the core-mantle boundary. The mantle convects at different scales, which is an important process driving plate tectonics and the subsequent exchange of matter and energy at the surface of the Earth. These exchanges create chemical gradients and thermodynamic potentials that help drive biosynthesis near hydrothermal-vent biological communities.

Cross-References

- ▶ [Asthenosphere](#)
- ▶ [Crust](#)
- ▶ [Jupiter](#)
- ▶ [Magma](#)
- ▶ [Mantle Plume, Planetary](#)
- ▶ [Mid-ocean Ridge](#)
- ▶ [Olivine](#)
- ▶ [Peridotite](#)
- ▶ [Plate Tectonics](#)

Mantle Plume, Planetary

Ian Campbell

Research School of Earth Sciences, The
Australian National University, Canberra, ACT,
Australia

Keywords

Flood basalt · Hotspot · Mantle plume · Mass
extinctions · Ocean island basalt

Synonyms

Hotspot

Definition

Mantle plumes are columns of hot buoyant ► [mantle](#) that originate from a thermal boundary layer deep in the Earth. The most likely source of plumes is the core-mantle boundary at a depth of 2900 km, although it has been suggested that small plumes may originate from the boundary between the upper and lower mantle at 670 km depth.

History

The Canadian geologist Tuzo Wilson suggested in 1963 that the age progression in the Hawaiian Islands was due to the oceanic lithosphere moving over a stationary “hot spot” in the mantle. Seven years later, the US geophysicist Jason Morgan recognized that Wilson’s hot spots were plumes of hot mantle that originated from the thermal boundary layer above the core.

Overview

Plumes must originate from thermal boundary layers, which in the case of Earth’s mantle is the core-mantle boundary or perhaps the boundary between lower and upper mantle. The core is hotter than the overlying mantle and it cools by conduction to the mantle, forming an

approximately 100 km thick boundary layer of hot, buoyant material. Before the buoyant mantle can rise at an appreciable rate, it must acquire enough buoyancy to overcome the viscosity of the cooler overlying mantle. As a consequence, starting plumes have a large head. Upwelling continues along the narrower high-temperature, low-viscosity pathway of the tail. The narrow diameter of mantle plumes conduits (<50 km) is a result of the strong temperature dependence of mantle viscosity. Some models predict that plume heads initially have a diameter of about 200 km but that they grow by entrainment as they rise, reaching a diameter of 1000 km at the top of the mantle. Here, they flatten to form disks about 2000 km across. Other models predict more complex geometry and dynamics. If a plume head is compositionally heterogeneous, it can stall at the upper mantle-lower mantle boundary and give rise to one or more smaller, secondary plumes. The plume heads melt to form flood ► [basalts](#) when they ascend beneath continents or oceanic plateaus when they ascend beneath oceans. Flood basalts and oceanic plateaus have observed lateral dimensions of 2000 by 2000 km, similar to the predicted dimensions of a flattened plume head. The Siberian and Deccan Traps, which erupted 250 and 65 Ma ago, respectively, are examples of continental flood basalts, and the 122 Ma old Ontong Java plateau is an example of an oceanic plateau. Eruption is usually rapid and in these three cases probably took less than 1 Myr. Flood basalts are the most voluminous eruptions in the geological record. It is not by coincidence that the two largest examples, the Siberian and Deccan Traps, correlate with the two biggest mass extinctions, the Permian-Triassic and the Cretaceous-Tertiary extinctions. More recent flood basalts, like the Deccan Traps, are connected by a chain of volcanic islands (Chagos-Laccadive ridge) to the current position of a plume or hot spot, which is now situated below Reunion Island. The island chain formed by melting the plume tail and produced a track across the sea floor because motion of the plate transported the flood basalt away from the current position of the plume. Large planetary volcanic structures, such as ► [Olympus Mons](#) on Mars and Artemis on Venus, have also been attributed to mantle plumes.

Cross-References

- [Basalt](#)
- [Deccan Trapps](#)
- [K/T Boundary](#)
- [Mantle](#)
- [Olympus Mons](#)

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Mantle Redox State

- [Mantle, Oxidation of](#)

Mantle Volatiles

Bernard Marty

Institut Universitaire de France, Ecole Nationale Supérieure de Géologie, Centre de Recherches Pétrographiques et Géochimiques (CRPG), CNRS, Vandoeuvre les Nancy Cedex, France

Keywords

Terrestrial mantle · Volatile elements · Noble gases · Water · Carbon · Nitrogen

Definition

Volatile elements are elements that are in gaseous, liquid, or icy form at temperature and pressure conditions of the Earth's surface. ► [Mantle](#) volatiles are those elements present in the terrestrial mantle. These are mainly hydrogen (water), carbon, nitrogen, and noble gases. Sulfur species and halogens are also transferred from the mantle to the Earth's surface in gaseous form and are considered as mantle volatiles. These elements were trapped in the solid Earth during terrestrial accretion and were exchanged with the Earth's surface through mantle-derived volcanism and plate ► [subduction](#). Some of them (e.g., helium and neon) have never seen the surface and are called primordial volatiles.

Overview

Mantle-derived basalts and volcanic gases contain volatile elements such as water, carbon, nitrogen, sulfur halogens, and noble gases, whose isotopic composition indicates that they do not originate from the local crust or atmosphere/hydrosphere but come from the underlying mantle. In particular, helium in mantle-derived volcanic rocks and gaseous emanations is enriched in the rare isotope ^3He , otherwise abundant in extraterrestrial material. Likewise, mantle neon has an isotopic composition different from that of the Earth's atmosphere and comparable to values found in the Sun or in material irradiated by the solar wind. The stable isotopes of H and N indicate that volatile elements in Earth were trapped from a source sharing similarities with primitive ► [meteorites](#). Some of the noble gas isotopes are formed from extant and extinct radioactive decays, allowing quantification of mantle degassing through time. Comparison of the relevant isotopic ratios of the mantle and of the atmosphere indicates that mantle degassing was very active during the first tens to hundreds of Ma, resulting in the development of a stable atmosphere early in Earth's history. In contrast to noble gases, major volatiles (H, C, N, S) have been exchanged between the

mantle and the Earth's surface because they can be trapped as solids in minerals and reinjected into the mantle at subduction zones.

Mantle degassing takes place at mid-ocean ridges and at mantle plume localities, during magma generation. Volatile elements originally trapped in mantle minerals enter preferentially the magmas and degas to the atmosphere and hydrosphere during volcanic eruptions. Mantle ingassing occurs at subduction zones where the hydrated and carbonated oceanic plates are plunging into the mantle. Some of volatile elements are expelled during dehydration of plates and released back to the surface through arc magmatism, but a significant fraction of volatile elements survives dehydration and returns to the mantle, possibly at the core-mantle boundary. The mantle is a well-degassed reservoir: It contains $\sim 10^{-3}$ times less volatiles than primitive (► [chondrite](#)) meteorites. This depletion is the result of a combination of processes: volatile element depletion of the Earth's building blocks impacts degassing of accreting bodies and mantle degassing through convection and magmatism. It is possible that mantle volatiles were acquired during the late accretion (i.e., after terrestrial differentiation) of a small fraction of volatile-rich material, a process known as the "late veneer" accretion.

Cross-References

- [Chondrite](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Late Veneer](#)
- [Mantle](#)
- [Meteorites](#)
- [Subduction](#)
- [Volatile](#)

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Mantle, Oxidation of

Daniele L. Pinti

GEOTOP, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Archean mantle · Atmosphere composition · Hadean Mantle · Oxygen fugacity · Redox buffers · Outgassing

Synonyms

[Mantle redox state](#)

Definition

The oxidation state of the mantle generally refers to the redox conditions prevailing in the mantle. The mantle redox state is controlled by the oxygen fugacity, which can be delimited using specific pairs of *redox buffers* (i.e., an assemblage of minerals or compounds that constrains oxygen fugacity as a function of temperature). Being iron the Earth's most abundant element having multiple valences, usually the measurement of the $\text{Fe}^{3+}/\Sigma\text{Fe}$ ratio in rocks and minerals allows defining the oxygen fugacity and thus the oxidation state of the mantle.

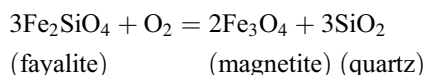
Overview

Determining the oxygen fugacity ($f\text{O}_2$) of Earth's mantle is of primary importance because it

controls the speciation of C-O-H-bearing fluids and melts. This in turn can have an effect on the mantle solidus and properties of the resulting liquids, i.e., influencing, for example, magma degassing styles (Frost and McCammon 2008). In other words, it affects the speciation and mobility of volatile elements in the interior and has control on the character of degassing species from the Earth since the planet's formation, i.e., the secondary atmosphere composition of the Earth (Stagno et al. 2013).

Mantle oxygen fugacity can be evaluated by oxythermobarometry measurements, mainly by measuring the $\text{Fe}^{3+}/\Sigma\text{Fe}$ ratio in rocks and minerals from the mantle: basalt glasses from mid-ocean ridges (MORBs; e.g., Cottrell and Kelley 2011) and oceanic islands (OIBs; e.g., Ballhaus 1993), and spinel- and garnet-bearing peridotites for the upper mantle (Canil et al. 1994); perovskite (CaTiO_3), ferropericlasite (Mg, FeO), or garnets as inclusions in diamonds for the transition zone down to the lower mantle (e.g., Stagno et al. 2013; Kaminsky et al. 2015; Kiseeva et al. 2018) (see also Frost and McCammon 2008 for a complete review on the subject).

Typical mantle oxygen fugacities recorded by spinel-bearing peridotite rocks originating at depths of 30–50 km in the mantle ranges from 3 log units below to 2 log units above the $f\text{O}_2$ imposed by the fayalite–magnetite–quartz (FMQ) buffer equilibrium ($f\text{O}_2 \approx 10^{-8.5}$; Frost and McCammon 2008):



The $\log(f\text{O}_2)$ value is defined as the logarithmic difference between measured oxygen fugacity conditions and those imposed by the FMQ buffer and the units are termed as ΔFMQ .

At depths of 200–250 km, subducted lithospheric mantle $f\text{O}_2$ ranges from -4 to -6 log ΔFMQ units (Tumiati and Malaspina 2019). At the transition zone (depths >410 km) the $f\text{O}_2$ is -0.26 to $+3$ log ΔIW units, these latter defined as relative to the Fe–FeO (iron–wüstite) or IW oxygen buffer ($f\text{O}_2 \approx 10^{-12}$) (Kiseeva et al. 2018).

Mantle redox conditions might have varied with time. The Hadean and the Archean lithospheric mantle could have been more reduced than the present day ($f\text{O}_2$ within the FMQ buffer), with oxygen equivalent to the iron–wüstite (IW) buffer (Kasting et al. 1993). This is an important point to be determined because the mantle oxidation conditions have certainly had a role in the type of degassing volatile species that composed the primitive secondary atmosphere. Modern volcanic gases are relatively oxidized: typical $\text{H}_2/\text{H}_2\text{O}$ and CO/CO_2 ratios are ≈ 0.01 and ≈ 0.03 , while reduced species such as NH_3 and CH_4 are virtually absent (Holland 1984). Their composition is consistent with that predicted for equilibrium with a magma whose oxygen fugacity is close to that of the FMQ equilibrium. In the Archean, more reduced gases, predominantly H_2 and CO in equilibrium with a magma whose oxygen fugacity was close to that of the IW buffer, might have dominated the atmosphere and acted as an important O_2 sink (Kump and Kasting 2001). The oxygen sink, by oxidation of the reduced volcanic outgassing flux, could have overwhelmed the photosynthetic O_2 source, contributing to maintain a reducing atmosphere up to the Archean/Proterozoic boundary. However, variations in the contents of vanadium (V) and other redox-sensitive elements in Archean lavas and peridotites suggest that the oxygen fugacity in the Archean mantle was a little different (Berry et al. 2008) or more oxidizing than that of the modern mantle (Canil 2002).

It is known that the mantle above subduction zones is more oxidized than is oceanic or ancient cratonic mantle (e.g., Brandon and Draper 1996). Oxidation could have caused by ingassing of oxidized volatile species and/or an agent ranging in composition from solute-rich hydrous fluid to water-bearing silicate melt (Brandon and Draper 1996). Recent studies based on the isotopic evolution of xenon in the mantle has suggested that volatile recycling was minimal until 2.5 Ga ago, which roughly corresponds to the period (3.0–2.5 Ga) when modern plate tectonics became dominant on Earth (e.g., Mukhopadhyay and Parai 2019; Perron and Moreira 2018).

Cross-References

- [Archean Mantle](#)
- [Oxygen Fugacity](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Peridotite](#)
- [Plate Tectonics](#)

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Mare Plains

- [Mare, Maria](#)

Mare, Maria

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Keywords

Basaltic flood volcanism · Lava · Mercury · Moon · Titan

Synonyms

[Basaltic flood plains](#); [Mare plains](#)

Definition

Maria are medium- to large-size mostly circular flat-floored low-albedo plains on the Earth's Moon and the Saturnian ► [satellite Titan](#). On the ► [Moon](#) maria are formed by basaltic flood volcanism and are predominant on the lunar nearside. On Titan, maria are postulated to be filled with liquid ► [hydrocarbon](#) compounds, in particular ► [methane](#) and ethane.

Overview

The term mare originally referred to large-size low-▶ [albedo](#) features on the Moon. Lunar mare are lava plains characterized by low-viscosity basaltic flood lava. The use of the term mare has been extended to other terrestrial bodies in the solar system, especially to Titan where maria are radar-dark features that are assumed to be large lakes of liquid hydrocarbon compounds.

On the Moon, the term *mare basin* refers to an impact structure filled by flood lava. Although lunar maria and impact basins are spatially related, mare materials were emplaced later when compared to impact basins formed during the Nectarian heavy bombardment period, as radiometric ages of samples and chronostratigraphic relationships demonstrate. Radiometric sample ages as well as crater-size-frequency model ages of lunar maria are primarily in the range of 3.16–4.2 Gyr but may be as young as 1.2–1.5 Gyr.

Despite a homogeneous impact basin distribution on the Moon, maria are usually found on the near side, which is considered to be the result of the Moon's crustal dichotomy and is often associated with high mass concentrations (MASCONS) and large gravitational anomalies.

Maria are rich in geologic features characteristic of emplacement of flood lava, such as lava flows, lobate flow scarps, volcanic domes and cones, lava ponds, sinuous and arcuate rilles, and wrinkle ridges.

Maria were sampled during the Luna and Apollo missions, and the returned samples as well as remotely sensed spectra showed a mafic (Mg/Fe) composition with modal plagioclase contents of up to 50 wt% and high FeO contents of up to 20 wt%, as well as high Ca/Al ratios when compared to lunar highland rocks. They show varying amounts of Ti, reaching up to 15 wt% TiO₂ for *high-Ti* mare basalts. They are considered to be produced by partial melting of mafic rock in the lunar ▶ [mantle](#) at depths of up to 500 km.

On Saturnian satellite Titan, maria refer to flat, low-albedo, radar-dark areas investigated in the infrared and radar spectrum by the ▶ [Cassini](#) Spacecraft in 2006–2007. They are considered to be formed by liquid ▶ [hydrocarbons](#), especially methane. Ligeia Mare has a diameter of 500 km.

Cross-References

- ▶ [Albedo Feature](#)
- ▶ [Apollo Mission](#)
- ▶ [Cassini Spacecraft](#)
- ▶ [Earth](#)
- ▶ [Hydrocarbons](#)
- ▶ [Impact Basin](#)
- ▶ [Lacus](#)
- ▶ [Mantle](#)
- ▶ [Methane](#)
- ▶ [Oceanus, Oceani](#)
- ▶ [Palus, Paludes](#)
- ▶ [Rille](#)
- ▶ [Rock](#)
- ▶ [Satellite or Moon](#)
- ▶ [Saturn](#)
- ▶ [Titan](#)

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Margulis, Lynn

Ricardo Amils
Centro de Biología Molecular Severo Ochoa
(CSIC-UAM), Universidad Autónoma de Madrid, Madrid, Spain

Overview

Lynn Petra Alexander (March 5, 1938 – November 22, 2011) pioneered modern evolutionary biology with her revolutionary theory

that symbiosis was responsible for the origin of the eukaryotic cells. She also developed with James Lovelock the concept that Earth functions as a self-regulating system, known as the Gaia hypothesis.

Born in Chicago, she graduated in Biology at the University of Chicago and obtained her PhD at Berkeley University in 1965. Soon after she moved to Boston University where she taught biology for 22 years. Finally, in 1988, she moved to Amherst as she was appointed Distinguished Professor of Botany, later of Biology and finally of Geosciences at the University of Massachusetts.

Her seminal paper “On the Origin of Mitosing Cells” (Sagan 1967), which can be considered as a landmark of the endosymbiotic theory, was finally published in the *Journal of Theoretical Biology* after many rejections. Margulis was famous for her stubbornness defending her theory against the neodarwinists. The molecular demonstration that eukaryotic organelles, mitochondria and chloroplasts, were bacterial descendants proved that she was right and can be considered the first experimental evidence of the endosymbiogenesis theory.

She defended cooperation rather than competition between species as the most important evolutionary driver.

Being interested in the importance of gases as microbial metabolic substrates and products she met Lovelock and started a very productive collaboration. In 1974, they published a seminal paper describing the bases of the Gaia hypothesis.

Margulis was a prolific author of scientific papers and books, a science educator and very committed with science popularization. She received many awards throughout her career, and in 1983, she was elected member of the National Academy of Sciences.

Cross-References

- [Chloroplast](#)
- [Eukaryote](#)
- [Gaia Hypothesis](#)
- [Symbiosis](#)

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Mars

François Forget¹ and Ernst Hauber²

¹Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, UMR 8539, Université Paris 6, Paris, France

²Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Keywords

Atmosphere · Climate · Habitability · Ice · Interior · Surface · Tectonics · Volcanism · Water

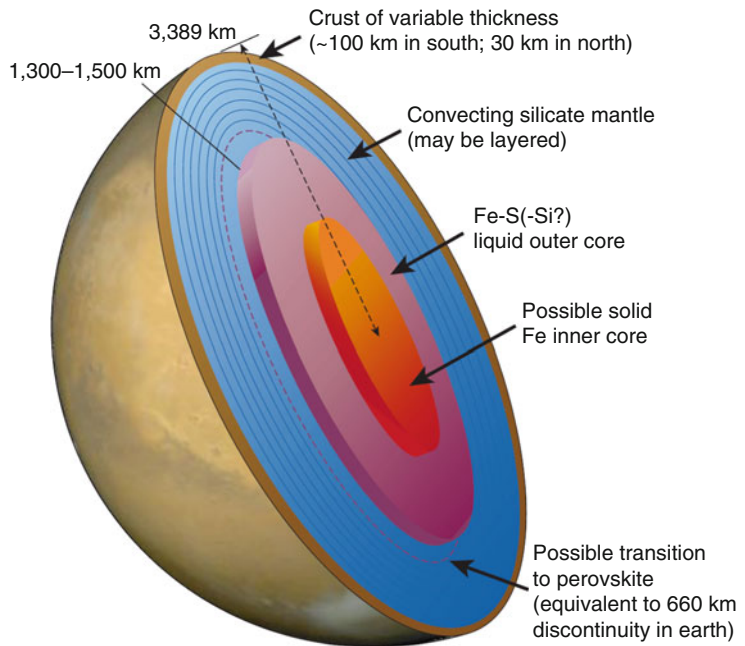
Definition

Mars is the fourth ► [Planet](#) from the Sun and one of the terrestrial planets. It is named after the Roman god of war.

Overview

Mars accreted rapidly in a couple of million years (Brasser 2013) and differentiated within a few tens of millions years after the formation of the ► [Solar System](#) into a core, ► [mantle](#), and ► [crust](#), as indicated by isotope geochemistry (Lee and Halliday 1997; Mezger et al. 2013). It is commonly thought that the bulk composition of Mars is “chondritic” (Dreibus and Wänke 1985), i.e., similar to the composition of Carbonaceous Chondrites, the most primitive materials in the Solar System. The Fe-Ni-FeS core is dense and metal rich (Fig. 1) and its radius is about 50% of the surface radius, the exact value depending on

Mars, Fig. 1 Tentative cutaway view of the Martian interior. (From Stevenson 2001; reprinted with permission, © Nature Publishing Group)



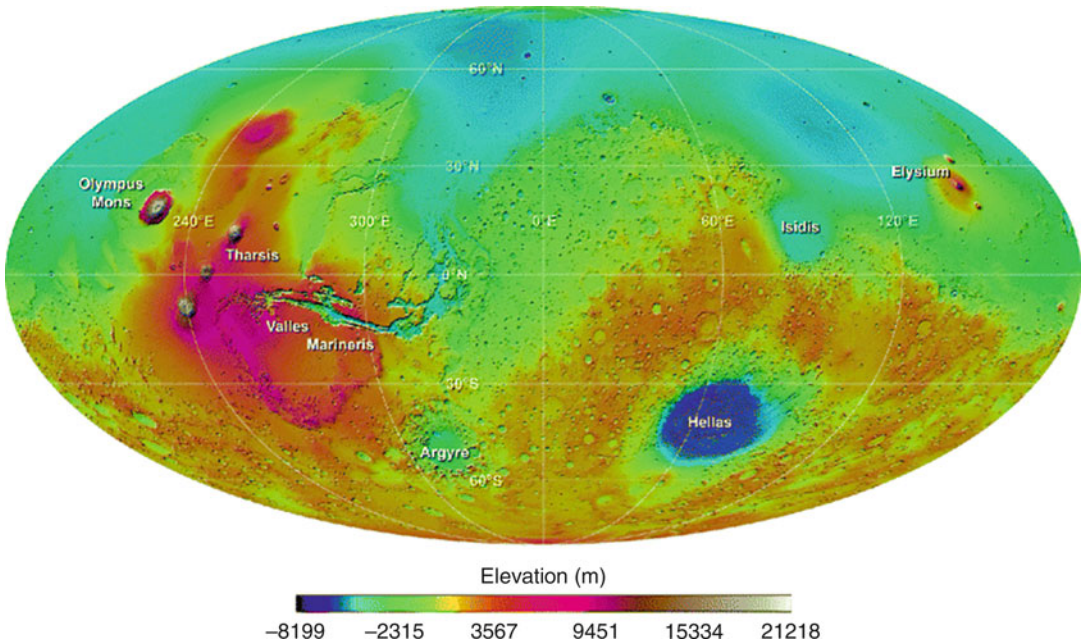
its content of lighter elements like sulfur. The remnant magnetization of parts of the Martian crust indicates that core convection induced by energy from core cooling and/or inner core growth might have produced a core magnetic dynamo and a global [magnetic field](#) (Stevenson 2001). Evidence for crustal magnetization is mainly found in very old terrain and is absent in the largest impact basins, so the dynamo likely ceased before their formation about 4 Ga ago (Acuna et al. 1999) although this conclusion has been challenged (Schubert et al. 2000). For a discussion of the Martian dynamo see Connerney et al. (2004).

The dynamic range of geopotential topography (i.e., the topography after subtraction of the gravitational potential or *areoid* from planetary radii) on Mars is 29.5 km, the largest of all terrestrial planets (Fig. 2). The major features – the lowest and highest elevations – are represented by deep impact basins and large shield volcanoes, respectively. The lowest single point of the Martian surface is located in Hellas Planitia (−8180 m below the Martian datum) and the highest point is the summit of Olympus Mons (+21,300 m). The current thick elastic lithosphere of Mars allows maintaining such huge surface loads (e.g., Smith

et al. 2001). The surface shows a global dichotomy or asymmetry in topography as well as in morphology (Watters et al. 2007). The southern hemisphere (about two third of the planet) displays significantly higher elevations and a rougher morphology, dominated by heavily cratered terrain. The border between the two hemispheres is in large parts marked by a topographic scarp with heights of up to several kilometers. An overview of basic facts about Mars is given in Tables 1 and 2.

Crust and Mantle

The Martian crust has a mean thickness between 30 and 80 km (perhaps up to 100 km), as inferred from gravity and topography (e.g., Zuber et al. 2000; Neumann et al. 2004). It is thicker in the southern highlands and thinner in the northern lowlands. The bulk composition of the Martian crust is assumed to be basaltic (Fig. 3), although minor amounts of alteration products have been identified (overviews on surface composition are given in Bell 2008). Thermochemical evolution models (reviewed by Breuer and Moore 2007) suggest that most of the crust was produced during the first billion years. According to the widely accepted compositional model of Wänke and



Mars, Fig. 2 Topography of Mars (shaded and color-coded elevation model derived from the Mars Orbiter Laser Altimeter (MOLA) data; Mollweide projection)

Dreibus (1994), the silicate mantle of Mars is Fe-rich and contains radiogenic elements in terrestrial abundances. Converting this composition to a pressure-dependent mineralogy, Longhi et al. (1992) obtain a layered mantle structure with an olivine-rich upper part, a transition zone of silicate spinel, and a lower part consisting mainly of perovskite (see Sohl and Schubert 2007, for a discussion of interior structure models). The thickness of the elastic lithosphere is variable over space and time and it is currently up to three or four times thicker at the North Pole (>300 km) than at the Tharsis volcanoes (Grott and Breuer 2010). The average surface heat flow estimated from the elastic lithosphere thickness variation over time decreased from higher values in the ► **Noachian** ($\sim 50\text{--}100 \text{ mW m}^{-2}$) to current values of the order of $\sim 10\text{--}20 \text{ mW m}^{-2}$ (Grott et al. 2013).

Global Geology

The geologic surface record of Mars spans more than four billion years (Ga). Following the accepted stratigraphic system for Mars, this time is subdivided into the Noachian ($\sim 4.1 \text{ Ga}$ to

$\sim 3.6 \text{ Ga}$), the ► **Hesperian** ($\sim 3.6 \text{ Ga}$ to $\sim 3 \text{ Ga}$), and the ► **Amazonian** ($\sim 3 \text{ Ga}$ to present) periods (Tanaka and Hartmann 2008). The precise boundaries between the periods depend on the cratering model that is used to derive absolute ages from crater size frequency distributions (Hartmann and Neukum 2001). The pre-Noachian is not represented by surface outcrops. More than 40% of the surface is Noachian in age (Fig. 4), as well as the largest well-preserved impact basins Hellas, Argire, and Isidis (Solomon et al. 2005). Noachian rocks are primarily found in the southern highlands, whereas Hesperian surfaces are more widely scattered. Large portions of the ancient crust in the northern lowlands are overlain by a relatively thin Hesperian cover of volcanic and sedimentary materials. Amazonian rocks are concentrated in volcanic regions (see below). The geologic surface inventory of Mars is very diverse and reflects the action of both endogenic and exogenic processes (Carr 2006).

Volcanism and Tectonics

Evidence for volcanism on Mars is abundant (Greeley and Spudis 1981). About 15 huge

Mars, Table 1 Successful Mars missions

Mission	Launch date	Type
Mariner 4	November 28, 1964	Flyby
Mariner 9	May 30, 1971	Orbiter
Viking 1	August 20, 1975	Orbiter and Lander
Viking 2	September 09, 1975	Orbiter and Lander
Phobos 2	July 12, 1988	Orbiter/attempted Phobos Landers
Mars Global Surveyor	November 07, 1996	Orbiter
Mars Pathfinder	December 04, 1996	Lander and Rover
2001 Mars Odyssey	April 07, 2001	Orbiter
Mars Express	June 02, 2003	Orbiter and Lander
Spirit (Mars Exploration Rover-A)	June 10, 2003	Rover
Opportunity (Mars Exploration Rover-B)	July 7, 2003	Rover
Mars Reconnaissance Orbiter	August 10, 2005	Orbiter
Phoenix	August 04, 2007	Scout Lander
Curiosity (Mars Science Laboratory Mission)	November 26, 2011	Rover

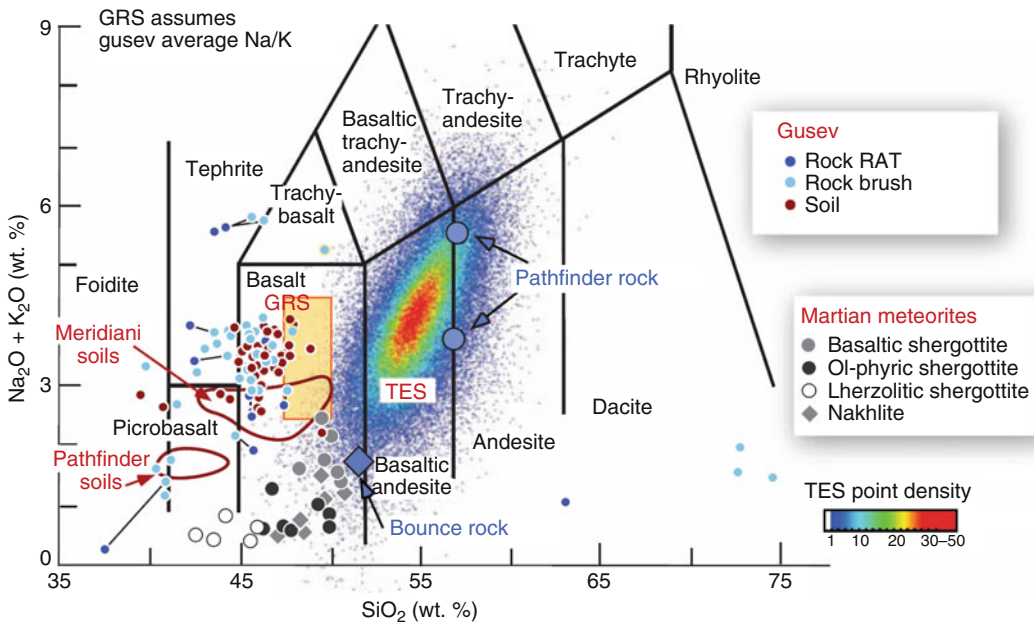
volcanic shields, including the largest volcano in the Solar System, ► [Olympus Mons](#), as well as hundreds of smaller edifices and spatially extensive volcanic plains attest to the significant magmatic activity of Mars. Volcanism was active over all of Mars’ history, but the intensity has decreased over time. After the Noachian, volcanic resurfacing mainly focused on the two largest volcanic provinces of the planet, ► [Tharsis](#) and Elysium (Fig. 4). Volcanic eruption products are mainly basaltic, based on the analogy to terrestrial basaltic landforms, the analysis of ► [SNC Meteorites](#), the in situ investigation of rocks and soils by landed missions, and spectral measurements from orbit (Fig. 3) (e.g., Grott et al. 2013). The Martian environment, in particular the low atmospheric pressure, leads to different eruption conditions as compared to Earth (Wilson and Head

Mars, Table 2 Bulk properties of Mars and Earth

Bulk parameters	Mars	Earth	Ratio (Mars/Earth)
Mass (10^{24} kg)	0.64185	5.9736	0.107
Volume (10^{10} km ³)	16.318	108.321	0.151
Equatorial radius (km)	3396.2	6378.1	0.532
Polar radius (km)	3376.2	6356.8	0.531
Volumetric mean radius (km)	3389.5	6371.0	0.532
Core radius (km)	1700	3485	0.488
Ellipticity (Flattening)	0.00648	0.00335	1.93
Mean density (kg/m ³)	3933	5515	0.713
Surface gravity (m/s ²)	3.71	9.80	0.379
Surface acceleration (m/s ²)	3.69	9.78	0.377
Escape velocity (km/s)	5.03	11.19	0.450
GM ($\times 10^6$ km ³ /s ²)	0.04283	0.3986	0.107
Bond albedo	0.250	0.306	0.817
Visual geometric albedo	0.150	0.367	0.409
Visual magnitude V (1,0)	−1.52	−3.86	—
Solar irradiance (W/m ²)	589.2	1367.6	0.431
Black-body temperature (K)	210.1	254.3	0.826
Topographic range (km)	30	20	1.500
Moment of inertia (I/MR ²)	0.366	0.3308	1.106
J ₂ ($\times 10^{-6}$)	1960.45	1082.63	1.811
Number of natural satellites	2	1	
Planetary ring system	No	No	

1994). Since magma contains volatiles, volcanism has released large amounts of water and other volatile species (e.g., CO₂) into the Martian atmosphere (outgassing). The rates, timing, and total amount of outgassing are poorly constrained.

Mars, like the Moon or ► [Mercury](#), is a one-plate planet. There is no morphological surface record of plate tectonics. However, a very early phase of plate tectonics could help explain the



Mars, Fig. 3 Composition of Martian surface materials shown in a diagram of total alkalis (vertical axis) versus silica. The bulk of the Martian crust plots in the basaltic domain (From McSweeney et al. 2009; reprinted with permission, © Science Magazine). Data from Mars meteorite analysis, Mars Pathfinder, Mars Odyssey Gamma Ray

Spectrometer (GRS), Mars Global Surveyor Thermal Emission Spectrometer (TES), Mars Exploration Rover (MER) investigation using soil sample, brushed rocks or rock processed by the Rock Abrasion Tool (RAT) are combined

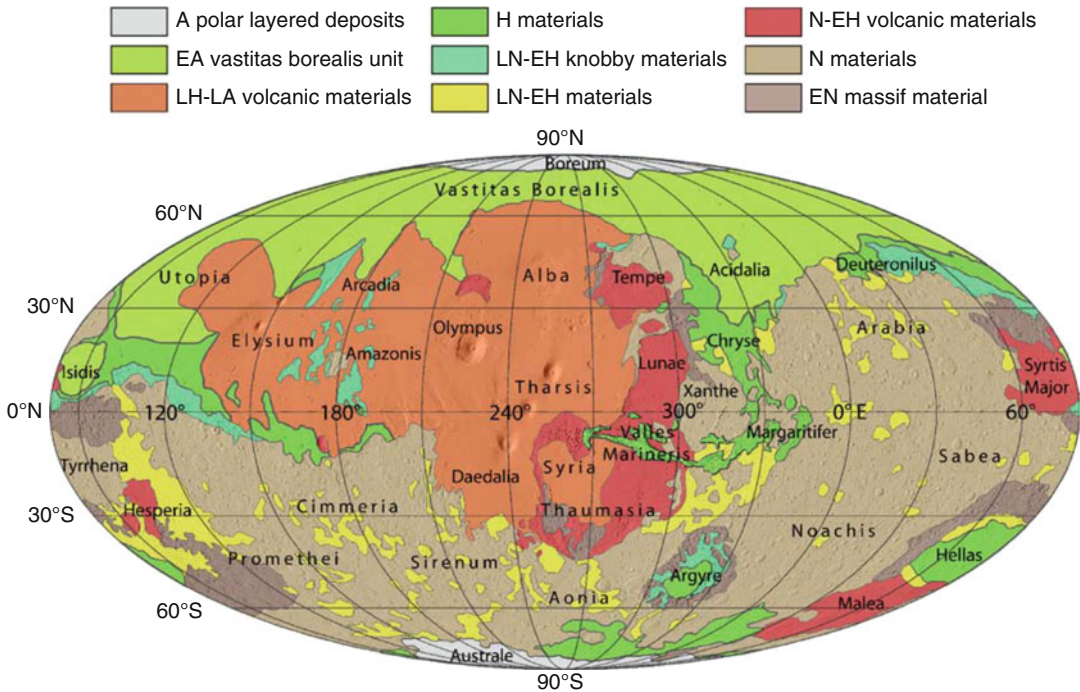
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dynamo activity and would have avoided early massive melting on Mars. Its morphological traces might have been overprinted by later resurfacing processes.

The single largest tectonic feature on Mars is the global dichotomy, which separates the southern highlands from the northern lowlands. The origin of this global dichotomy remains unknown, despite attempts to explain it as a consequence of an early Magma Ocean, mantle convection, an early phase of plate tectonics, or an exogenic process involving one or more impacts (Solomon et al. 2005). It was long thought that the southern highlands are much older than the northern lowlands, because much fewer craters were visible on images of the latter. Highly accurate topographic data from laser altimetry showed a large population of craters in the northern lowlands that have a very subdued topographic expression, obscuring their visibility in imaging data. If these craters are taken into account, the bulk of the crust in the northern lowlands seems to

be as old as in the southern highlands (Frey et al. 2002).

Except for the dichotomy, the Tharsis rise in the western hemisphere and, less importantly, the formation of Isidis Planitia and the Elysium rise in the eastern hemisphere clearly dominate the tectonic map of Mars on a global scale (Banerdt et al. 1992). Tharsis, the key to the tectonic evolution of Mars, is often considered to be the possible expression of a hot spot or mantle plume. (For an alternative view, see Schumacher and Breuer 2007). Deformation modeling indicates that large-scale lithospheric (magmatic) loading over Tharsis, which is large relative to the radius of the planet, is dominated by membrane stresses, and generates concentric extensional stresses around the periphery and radial compressional stresses closer to the center of Tharsis, which were accommodated by the formation of radial grabens and rifts and concentric wrinkle ridges (Golombek and Phillips 2010). As for the volcanism, tectonic activity on Mars seems to have



Mars, Fig. 4 Simplified global geology of Mars. The three major physiographic features are the southern highlands, the northern lowlands, and the volcanic provinces of

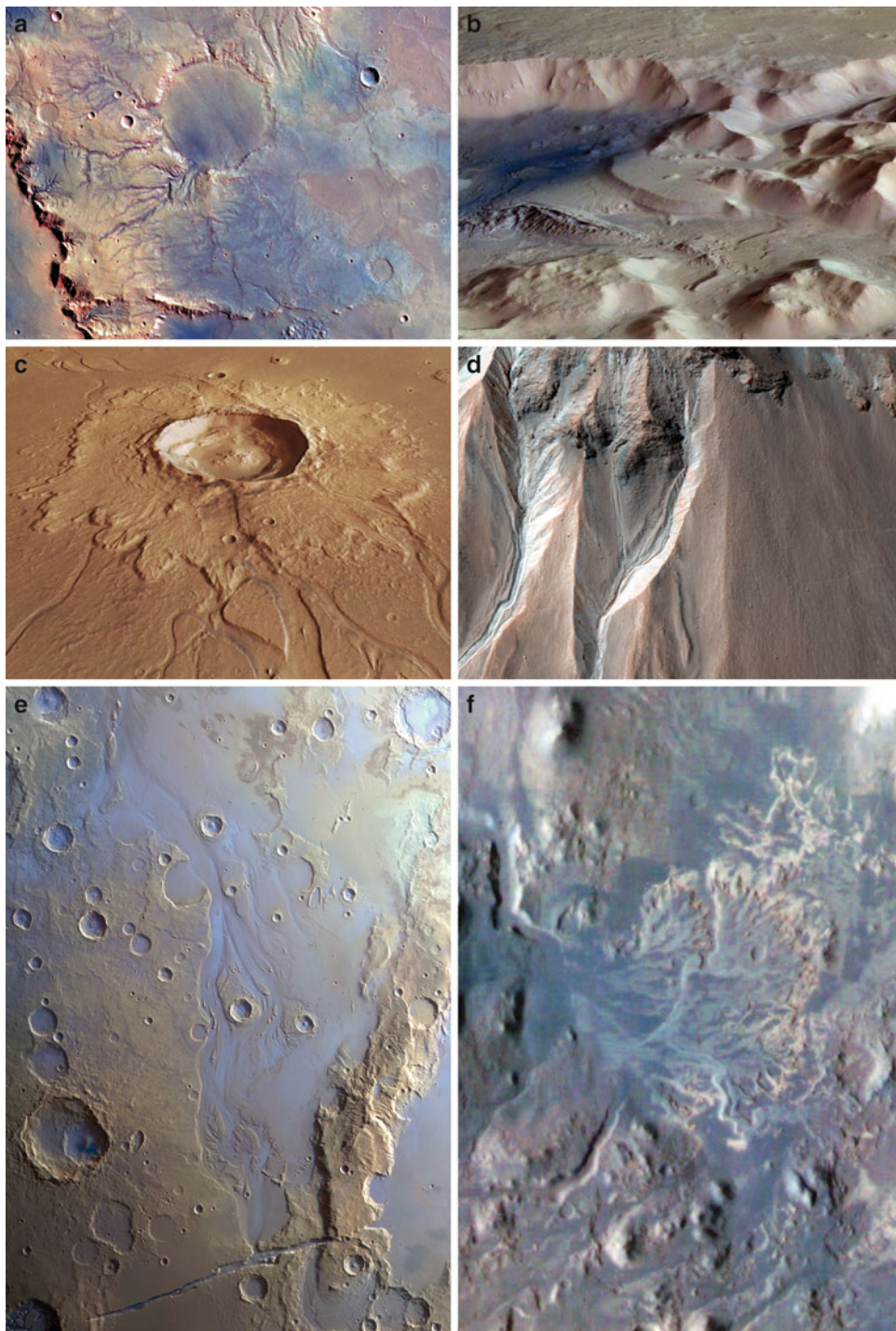
Tharsis and Elysium (From Nimmo and Tanaka 2005). Unit age abbreviations: *N* Noachian, *H* Hesperian, *A* Amazonian, *E* Early, *L* Late

peaked early and has gradually waned with time, although punctuated by episodes of higher and lower intensity. In general, vertical deformation is dominant and seems to be mainly associated with impact basins and large volcanic provinces.

Exogenic Surface Features

Impact craters are found on virtually every surface on Mars. Of particular interest are craters with unique morphologies that reveal the distribution of water or ice at the surface or in the subsurface (Martian crater morphologies are reviewed by Barlow 2010). Rampart craters (Fig. 5c) are only observed on Mars. It is thought that they penetrated the ground down to an ice- or water-rich layer. The minimum (or onset) diameter of rampart craters, therefore, can be used to determine the maximum depth of the ice or water table at the time of the impact. Other impacts might have strengthened (armored) an ice-rich target against erosion (e.g., by covering the ice by ejecta and protecting it from sublimation), so the present crater and its ejecta are

elevated with respect to their surroundings (“pedestal” craters). Wind-blown materials (sand and dust) are also widespread and can be observed on almost any high-resolution image, where they build aeolian bedforms such as ripples and different types of dunes. Wind was (and most probably still is) also an erosional force, and can be considered to be the most active geological agent on present-day Mars (Greeley and Iverson 1985). ► [Valley Networks](#) (Fig. 5a) and ► [outflow channels](#) (Fig. 5e) resemble erosional patterns carved by water and are discussed below. Many young (Amazonian) landforms on Mars that were probably formed by exogenic processes show a latitude-dependent geographic distribution. They include surface mantling, lobate debris aprons, lineated valley fill and concentric crater fill, viscous flow features, ► [gullies](#), and patterned ground. Collectively, these landforms (many of which are morphologically analogous to glacial and periglacial landforms on Earth) are hypothesized to represent the surface records of Martian ice ages (Head et al. 2003) that were induced by



Mars, Fig. 5 Evidence for liquid water at the Martian surface: (a) valley network; (b) deltas (c) lobate ejecta crater; (d) gullies; (e) outflow channel with streamlined “islands”; (f) fluvial delta with inverted channels. Images

a, b, c, e, f are from the Mars Express High Resolution Stereo Camera (HRSC), and d from the Mars Reconnaissance High Resolution Imaging Science Experiment (HiRISE)

astronomical forcing and associated climate changes (see below).

Atmosphere and Present-Day Climate

The Martian atmosphere is primarily composed of CO₂ (95%) with a little nitrogen, argon, and oxygen (Table 3). The atmospheric pressure at the surface ranges from 1 to 14 mbar depending on location and season (compared to 1013 mbar on average at sea level on Earth). In spite of these differences, the Martian climate system is similar to the Earth climate system in many aspects. The two planets rotate with almost the same rate and a similar obliquity. The length of day is thus almost the same (24 h and 40 min on Mars) and the seasonal cycle is comparable. In such conditions, the general circulation is controlled by similar processes (Read and Lewis 2004): On both planets, the Hadley circulation (the process that generates the trade winds) is important at low latitudes, whereas “baroclinic” planetary waves (a succession of low- and high-pressure zones) dominate the weather system at midlatitudes. However, with such a thin atmosphere and a dry soil, diurnal and seasonal surface temperature variations are much more marked, with temperatures typically ranging between 20 °C and –135 °C). Briefly, the climate of Mars is “hyper-continental.” To first order, the Martian meteorology can thus be compared with what one would expect on a cold, dry desert-like Earth. However, just like the climate system on the Earth is not controlled only by temperature gradients and the atmospheric circulation because of the presence of oceans and water clouds, several phenomena make the climate system more complex on Mars.

Mars, Table 3 Principal constituents of the atmospheres of Mars (volume mixing ratios), compared to the Earth

Gas	Symbol	Mars (%)	Earth (%)
Carbon dioxide	CO ₂	95.32	0.035
(Molecular) nitrogen	N ₂	2.7	78
Argon	Ar	1.6	0.93
(Molecular) oxygen	O ₂	0.13	20.6
Carbon monoxide	CO	0.07	0.00002
Water	H ₂ O	~0.03	~0.4

Firstly, as much as 30% of the ► carbon dioxide atmosphere condenses every winter at high latitudes to form polar caps, inducing surface pressure variations all over the planet (CO₂ cycle). Secondly, a highly variable amount of suspended dust modifies the radiative properties of the atmosphere, with global dust storms sometimes totally shrouding the planet (dust cycle). Finally, a peculiar hydrological cycle occurs on Mars, with water vapor transported by the atmosphere and the formation of clouds, hazes, and frost (water cycle).

Water on Mars Today

Water is almost everywhere on present-day Mars, in solid or gaseous state (Carr 1996). There are several known types of reservoirs:

First, relatively pure, white ice is directly exposed at the surface of Mars in an area of about 1000 km in diameter around the north pole. The thickness of this ice layer may vary from a few millimeters at its boundary up to a few meters or a few tens of meters in some locations near its center.

This ice layer is in direct interaction with the atmosphere, and is the principal surface reservoir involved in the atmospheric water cycle: in summer, the ice is warmed by the sun and sublimates. For a few weeks, the northern polar region becomes a source of water vapor that is transported away within the atmosphere. During the rest of the year, most of this water ultimately comes back to the northern polar cap through various transport mechanisms. The cycle is closed and near equilibrium. The amount of water involved in the seasonal water cycle is small. If one could precipitate the water content of the atmosphere on the surface, a layer thinner than a few tens of micrometers would be obtained even in the “wettest” regions. In the cold Martian conditions, though, saturation is often reached. Therefore, clouds form in the atmosphere and frost can condense onto the surface. The atmospheric water vapor should also be able to diffuse into the porous subsurface.

The surface ice near the northern pole appears to cover a much bigger structure made of thousands of layers of ice and dust that have

accumulated over more than 3000 m in thickness (see Clifford et al. 2000). These northern polar layered deposits are thought to be comparatively young, preserving a record of the seasonal and climatic cycling of atmospheric CO₂, H₂O, and dust over the past million years.

Radar observations of the south polar region demonstrated that the thick southern polar layered deposits (about 1000 km in diameter, and 2-km thick) accumulated around the pole are also composed of relatively pure water ice (Plaut et al. 2007), currently isolated from the atmosphere by a layer of dry sediments in most locations.

Near the south pole, the small (300 km), white, bright residual cap is primarily composed of carbon dioxide ice, and for a long time it had been assumed that no water ice layer was present at the surface in the southern polar region. Observations of the imaging spectrometer OMEGA (Observatoire pour la Minéralogie, l' Eau, les Glaces, et l' Activité) aboard ► [Mars Express](#), however, revealed the presence of perennial water ice deposits at the edges of the CO₂ ice bright cap, and even in large areas tens of kilometers away from it. Most likely, the permanent CO₂ ice cap lies on an extended water ice layer (Bibring et al. 2004).

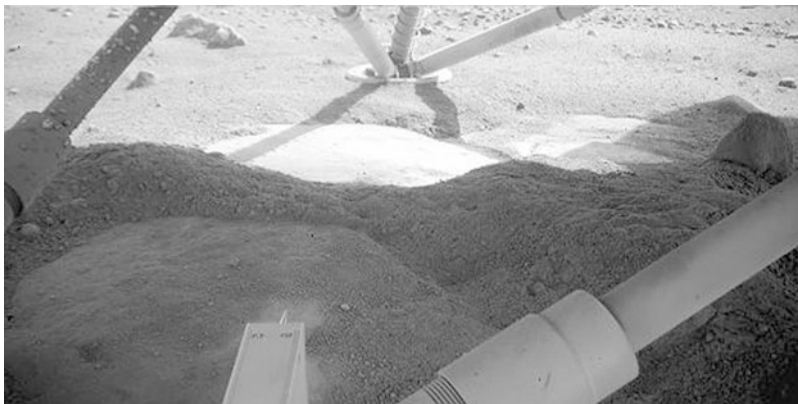
In both the northern and southern hemisphere, poleward of about 55–60° latitude, the Mars Odyssey Gamma-Ray Spectrometer investigation

has shown that where ice is not exposed at the surface, it is still present just beneath the surface (below an ice-free layer a few centimeters thick), typically in the form of a dirty ice layer more than 1-m thick and with no less than 50% of ice. Moreover, in these areas the unique morphology of the ground is consistent with the presence of a few meters thick ice layer coating the surface (see a synthesis in Head et al. 2003). In 2008, the NASA Phoenix mission landed near 69°N in order to confirm the presence of ice and better understand its origin and its environment. As expected, a layer of ice was found just a few centimeters below the surface (Fig. 6).

In specific locations in midlatitudes and even in the tropics, there is geomorphologic and radar sounding evidence of buried ice landforms that are reminiscent of the debris-covered glaciers that can be found on Earth. The ice is thought to have been transported in the atmosphere, deposited, and then insulated and protected by a layer of sediments. The origins of these deposits could be related to climate changes due to time variations of orbital parameters (see below).

Below these buried ice layers, and even at lower Martian latitudes, it is likely that the large pore volume of the Martian subsurface regolith might be partly filled by ice. Calculations of the thermodynamic stability of ground ice suggest

M



Mars, Fig. 6 An image of the Martian surface beneath NASA's Phoenix Mars Lander taken by Phoenix's Robotic Arm Camera (RAC) on the eighth Martian day of the mission on June 2, 2008. A superficial dust layer, shown in the dark foreground, has been blown off by Phoenix's

thruster engines, exhibiting an ice-rich layer a few centimeters below the surface. The presence of the ice in Mars high latitudes had been remotely detected by the Mars Odyssey Gamma-Ray Spectrometer investigation in 2002. (Image: NASA/JPL)

that it can exist very close to the surface at high latitudes, but can persist only at substantial depth (several hundred meters) near the equator (Squyres et al. 1992). Observational evidence of the subsurface ice might be the presence of impact craters with distinctive lobate ejecta (*rampart craters*; Fig. 5c) that are not found on the Moon, and that apparently owe their morphology to the melting and vaporizing of ground ice during the impact. The size frequency distribution of these craters is consistent with the depth distribution of ice inferred from stability calculations. Small, fresh impact craters in mid-latitudes have excavated water ice and hence unambiguously demonstrate that water ice is present in the very shallow subsurface (Byrne et al. 2009).

Liquid Water on Mars Today

To form liquid water, H₂O must be exposed to a pressure above 6.1 mbar and a temperature above the freezing point (0 °C for pure water), and below the boiling point (which depends on pressure). Such conditions are not uncommon at the surface of Mars, for instance in the lower plains in summer in early afternoon. They last only a few hours at most, however, and only the first few millimeters below the surface can be heated above 0 °C. Because of the low vapor pressure of water in the atmosphere, any ice that may be present at the surface (in the morning, for instance) sublimates into the atmosphere well before it can melt (e.g., Haberle et al. 2001). The existence of liquid water in a “metastable” state in some specific circumstances has been suggested, but remains unlikely. In some cases, dissolved salts could form a brine, which can be liquid at temperatures well below the freezing point of pure water (Fairén et al. 2009).

Liquid water may exist in the subsurface, more likely at several thousands of meters below the surface, where water present in the pore space could be heated by the geothermal flux (Squyres et al. 1992). The most “optimistic” scientists imagine that liquid water aquifers could exist at much shallower depth, up to a few tens of meters below the surface, as a consequence of local geothermal activities, but, again, this remains speculative. In particular, radar soundings have not yet been able

to detect any liquid water aquifers, in spite of the fact that the liquid water dielectric properties should make it detectable in theory.

Climate Changes Due to Obliquity and Orbital Parameters Variations

As on Earth, the climate on Mars depends on the planet’s orbital and rotational parameters, and in particular its obliquity (inclination of Mars’ axis of rotation with respect to its orbit plane). For Earth, such oscillations are small ($\pm 1.3^\circ$ for the obliquity), but they are thought to have played a key role in the glacial and interglacial climate cycles. For the case of Mars, calculations have shown that Mars’ obliquity varied widely and somewhat erratically in the past, between 0° and more than 60° (the current obliquity is 25.2°) (Laskar et al. 2004). These variations must have had a strong impact on the Martian climate. A quantified description of these past climates is not easy because one has to predict the response of a complex system that includes the atmospheric circulation and the coupled CO₂, dust, and water cycles. Nevertheless, on the basis of theoretical considerations and with the help of numerical climate simulations, we can speculate about the major changes.

During periods of low obliquity, with an obliquity below 20°, the seasonal cycle is weaker than today. The latitudinal extension of the seasonal polar caps is reduced. The polar regions experience a net decrease in solar heating (the sun is lower on the horizon) and thus a net cooling. It is likely that the mass of frozen atmosphere trapped at the poles (currently near the southern pole) increases at the expense of the total atmospheric mass. Models also show that in such conditions the water and dust cycle are much less active. The atmosphere is thinner and clearer. Mars is then a frozen world.

During periods of high obliquity. Beyond 30° of obliquity, the seasonal cycle is stronger than today. For instance, the CO₂ ice seasonal polar caps extend to the tropics in winter when the obliquity reaches 40°. In the polar regions, the increase of annual mean insolation leads to a warming of the relatively deep subsurface. In summer, the polar water ice reservoir is strongly

heated and releases tens to hundred times more water than today, inducing a very active hydrological cycle (vapor, clouds, frost). Beyond obliquities of 35–45°, computer simulations of the Martian climate suggest that warming of any ice left at the poles would liberate such a large amount of water into the atmosphere that, in certain areas, water vapor would condense and precipitate out much more readily than it could sublime. In these areas, ice would therefore have accumulated (as long as there was still a source at the pole) and might even have formed glaciers (Forget et al. 2006). The remains of these glaciers (moraines) and possibly debris-covered glaciers have indeed been found where the models indicate they once existed. Today, it seems that a large amount of the ice that may have been transported in and out of the polar regions is back at the poles. If this scenario is confirmed, the polar layered deposits can probably be attributed to the past oscillations of the climate.

Evidence for Transient Liquid Water on Mars in the Recent History: Outflow Channels, Gullies and Recurrent Slope Lineae

Three types of very different geological landforms suggest that liquid water may occasionally flow briefly on Mars in the relatively recent geological past (Baker 2001).

Outflow channels (Fig. 5e) are immense and deep channels that appear to have been carved by flowing water, mud, or glaciers (Baker 1982). Their widths can exceed 100 km, and they can reach lengths of >1000 km. Most are several billions years old, but seem to have been episodically active in several stages, and some outflow channels appear to be less than a few tens of millions of years old. Outflow channels show a peculiar morphology: they have no tributaries, and their geographical origin is quite localized. On their floors, large numbers of channels sweep around prominent obstacles such as impact craters, sculpting teardrop-shaped structures tapering in the direction of the flow. The geometry of these streamlined “islands” has led researchers to conclude that they were shaped by very turbulent liquid water, rather than by ice, lava or mud, and that only sudden, short-lived bursts of vast

amounts of water can explain the characteristics of the outflow channels. The water could have been suddenly liberated from a pressurized underground water reservoir, trapped beneath the Martian ► [cryosphere](#) (Lasue et al. 2013). The formation of the outflow channels does not require the climate to have been very different from what is observed today.

► *Gullies* (Fig. 5d) are hundreds of meters to kilometer-long structures usually found on steep slopes with an apron or fan of debris at the distal end. They seem to have been created by flowing water in geologically recent times: perhaps a few million years ago, perhaps much more recently. Since their discovery in high-resolution images (Malin and Edgett 2000a), their origin is debated. Some researchers put forward the idea that there are aquifers below ground, warmed by energy from within Mars. These could flow at the surface intermittently. However, this scenario does not satisfactorily explain the distribution of the flow features: they seem unconnected with any volcanism. Neither does it address the fact that these features are observed on isolated peaks and even on dunes, where groundwater is not expected. An alternative scenario would be simply to assume that they were formed when ice or snow deposited during period of high obliquity (see above) may have briefly melted, inducing debris flows and gullies.

Recurrent Slope Lineae are albedo markings that recurrently appear and disappear in seasonal cycles on relatively steep, equator-facing slopes in the southern mid-latitudes during summer (McEwen et al. 2011). They resemble water tracks propagating downslope, although there is probably no water directly exposed at the surface. More likely, water may seep through the very shallow subsurface and wettens the overlying regolith, making it appear darker. The source of this hypothesized water, which may occur in the form of brines with a depressed freezing temperature, is unknown.

Early Mars: A Potential Habitable Planet More Than 3.5 Billion Years Ago

About half of the surface of Mars is extremely ancient, dating back from prior to 3.8 billion years

ago, a time when the impact rate from infalling meteoroids and planetesimals was much higher than today. This part of the Martian surface, mostly in the southern highlands, has also kept the record of a period where the environment was much different from what it became afterward. There is evidence that, at this time, liquid water was present on the surface of Mars and could have formed rivers, lakes, and possibly an ocean.

- *Valley networks* (Fig. 5a). Valleys, with characteristics very similar to terrestrial river drainage valleys, were discovered in 1971 by the Mariner 9 orbiter. Smaller valleys coalesce downhill into larger valleys, forming a dendritic network. These valleys are observed on most of the surfaces older than 3.5–3.8 billion years (Carr 1996), but only very few have been identified on more recent terrain. This finding suggests that Mars enjoyed an environment suitable for the formation of these valleys more than ~3.5 billion years ago (at least periodically), but that such conditions rarely occurred later. The recent exploration era is revealing more and more valley morphologies that suggest that precipitation and runoff was involved, perhaps generated by snow melt.
- *Lacustrine deposits?* (Fig. 5b and f). High-resolution images provided new evidence of deposits, mostly within craters, that have an appearance similar to layered lacustrine deposits, deltas, sedimentary terraces, and shorelines (Malin and Edgett 2000b, 2003; Kleinhans 2010). Well-defined layering has been identified within these deposits, supporting the idea of standing water, although windblown or airfall sediments could account for some of the observations.
- *An ancient ocean?* Most outflow channels seem to end downstream in the northern lowlands, which would have acted as a huge sink for water and sediments. If the Noachian were warm enough to prevent the formation of a sufficiently thick ► [cryosphere](#), which could trap pressurized groundwater beneath and maintain an elevated global water table, the formation of a primordial ocean in the lowest part of the global topography (e.g., Hellas, northern lowlands) would seem plausible, if not inevitable (Clifford and Parker 2001). According to this model, such an ocean would have frozen with time, and finally the water would have been assimilated in the crust in a thickening cryosphere. It has to be noted, however, that there is no unambiguous morphologic or mineralogic evidence for an ancient ocean on Mars, and its existence is still contentious.
- *Erosion rate:* A detailed analysis of the ancient terrains reveals that old impact craters larger than about 15 km in diameter have a substantially degraded appearance. Crater rims, ejecta blankets, and central peaks have been removed in many cases and the crater interiors have been filled in with debris. Craters smaller than about 15 km have been erased entirely. However, craters formed in regions a few hundreds of millions years younger are much better preserved. This observation suggests that in the distant past, before 3.8 billion years ago, the erosion rate was orders of magnitude more efficient than later in the history of Mars (Jakosky and Phillips 2001). While this erosion could have many possible causes, it is generally thought that liquid water was the eroding agent.
- *Mineralogy:* On Earth, the composition of many rocks and soils points to their formation in the presence of liquid water (e.g., hydrated materials). On Mars, such evidence is rarer. The observations gathered by the thermal infrared spectrometer TES (Thermal Emission Spectrometer) aboard Mars Global Surveyor and by the near infrared imaging spectrometers OMEGA and CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) aboard Mars Reconnaissance Orbiter suggest that most surfaces are either of volcanic origin, or covered by dust (Christensen et al. 2001; Bibring et al. 2005). However, in 1998, TES revealed the presence of three regions with an exposed surface enriched in the iron oxide mineral ► [hematite](#), a weathering product inferred to have been precipitated from water flowing through the crust. One of these regions, Sinus Meridiani, was selected to be

explored by Opportunity, one of the two Mars Exploration Rovers that began their mission in January 2004. Opportunity did confirm the presence of hematite, and made an even more interesting discovery: it detected the presence of the sulfate salts jarosite ($\text{KFe}_3^{(\text{III})}(\text{SO}_4)_2(\text{OH})_6$) and magnesium sulfates like kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) in the sedimentary outcrops of the area, with physical characteristics indicative of aqueous transport (Squyres et al. 2004). On this basis, the Opportunity team concluded that these rocks probably record episodic inundation by shallow surface water, evaporation, and desiccation. At the same time, OMEGA actually discovered and mapped hydrated sulfates – kieserite, polyhydrated sulfates, and even gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) – mostly in light-toned layered terrains located in Terra Meridiani, ► [Valles Marineris](#), and Margaritifer Sinus. Even more interestingly, the OMEGA team discovered clays (phyllosilicates, primarily iron/magnesium smectites) in several locations restricted to the most ancient terrains (Poulet et al. 2005), suggesting that clay formation may have taken place primarily during the earliest portion of Martian history. Clays were probably formed by the action of liquid water on volcanic rocks such as ► [basalt](#), over tens of thousands of years. Altogether, the mineralogical investigations suggest that Mars experienced, early on, a period when liquid water was probably abundant, and able to soak soils during episodes long enough for clays to form. Later, in a drier and more acidic environment, sulfate salts were more likely to form (Bibring et al. 2006). The fact that some alteration minerals can still be observed at present, although they formed several billion years ago and are easily transformed into other materials by, e.g., ► [diagenesis](#), suggests that water was very limited on the Martian surface from soon after their formation until today (Tosca and Knoll 2009).

The Early Mars Climate enigma. The possible existence of relatively warm conditions suitable for surface liquid water on Mars 3.8 billion years

ago is unexpected. Most experts believe that at that time, the young sun was less intense than today and its luminosity 25% lower than at the present time. Since Mars is about 1.5 times more distant from the sun than the Earth, the solar energy available on Mars then was only one third of what we enjoy on Earth today. In such conditions, the radiative equilibrium temperature (► [effective temperature](#)) of the planet should have been -75°C , not taking into account the atmosphere. In such conditions, what could have made the climate so warm and wet?

- *Atmospheric greenhouse effect:* The composition of the early Mars atmosphere is not well constrained, but it was probably mostly composed of carbon dioxide with a surface pressure between a few hundreds of millibars to a few bars. Such amounts are consistent with the initial volatile inventory of a planet like Mars, and it is likely that large amounts of CO_2 and H_2O should have been released in the atmosphere by the substantial volcanism that occurred on early Mars, associated with the formation of the volcanic plains and the Tharsis bulge. Both CO_2 and H_2O are greenhouse gases (► [greenhouse effect](#)), but their ability to warm the planet through greenhouse effects is limited, and they may not have been able to solve the early Mars climate enigma by themselves (see review in Haberle 1998). Other greenhouse gases, such as NH_3 , CH_4 , or SO_2 have been proposed to help solve the enigma, but they should have been photochemically unstable in the early Mars atmosphere and rapidly exhausted, unless produced by a surface or subsurface source (volcanism? life?). However, the presence of sulfate salts on Mars has motivated recent studies involving SO_2 in the atmosphere. Another possibility is that Mars was warmed by CO_2 ice clouds. These clouds tend to form in a thick CO_2 atmosphere. Models show that they can reflect a significant part of the thermal infrared radiation emitted by the surface and warm the planet through an exotic “scattering greenhouse effect” (Forget and Pierrehumbert 1997). An unsolved problem with CO_2 -supported

greenhouse scenarios involving a thick ($\gg 1$ bar) atmosphere is that it is not easy to explain the loss of this atmosphere into space with known escape processes. If there was indeed a thick CO_2 atmosphere on early Mars, much of it should be stored as carbonates in subsurface reservoirs (Lammer et al. 2013).

- *Role of geothermal flux.* Some geological evidence related to liquid water on early Mars could be explained by the early large geothermal heat flux (estimated to be 5–10 times the present-time values on average) that contributed to warm the near subsurface and probably induced intense geothermal activity. Volcanic intrusions may have locally caused even larger heat flow values.
- *Asteroid impacts.* Large impacts during the heavy bombardment may have warmed the climate episodically by generating a transient steam atmosphere. The water vapor in this steam atmosphere may have acted as greenhouse gas, and rain may have been generated (review by Toon et al. 2010).

Life on Early Mars?

Life was probably present on Earth when Mars enjoyed habitable conditions more than 3.8 billion years ago. If life on Earth arose as a result of fundamental and repeatable physicochemical processes, there is no a priori reason why life might not also have emerged on the Red Planet, more than 3.5–4 billion years ago. The study of Mars shows that conditions at its surface were such that widespread liquid water could have been present there for a limited period only – most likely during the first ~ 1 billion years of Martian history. On Earth, the first multicellular organisms (and, a fortiori, the first animals and plants) appeared after more than 2 billion years of unicellular predecessors. If any life form evolved on Mars, this suggests that it was probably primitive. However, it is not clear if such a long evolution time is required for genetic evolution, or because physical and chemical conditions on Earth (e.g., amounts of oxygen) were incompatible with the existence of more complex creatures? Perhaps evolution did not proceed in the same way on Mars, and some optimistic scientists have

speculated that more evolved forms of life could have existed on Mars at the same epoch.

Life on Mars Today?

Mars today is cold and dry. If one assumes that Martian life requires the same necessary ingredients as life as we know it on Earth (Jakosky et al. 2007), the primary challenge for potential Martian organisms would be the access to liquid water. This is especially true at the surface or near the surface. Moreover, the Martian surface is exposed to intense [▶ ultraviolet radiation](#), which should be lethal for most living organisms although there are microorganisms that have been reported to survive high radiation doses. Also, the upper few meters of the soil seem to have been sterilized by highly oxidizing compounds. In such conditions, assuming that life ever did get started on Mars, how could it have survived until today? If life has survived until the present day on Mars, we will have to look for it in those niches where liquid water may still be present. One possibility is several kilometers underground, where the planet's internal heat source ensures that temperatures remain above 0°C . “Interstitial” water could harbor life, as observed in deep Earth crust samples. Nearer to the surface, Martian volcanism, which, though on the decline, still might occur (Hauber et al. 2011), probably creates warmer places. Just as on Earth, organisms might exploit the relatively rich chemical resources found in such locations. It must be stated, however, that for life to have held out this long on the planet, Martian organisms would have needed a stable environment in their “bio-niches” for billions of years.

The detection of life on the Martian surface was one of the main objectives of the [▶ Viking](#) Landers (1976). An articulated arm, capable of digging into the surface, gathered samples of Martian soil. The samples were subjected to three investigations: the Pyrolytic Release, Gas Exchange, and Labeled Release experiments, which yielded negative or ambiguous results. However, the official verdict was finally negative (Klein et al. 1992), because the gas chromatograph coupled with a mass spectrometer, capable of detecting organic molecules at a concentration below one part per billion, found nothing.

An alternative way to detect biological activity on Mars is to monitor the presence of gases possibly produced by biological activity and which could not be present at a given level without the presence of life, like molecular oxygen on the Earth. There is no such obvious biogenic gas on Mars. However, the reported discovery of ► [methane](#) since 2004 from Earth-based and orbital observations has reactivated this investigation. Methane should be unstable in the Martian atmosphere, so its presence requires the existence of a source. In theory, this source could be unrelated to life. For instance, some methane on Earth is produced by hydrothermal activity, which leads to the oxydoreduction reaction between iron-bearing primary silicates (olivine and pyroxene) and water to form hydrogen and Fe(III)-bearing phyllosilicates, a process called ► [serpentinization](#). The hydrogen can then be used to produce methane by biologic and non-biologic mechanisms. However, the intensity of the source of methane inferred from the observations (local bursts of methane have been reported) is such that it would be comparable to the production of methane by serpentinization along the entire Mid-Atlantic Ridge on Earth (50,000–130,000 t/year). On a ► [planet](#) where the volcanic activity appears to be low at present, this would be unexpected. Because most of the methane produced on Earth is biogenic, it is thus tempting to speculate on a possible subsurface biological production. Nevertheless, the current environment on Mars would constitute a great challenge for life as we know it. The temperature and atmospheric pressure commonly prevent liquid water to be stable at the surface, which is also chemically harsh and affected by intense radiation. It is doubtful that organisms can survive today at the Martian surface (Knoll and Grotzinger 2006).

Future Directions

The exploration of Mars continues with the Mars Atmosphere and Volatile Evolution Mission (MAVEN), that was launched in November 2013. MAVEN will explore the planet's upper

atmosphere, ionosphere, and interactions with the sun and the solar wind. Scientists will use these data to determine the role that loss of volatile compounds, such as CO₂, NO₂, and H₂O, from the atmosphere to space has played through time, giving insight into the history of the Martian atmosphere and climate, liquid water, and planetary habitability. In 2016, an ESA orbiter with Russian contributions will search for trace gases such as methane, and will try to map their variations over time and location in the Martian atmosphere. The same orbiter will carry a demonstration lander. Also in 2016, NASA's InSight Mission will put a seismometer and a heat flow probe onto the surface of Mars. ESA's ExoMars rover (current launch date: 2018) will have the capability to drill 2 m into the ground to search for traces of life. NASA plans to send a rover to Mars in 2020 that searches for biosignatures and stores a diverse set of samples in a cache for potential return to Earth at a later stage. In the more distant future, the actual return of samples from Mars to Earth (► [Mars Sample Return Mission](#)) would be the most important step in Mars Exploration.

Cross-References

- [ALH 84001](#)
- [Basalt](#)
- [Carbon Dioxide](#)
- [Carbonaceous Chondrite](#)
- [Core, Planetary](#)
- [Crater, Impact](#)
- [Crust](#)
- [Cryosphere](#)
- [Diagenesis](#)
- [Dynamo, Planetary](#)
- [Effective Temperature](#)
- [Evaporite](#)
- [Greenhouse Effect](#)
- [Gullies](#)
- [Heat Flow, Planetary](#)
- [Hematite](#)
- [Impact Basin](#)
- [Jarosite](#)
- [Lithosphere, Planetary](#)

- ▶ [Magnetic Field](#)
- ▶ [Mantle](#)
- ▶ [Mars Express](#)
- ▶ [Mars Global Surveyor](#)
- ▶ [Mars Pathfinder](#)
- ▶ [Mars Sample Return Mission](#)
- ▶ [Mars Stratigraphy](#)
- ▶ [MER, Spirit, and Opportunity \(Mars\)](#)
- ▶ [Mercury](#)
- ▶ [Meridiani \(Mars\)](#)
- ▶ [Methane](#)
- ▶ [Moon, The](#)
- ▶ [Noachian](#)
- ▶ [Olympus Mons](#)
- ▶ [Outflow Channels](#)
- ▶ [Permafrost](#)
- ▶ [Phobos-Grunt](#)
- ▶ [Phyllosilicates, Extraterrestrial](#)
- ▶ [Planet](#)
- ▶ [Plume](#)
- ▶ [Polar Caps \(Mars\)](#)
- ▶ [Polar Layered Deposits \(Mars\)](#)
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- ▶ [SNC Meteorites](#)
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- ▶ [Sun \(and Young Sun\)](#)
- ▶ [System Solar Formation, Chronology of](#)
- ▶ [Terrestrial Planet](#)
- ▶ [Tharsis](#)
- ▶ [UV Radiation](#)
- ▶ [Valles Marineris](#)
- ▶ [Valley Networks](#)
- ▶ [Viking](#)

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Mars 2020

Michel Viso
Innovaxiom, Paris, CX, France

Definition

Mars 2020 was designed on the technical heritage of → Curiosity (launched November 26, 2011; landed on Mars August 6, 2012) but aims to answer new science and technological questions and prepare a future return of Martian samples. The major components of this Mars 2020 mission are the cruise stage, the aeroshell composed of the front heat shield and the back shell. This aeroshell hosts descent stage which performed the Skycrane, lowering smoothly → Perseverance onto the Martian surface.

The Mission Mars 2020 was launched July 30, 2020, from Cape Canaveral (Florida USA). After around 6 month and a half of cruise, Perseverance successfully landed in Jezero crater February 18, 2021 (Fig. 1).



Mars 2020, Fig. 1 The illustration, almost the last terrestrial view of the descent stage, displays the actual components of the mission from top to bottom: the cruise stage, the back shell, intricately together the Skycrane and the rover Perseverance, the black box protecting the helicopter → Ingenuity attached under the belly of the rover and the front heat shield. (Credit NASA/JPL-Caltech/KSC. Original image: <https://mars.nasa.gov/resources/25060/one-last-earthly-look/>)

Cross-References

- Curiosity
- Ingenuity
- Perseverance

Mars Analogue Sites

Richard Léveillé
Natural Resource Sciences, McGill University,
St. Anne de Bellevue, Québec, Canada

Keywords

Astrobiology · Analogue sites · Mars · Exploration · Extremophiles · Biosignatures · Missions · Extreme environments · Comparative planetology

Definition

Mars analogue sites are places on Earth that present one or more geological or environmental features similar to those found on Mars, either current or past.

History

Studies of ► [Mars analogue](#) sites have been an integral part of comparative planetary science, space exploration, and astrobiology for over a half-century (Léveillé 2010a). Following the successful Mariner missions of the 1960s, planetary scientists began studying in more detail Mars-like features and environments on Earth, including volcanic and erosional systems, glacial and thermokarst features, dunes, playas, and impact craters. Mars analogue sites were later studied in order to plan for possible landing sites for the Viking mission. Similarly, Mars analogue sites were used to test ► [NASA's](#) earliest life-detection instruments. Early microbiological studies of desert soils, including some from Antarctica and the Atacama, focused on the adaptations and survivability of microorganisms under Mars-like conditions. Since the Viking mission and more recent orbital and rover missions, new Mars analogue sites have been continually identified and studied as new data are returned to Earth and our understanding of Mars is deepened.

Overview

Mars analogue sites are defined as places on Earth that share one or more physical, chemical, or geological similarities with Martian ► [environments](#), either current or past (Farr 2004; Osinski et al. 2006; Léveillé 2009). Studies of analogue sites are an essential aspect of understanding remote or in situ robotic observations of Mars and to ultimately better understand our solar system (Chapman 2007). With respect to astrobiology, analogue sites provide insight into the limits to life on Earth, adaptations of organisms to extreme conditions, and the diversity and

distribution of habitable environments on Earth and possibly elsewhere in our Solar System (Rothschild and Mancinelli 2001; National Research Council 2007; Léveillé 2010b). Analogue sites are also indispensable to the study of the formation and preservation of microbial biosignatures, in both ancient and modern systems. Though no location on Earth is identical to any location on Mars, many terrestrial analogue sites do approximate conditions or features found on Mars. Extreme cold and dry conditions are perhaps the most important present-day Mars-like conditions that are especially relevant to astrobiology. Mars-like geological features on Earth include volcanic systems (including lava tubes), salt and sand dunes, gullies and canyons, polar and alpine deserts, and impact craters, as well as various hydrothermal and sedimentary systems (Farr 2004; Osinski et al. 2006; Chapman 2007; Léveillé 2009, 2010b).

Basic Methodology

The term fidelity is used to describe the similarity of an analogue site with respect to the extraterrestrial environment to which it is compared (e.g., Snook et al. 2007; Léveillé 2009). Analogue sites with multiple attributes that are closely related to Mars are said to offer a high fidelity. Several different analogue sites may be studied in order to fully understand the data generated during a space mission or to explain an extraterrestrial process. In studying Mars analogue sites, it is important to take into account what is similar and what is different to Mars and to ensure that differences do not affect the analysis for which the analogue site is used (National Research Council 2007).

With respect to astrobiology and ► [Mars](#), analogue sites can be used in at least three fundamental ways:

1. To better understand data returned from a Mars mission in order to assess the habitability potential of studied sites.
2. To predict and identify where past habitable environments may have existed on Mars.

3. To identify biosignatures (or biosignature suites) that may be searched for at a given location on Mars.

Results from such analogue studies can directly assist in the formulation of scientific objectives, as well as help to define operational and instrumentation requirements for future planetary missions.

Applications

Analogue sites have been used extensively to test hypotheses about possible extraterrestrial processes, including biosignature formation, degradation, and preservation. They can also be used to test exploration strategies, biosignature detection and measurement techniques, sample-handling protocols, and mission concepts in a variety of geological and environmental settings. Analogue sites can also be used to test and validate science instruments, robotic systems, and integrated hardware packages in challenging environments and under operating conditions representative of actual missions, at a relatively low cost and risk (Léveillé 2009).

Studies of analogue sites can also help to establish baseline abiotic signatures or provide positive controls for life-detection instruments. Similarly, issues of forward contamination and cross-contamination, as well as mitigation strategies and cleaning protocols, can be incorporated into many types of field-based studies at analogue sites.

Studies of analogue sites are also useful for the training of scientists and engineers (including remote science and engineering operations teams), mission planners, ground operation crews, and even astronauts, in a cost-effective, low-risk way (National Research Council 2007). By studying analogue sites, science teams can learn how to remotely detect and identify planetary features and perfect decisional protocols before missions begin (Chapman 2007). Field-based projects also help to train students in the tools and knowledge needed to participate in future astrobiology research, payload development, and ultimately missions. Some important examples of analogue sites for

astrobiology include the Haughton impact crater on ► [Devon Island](#) and the perennial springs of Axel Heiberg Island, Canada; the Antarctic Dry Valleys; the acidic river system of Rio Tinto, Spain; acidic lakes of Australia; and the ► [Atacama Desert](#), Chile. Other types of analogue sites showing promise with respect to astrobiology and Mars exploration include sites of active terrestrial serpentinization and exposed basaltic glass, lava tubes and caves, playa lakes, hydrothermal springs, as well as ► [permafrost](#) and ground-ice-containing areas.

Analogue missions refer to simulations of planetary surface missions that involve an integrated set of scientific and operational activities at an analogue site (Snook et al. 2007; Léveillé 2009). Analogue missions can specifically target operational requirements and produce lessons learned in order to reduce costs and risks associated with future missions. For example, analogue missions can help to develop and test sampling strategies and measurement requirements, make ground truth measurements, direct training in planning science operations, promote team building, and improve communications. Some examples of astrobiology-focused analogue missions include the MARTE drilling project at ► [Rio Tinto](#), Spain; the Life in the Atacama Desert project; and the AMASE project at Svalbard.

Future Directions

The US National Research Council has recommended that studies of analogue sites should be a fundamental component of Mars astrobiological research and the development of future robotic missions to Mars (National Research Council 2007). Testing Mars surface operations at analogue sites is also a high priority of the planetary science community (Farr 2004; Osinski et al. 2006). Integrated scientific and operational studies at analogue sites will likely be increasingly critical for Mars sample return missions, for which coordination of highly advanced technologies will be required at very carefully preselected sites (Borg et al. 2008). Analogue sites will also continue to be essential for

selecting landing and sampling sites, for sampling and site characterization strategies, and for planning overall mission operations, as well as for developing novel technologies for Mars missions. Increased international coordination and integrated field and remote operations teams will help to address future target mission requirements and scientific objectives.

Cross-References

- [Atacama Desert](#)
- [Crater, Impact](#)
- [Devon Island](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [Hydrothermal Environments](#)
- [Permafrost](#)
- [Rio Tinto](#)
- [Soda Lake](#)
- [Terrestrial Analog](#)
- [Yellowstone National Park, Natural Analogue Site](#)

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Mars Analogues

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Extreme field sites on Earth that mimic some Mars condition are considered Mars analogues. Some Earth natural field sites are extreme due to very low pH, oxidant conditions, low temperature, or low water activity. Those extreme conditions characterize the Mars surface environment. Atacama dessert in Chile is one of the best recognized analogues for Mars surface due to the very low water activity and high UV radiation on the surface. Other interesting Mars analogue due to the low pH and associated geochemistry and mineralogy is the Spanish Rio Tinto. Jarosite is precipitated in the river bed resembling the chemistry associated to Meridiani Planum in the red planet.

Mars Chamber

- [Simulation Chambers](#)

Mars Exploration Rovers

- [MER, Spirit, and Opportunity \(Mars\)](#)

Mars Express

Jean-Pierre Bibring
Institut d'Astrophysique Spatiale, Université
Paris Sud, Orsay, France

Keywords

ESA · Mars

Definition

The Mars Express mission is the first planetary mission of the European Space Agency (ESA). Decided in 1997, it was launched from Baïkonur on June 2, 2003, and was inserted into ► [Mars](#) orbit December 25, 2003, after proper maneuvers transferring the spacecraft into an elongated almost polar orbit. Mars Express started its orbital observations in early January 2004. The targeted duration of the mission was 1 Martian year (687 terrestrial days). However, the mission is still healthy and operating after more than 15 terrestrial years, and has been extended till the end of 2022, possibly till 2025. Some days before arriving at Mars, Mars Express ejected the Beagle 2 lander, designed to land and to perform surface measurements. Unfortunately, the contact with ► [Beagle 2](#) was lost and never recovered. However, the measurements and observations from orbit are making this mission one of the most successful for the exploration of Mars.

History

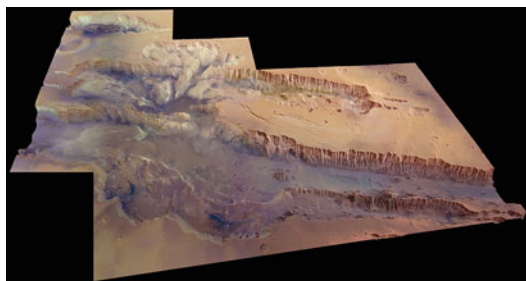
The Mars Express mission was conceived after the dramatic loss at launch of the Russian Mars 96 mission in November 1996. After being studied as a French then French/German “small mission,” embarking some spare models of instruments developed for Mars 96, it has been incorporated within the Horizon 2000 ESA science plan in 1997, as a “F-mission” (both Flexible and Fast), to be launched in 2003.

Overview

The 2003 launch opportunity was extremely favorable: a Soyuz rocket would be sufficient, and the overall cost could be capped at a very low level. To fit within the allocated mass of ~100 kg, five instruments were selected, out of the available spares developed for the Mars 96 mission: HRSC (High-Resolution Stereo Camera), built in Germany (G. Neukum, then R. Jauman, then R.T. Roatsch PI); OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité, a visible and infrared hyperspectral imager), built in France, Italy, and Russia (J-P. Bibring, then J. Carter PI); SPICAM (Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars, an ultraviolet and infrared atmospheric spectrometer), built primarily in France and Russia (J-L. Bertaux then F. Montmessin, PI); PFS (Planetary Fourier Spectrometer), primarily built in Italy (V. Formisano, then D. Grassi, then M. Giuranna, PI); and ASPERA (Analyzer of Space Plasmas and Energetic Atoms, an analyzer of ions and electrons in the outer atmosphere), primarily built in Sweden (R. Lundin, then S. Barabash, then M. Holmström, PI). ESA decided to add a lander (Beagle 2 was selected, C. Pillinger, PI) and an orbiter instrument to sound the subsurface: The selected one was named MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding, a subsurface and ionospheric radar sounder), built in cooperation between Italy and the USA (G. Picardi, then R. Orosei, PI). Finally, Mars Express would embark a Mars Radio Science Experiment (MaRS), with no specific hardware, using the radio signals to probe the planet atmosphere and surface (M. Pätzold, PI). With this suite of instruments, Mars Express is capable of sounding and analyzing, possibly in a coupled way, all Martian envelopes: its outer (ionized) atmosphere, its neutral atmosphere, its surface, and its subsurface, down to a few kilometers.

The variety and diversity of achievements is impressive. They cover all prime themes of Mars science, offering clues to decipher in an unprecedented fashion Mars' evolution at all timescales, from its seasonal changes to its climatic and

geological variations. It launched a profound revisiting of Mars properties and history.



Valles Marineris, seen by HRSC at an angle of 45 degrees to the surface in near-true color and with four times vertical exaggeration. The image covers an area of 630,000 sq. km with a ground resolution of 100 m per pixel. The digital terrain model was created from 20 individual HRSC orbits, and the color data were generated from 12 orbit swaths. The largest portion of the canyon, which spans right across the image, is known as Melas Chasma. Candor Chasma is the connecting trough immediately to the north, with the small trough Ophir Chasma beyond. Hebes Chasma can be seen in the far top left of the image.

Key Research Findings

Based on a list issued by ESA 10 years after launch, top ten scientific discoveries could be summarized as follows:

1. The ancient history of Mars has been fundamentally re-assessed after the detection by OMEGA of alteration minerals and phyllosilicates in particular. Hydrated phyllosilicates were formed, at a planetary scale, when long-standing bodies of water were present, either or both at the surface and subsurface levels: They record an ancient era of potential habitability. This happened during the first hundreds of millions years, while the dynamo was still active. OMEGA, then coupled to CRISM/MRO, have identified and located sites of astrobiological relevance, for future in situ and Mars Sample Return (MSR) missions.
2. Methane has been declared detected from orbit by the PFS spectrometer, with its spatial and vertical distribution mapped. Its presence would indicate that Mars is still either geologically or biologically active. It paved the way for further dedicated space investigations, with still controversial outcomes.
3. The HRSC has offered breathtaking 2D and stereoscopic views of the planet down a ~ 10 meters scale. It provides new insights into the planet's topography, allowing a much better understanding of the formation and evolution of the surface geological features in their diversity, at a global planetary scale. As examples, tropical and equatorial landforms have been identified, as well as possible glaciers active just a few thousand years ago: They likely trace the chaotic evolution of the planet obliquity.
4. The north and south polar layered deposits consist of nearly pure water ice, as deduced from the MARSIS radar data. Unique maps of H₂O ice and CO₂ ice in the polar regions have been produced by OMEGA: The CO₂ southern ices constitute a very thin veneer on top of a massive water ice glacier. Subsurface polar icy layers have also been tentatively identified by MARSIS.
5. The combination of digital terrain models with HRSC coverage at high resolution (better than 20 m/pixel) indicates very young ages for volcanic processes, which may have persisted until recent times, a few million years typically. They could still be active near the North Pole: Mars is just reaching its geological death.
6. The Analyzer of Space Plasma and Energetic Atoms (ASPERA) has found that the solar wind is slowly stripping off the high atmosphere down to 270-km altitude and has measured the current rate of atmospheric escape of planetary ion, which happens to be relatively low and occurs in bursts. The composition of the escaping plasma has been precisely measured.
7. SPICAM has enabled to build ozone and water vapor maps at a planetary scale, over all seasons, monitoring their respective

formation and evolution, essentially anti-correlated. Auroras have also been revealed by SPICAM, over midlatitude regions. They are produced by the precipitation of electrons, measured by ASPERA above regions with crustal paleomagnetic field. SPICAM has also detected airglows in the Martian nightside.

8. A transient ionospheric layer, due to meteors burning in the atmosphere, has been identified by radio occultation.
9. Phobos, the largest Mars moon (27 km large), has been intensively observed, by all instruments, during a few close flybys, down distances less than 100 km, never achieved before. It led to refined measures of its size, mass, density, interior and surface structure, and surface composition, with in particular no features associated with neither hydrated nor carbonaceous constituents.
10. Very-high-altitude (up to 80 km) mesospheric CO₂ ice clouds have been detected and characterized in the equatorial region of Mars. This discovery enlightens the processes responsible for the cloud formation at Mars and around Earth, as well as for the sustenance of surface liquid water during the early Mars history.

Although limited in cost and ambition, and started with the failure Beagle 2, the Mars Express mission has fundamentally contributed to the understanding of the processes which drove the evolution of Mars, all along its history.

It has launched ESA as a major actor of planetary space exploration.

Cross-References

- [CO₂ Ice Cap \(Mars\)](#)
- [CO₂ Ice Clouds \(Mars\)](#)
- [Dust Devils](#)
- [Ice](#)
- [Mars](#)
- [Mars Stratigraphy](#)
- [MRO](#)
- [Polar Caps \(Mars\)](#)

Mars Global Surveyor

François Forget

Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, UMR 8539, Université Paris 6, Paris, France

Keywords

Mars · Nasa

Synonyms

[MGS](#)

Definition

Mars Global Surveyor was a ► [NASA](#) orbiter that mapped and monitored planet ► [Mars](#) with five scientific instruments between its arrival at Mars on September 11, 1997, and November 2006. Mars Global Surveyor was the first fully successful mission around Mars since the ► [Viking](#) missions in 1976. It revolutionized our understanding of the red planet and ushered in a new era of Mars exploration.

History

After the very successful Viking missions launched in 1976, it took more than 16 years for NASA to select, design, and launch a new orbital mission to Mars: Mars Observer. It carried an ambitious scientific payload with seven instruments. Unfortunately, contact was lost 3 days before orbit insertion on August 21, 1993, due to an unknown failure of the spacecraft. The smaller Mars Global Surveyor project was then initiated on the ashes of Mars Observer, with the objectives of using spare models or copies of five of its experiments.

Overview

Mars Global Surveyor (MGS) was a 1060 kg (full mass at launch) spacecraft launched on November

7, 1996 and inserted into Mars Orbit on September 11, 1997. By March 9, 1999, MGS had slowly circularized through aerobraking to a Sun-synchronous, near-polar orbit with an average altitude of 378 km, mapping Mars at solar local time close to 2 am–2 pm (Albee et al. 2001). It operated until a battery failure in November 2007.

Its payload included five instruments that revolutionized our understanding of Mars's geophysics and climatology, and provided many reference datasets on the red planet. By helping scientists understand the nature of water reservoir and Mars, and the ancient Mars's possibly "wet" environment, many of their findings are of interest to exobiology. Mars Global Surveyor experiments were as follows:

- The *Mars Orbiter Laser Altimeter* (MOLA), which created the most accurate global topographic map of any planet in the solar system, giving scientists elevation maps precise to within about 0.3 m in the vertical dimension with a global resolution of typically less than 2 km (Smith et al. 2001). The topography and geodesy data identified pathways for the flow of past water and the locations, sizes, and volumes of water flows and reservoirs like the polar caps. The Laser altimeter was also used to detect ► [CO₂ ice clouds](#) in the polar night and monitor the amount and distribution of condensed carbon dioxide. In June 2001, part of the laser reached the end of its life, but a sensor continued to detect changes in surface brightness in the near infrared part of the spectrum.
- The *Mars Orbiter Camera* (MOC) science investigation used three instruments: a narrow angle camera that obtained grayscale (black-and-white) high-resolution images (long strip 3 km wide with typically 1.5–12 m per pixel), a red-and-blue wide angle camera for context (240 m per pixel) and a daily global imager (7.5 km per pixel). MOC operated in Mars orbit between September 1997 and November 2006. It returned more than 240,000 images. The high-resolution images allowed numerous key discoveries on Mars geomorphology (Malin and Edgett 2001), including the presence of numerous layered deposits (Malin and Edgett 2000b) and even deltas, which appears to have been formed in liquid water environment (Malin and Edgett 2003); the presence of ► [gullies](#) probably created by flowing water in geologically recent times (e.g., a few millions years ago) (Malin and Edgett 2000a).
- The *Thermal Emission Spectrometer* (TES) monitored the Martian surface and atmosphere using thermal infrared spectroscopy (from 6 to 50 μm with either 5 or 10 cm^{-1} resolution) together with a bolometric visible-NIR (0.3–2.9 μm) measurement. TES systematically monitored the Martian climate (retrieval of the atmospheric temperatures, dust loading, clouds, ► [polar caps](#), water vapor) from the beginning of the mission until a failure on August 31, 2004. It provided reference climatology (Smith 2004) and an unprecedented understanding of Mars meteorology. Surface monitoring allowed the mapping of the ground albedo and thermal inertia, and the retrieval of the abundance of several minerals (Christensen et al. 2001a). In particular, in specific locations, TES detected some crystalline ► [hematite](#), an iron oxide, whose formation often requires the presence of liquid water (Christensen et al. 2001b). Hematite was detected in ancient sedimentary regions on Mars, such as Meridiani, south of Arabia Terra. Meridiani was later the chosen site for in situ exploration by the Mars Exploration Rover Opportunity, which discovered an interesting terrain in which liquid water is thought to have played a key role.
- The *Magnetometer* combined with an electron spectrometer (MAG/ER) was designed to study the magnetic properties of Mars surface and its ionosphere (Acuña et al. 2001). It discovered that while Mars had no global ► [magnetic field](#) generated in the planet's core, significant fields could be detected in small, particular areas of the ► [crust](#) in the most ancient terrains on the planet. These are the vestigial signal of an ancient and once powerful magnetic field, capable of magnetizing the surface. This ancient field may have protected the early atmosphere from gas escape induced

by the solar wind, and contributed to the ancient Mars habitability.

- The *Radio Science Investigations* (RSI) used measurements of the Doppler shift of radio signals sent back to the Earth to determine a model of the Mars gravity field. The analysis of the signal passing through the atmosphere allowed the monitoring of the density and temperature of the lower atmosphere and of the ionosphere properties.

Cross-References

- [CO₂ Ice Clouds \(Mars\)](#)
- [Gullies](#)
- [Habitability of the Solar System](#)
- [Hematite](#)
- [Magnetic Field](#)
- [Mars](#)
- [Mars Exploration Rovers](#)
- [Polar Caps \(Mars\)](#)
- [Viking](#)

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Mars Odyssey

Frances Westall

Centre de Biophysique Moléculaire, CNRS, Rue Charles Sadron, Orléans, France

Keywords

Mars · NASA · Orbital measurements · Water

Definition

2001 Mars Odyssey, a name inspired by the works of the science fiction writer A.C. Clarke, is a ► [NASA](#) orbiter that was launched in 2001 to study the surface of ► [Mars](#) from orbit.

Overview

Mars Odyssey is still active and holds the record as the longest lived spacecraft in Martian exploration. Launched on 7 April 2001, the orbiter's instruments continue to contribute significantly to our understanding of Mars. The science objectives of the mission are wide ranging, but the theme “follow the water” is of particular importance. Other objectives include analysis of the surface elemental and mineralogical composition of the planet, indications of geological processes, such as volcanic activity, and measurement of the radiation environment in preparation for human exploration. These objectives were accomplished using the instruments THEMIS (The Thermal Emission Imaging System), the GRS (Gamma Ray Spectrometer-Neutron spectrometer), and MARIE (the Mars Radiation Environment Experiment). Mars Odyssey also serves as an important relay for the continuing ground-based rovers,

Spirit and Opportunity, the Mars Exploration Rovers (MERs).

The mission has been very successful. In particular subsurface water ice was detected in the form of elemental hydrogen in the near subsurface (below a few centimeters of dry sediments) in both hemispheres above about 60 latitude by the GRS instrument. Other areas of hydrogen concentration, for example, Arabia Terra, are most likely related to the presence of hydrated minerals or possibly to subsurface ice. Geomorphological evidence for the presence of water in the past (and possibly in more recent times) was revealed by the infrared camera THEMIS, which takes images during the day and at night, thus documenting subtle differences in the terrain that help distinguish features, such as channels features cut by water and melted snow, as well as sediments deposited by water. The detection of water ice is important for assessing water resources for future human exploration.

THEMIS has also mapped mineralogical variation in the surface composition of Mars and its results are pivotal to helping chose landing sites for the various Mars missions, Mars Exploration Rovers, Phoenix, Mars Science Laboratory in Gale Crater, Mars 2020 in Jezero Crater, as well as the European/Russian ExoMars 2022 mission that will land in Oxia Planum. Evidence for rocks with a felsic (i.e., rich in feldspath minerals) composition, as well as olivine-rich rocks, were detected, documenting the wide variety of rock types on the surface of the planet. The former represent evolved lavas and indicate a complex volcanic history for the planet. The latter, on the other hand, indicate little alteration of the original basalts during much of Mars' history. The THEMIS instrument was also designed to detect "hot spots" on Mars, which may correspond to local geothermal or hydrothermal activities. This research – of high interest with regard to the possibility of life in the near Martian subsurface – has been unsuccessful. Such spots may not exist or be very rare.

Measurement of galactic cosmic rays and solar energy particles by the instrument MARIE is important for determining the radiation environment to prepare human exploration.

Given its longevity, Mars Odyssey is turning its instruments on the moons of Mars, Phobos, and

Deimos, documenting changes in the physical properties of the Moons that will be useful for moon missions like the Japanese Martian Moons eXploration (MMX).

Finally, Mars Odyssey serves as an important relay center to transmit instructions to, and information from, vehicles on the surface of Mars.

Cross-References

- [Mars](#)
- [Mars Analogue Sites](#)
- [Mars Express](#)
- [Mars Global Surveyor](#)
- [Mars Pathfinder](#)
- [Mars Reconnaissance Orbiter](#)
- [Mars Sample Return Mission](#)
- [Mars Science Laboratory](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)
- [MMX](#)

M

Mars Orbiter Mission

Michel Viso¹ and Olivier Witasse²

¹Innovaxiom, Paris, CX, France

²European Space Agency, Noordwijk, The Netherlands

Synonyms

[Mangalayaan](#)

Abbreviation

MOM Mars Orbiter Mission

Definition

Mars Orbiter Mission (MOM) is India's first mission to Mars. It was approved for a total project cost of \$69 million in 2012 (actually \$74 million). It is, to date, the world's least-expensive Martian

mission. It was launched by a Polar Satellite Launch Vehicle (PSLV) on November 5, 2013, and inserted into Mars orbit on September 24, 2014 (Negi et al. 2020). The mission orbit is a wide ellipse (372 km x 70,000 km), inclined of 150° , with an orbital period of 65 h.

The small satellite, roughly a cube with of 1.50 m side, with a dry mass of 435 kg (Launch mass 1335 kg) has a power of 840 W provided by three solar panel energy generators (1.40×1.80 m).

It carries a science payload weighting 13.4 kg which includes five instruments (Kumar and Chauhan 2014).

- MCC: Mars Color Camera Mars Color Camera (MCC) operates in visible range from 0.4 to

$0.7 \mu\text{m}$ and uses a classical RGB Bayer pattern and has 16 modes of exposure to image the surface of Mars.

- TIS: Thermal Infrared Imaging Spectrometer. It can be operated day and night and it is mapping the mineralogy of the surface and monitor the concentration of CO_2 .
- MSM: Methane Sensor for Mars is a spectrometer analyzing the reflected sun light. After the orbit insertion, it appeared that because of a technical flaw the instrument is unable to measure methane concentration. It is now used to perform an albedo mapping.
- MENCA: Mars Exospheric Neutral Composition Analyzer: this quadrupole mass spectrometer is set to measure along the orbit, for four

Mars Orbiter Mission,

Fig. 1 Final integration of Mangalyaan on top of the fourth stage of PSLV25.



times an hour, the local neutral composition in a range from 1 amu to 300 amu.

- LAP: Lyman Alpha Photometer: this instrument is designed to determine the relative abundance of H and D in the upper atmosphere in order to evaluate the hydrogen and water escape in space.

The Mission is primarily a technological mission (Aruman and Satish 2015). Results include new data sets on exospheric composition, maps of the Phobos and Deimos moons, surface remote sensing, dust variability, and turbulence in the solar plasma.

Note that after approved registration the data from MOM are freely available for worldwide scientists at Indian Space Science Data Center.

Cross-References

► [Mars](#)

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Mars Pathfinder,

Fig. 1 *Sojourner* rover taking an APX-S measurement of the rock *Yogi*

Mars Pathfinder

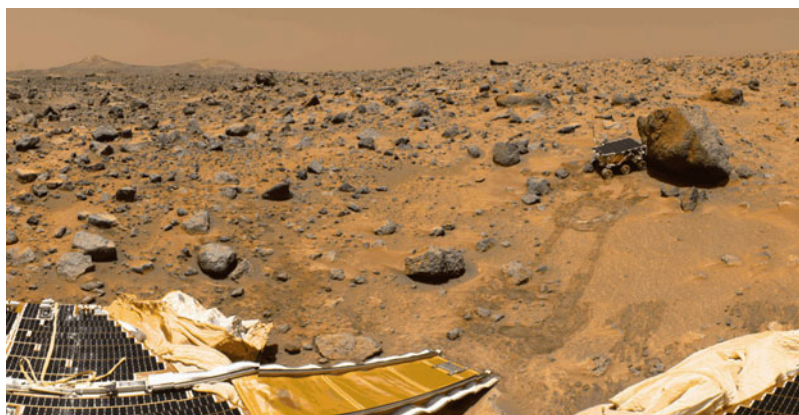
Claude D’Uston

Géophysique Planétaire & Plasmas Spatiaux, Institut de Recherche Astrophysique et Planétologique, Toulouse, France

Definition

Mars Pathfinder was the second discovery class mission of NASA. It was sent to planet ► [Mars](#) in order to demonstrate the capacity to deliver safely and to operate remotely robotic equipment on the surface of Mars. Launched on December 4, 1996, it had successfully landed on July 4, 1997, in an ► [outflow channel](#) called Ares Vallis (19.30°N, 33.52°W) and worked until the end of September 1997. It consisted of a lander equipped with a panoramic camera and a meteorology package, plus a small rover called Sojourner that carried another camera and the alpha, proton, and x-ray spectrometer APX (Fig. 1).

The fully successful mission provided many images of the landing site, and information on the diurnal variations of the meteorological conditions and on the composition of soils and of a few rocks; these were basaltic rocks covered by wind-blown dust. It was a precursor for the subsequent ► [Mars Exploration Rovers](#) SPIRIT and OPPORTUNITY.



Cross-References

- [Mars](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)
- [Outflow Channels](#)

Mars Reconnaissance Orbiter

Jean-Pierre Bibring
Institut d'Astrophysique Spatiale, Université
Paris Sud, Orsay, France

Keywords

Mars · NASA

Synonyms

[MRO](#)

Definition

Mars Reconnaissance Orbiter (MRO) is a ► [NASA](#) mission exploring ► [Mars](#) from a quasi-circular polar orbit, about 300 km in altitude. Launched on August 12, 2005, it arrived on March 10, 2006, and is still operating, at least till the mid-2020s, much beyond its designed duration of two terrestrial years. Its prime goals are to perform high-resolution observations of the surface, the atmosphere, and the subsurface, as well as to characterize landing sites of in situ missions.

Overview

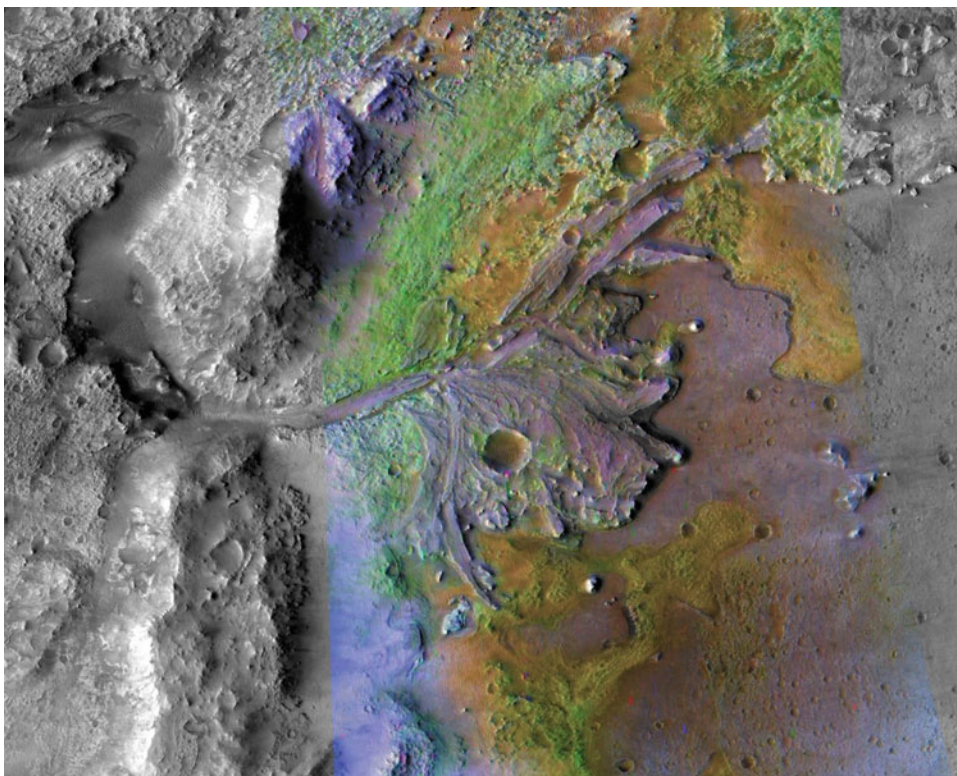
Mars Reconnaissance Orbiter (MRO) embarks six instruments and is capable to transmit to Earth ten times more data than previous missions. In particular, it enables to image the surface with unprecedented resolution (Fig. 1), both in the visible (20 cm footprint) and in the near infrared (20 m). It plays a unique role in deciphering the evolution of Mars, at all timescales.

MRO has been given the five following science objectives:

1. Characterize the present climate of Mars and its physical mechanisms of seasonal and interannual climate change.
2. Determine the nature of complex layered terrain on Mars and identify water-related landforms.
3. Search for sites showing evidence of aqueous and/or hydrothermal activity.
4. Identify and characterize sites with the highest potential for landed science and sample return by future Mars missions.
5. Return scientific data from Mars landed craft during a relay phase.

Six instruments were selected to achieve its goals and objectives:

- HIRISE (High-Resolution Imaging Science Experiment), a camera with unprecedented resolving capability: the pixel size can be as low as 20 cm, some six times better than the MOC camera on the NASA/MGS mission. When the mission will end, several percents of Mars surface will be covered.
- CTX (Context Camera), a wide-angle camera providing the optical context of the other instruments, in images 40 km in size, with a footprint of 8 m/pixel.
- MARCI (Mars Color Imager) produces each day a global image of Mars in five colors, to track changes in Martian weather (► [clouds](#) and atmospheric constituents). It monitors Mars atmosphere on diurnal, seasonal, and annual timescales.
- CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) is an hyperspectral imager: in each pixel, some 20 m in size, CRISM acquires the entire spectrum, in hundreds of contiguous spectral channels covering the visible and near-infrared range (from 0.4 to 4 μm). This enables to identify both surface (ices and frosts, as well as minerals) and atmospheric (gas, clouds, and aerosols) constituents. Its spatial resolution is one order of magnitude better than that of the OMEGA



Mars Reconnaissance Orbiter, Fig. 1 Jezero Crater, the Perseverance Landing site, in an image overprinting the findings of different MRO instruments. (Image Credit: NASA/JPL-Caltech/MSSS/JHU-APL)

M

instrument on the ESA/► [Mars Express](#) mission. The counterpart is that each image is less than 10 km large: a few percents of the global Mars surface should be mapped by CRISM in this high-resolution mode.

- SHARAD (Shallow Subsurface Radar) is designed to search for potential water (liquid or ice) down some hundreds of meters below the surface, using electromagnetic waves at ~ 20 MHz. Coupled to potential discoveries made by the MARSIS instrument on ESA/► [Mars Express](#), capable of penetrating some kilometers with a reduced vertical resolution, SHARAD would finely characterize shallower aqueous layers with a tenfold better accuracy, of ~ 10 – 20 m.
- MCS (Mars Climate Sounder) is a ► [spectrometer](#), primarily operating in the thermal infrared (12 – 50 μm), designed to quantify the global water vapor and dust content of the atmosphere, as well as its temperature. When pointing at the limb, its vertical resolution is ~ 5 km. Its diurnal maps enable a global monitoring of Mars atmospheric evolution.
- Finally, the fine monitoring of the spacecraft orbit provides an investigation of Mars' gravity, as a means to sound local variations of, for example, crustal or polar cap thickness.

Together with Mars Express, MRO is building one of the most impressive Mars dataset ever acquired, enabling a profound revisiting of Mars History at all timescales, from its ancient times to its recent evolution. Noticeably, it has played an essential role in the high-resolution characterization of the surface composition, with an emphasis on the compounds possibly recording astrobiologically related processes. As such, it contributed as the prime source of evidences to the selection of the recent NASA roving mission, Curiosity at Gale Crater and Perseverance at Jezero crater.

In addition to performing essential remote observations of Mars, MRO is one of the relay assets of in situ missions, necessary for transferring data from and toward Earth.

Cross-References

- [Mars](#)
- [Mars Express](#)

Mars Sample Return Mission

Michel Viso¹ and Denis J. P. Moura²

¹Innovaxiom, Paris, CX, France

²Centre national d'études spatiales, Toulouse, France

Keywords

Exobiology · Astrobiology · Mars · Mission design · Sample return · System architecture · Planetary protection · Quarantine

Acronyms

MSR

Definition

The Mars Sample Return (MSR) mission aims to retrieve soil, rock, and atmospheric samples from Mars to bring them to Earth to study them thoroughly in Earthian laboratories. MSR will be a key milestone in the exploration of ► [Mars](#) and the resolution of key questions in astrobiology and planetology.

The ambitious scientific objectives, the ► [planetary protection](#) issues, and the overall technical complexity of the program put a huge challenge on the design, development, and operations of this project which requires several successive space missions and significant ground infrastructures.

After several years of cooperation on the definition of a reference architecture proposed by an international working group, a joint letter of intent was signed in 2018 between NASA and ESA to set up a suite of missions to deliver Martian samples on Earth by the 30s.

History

Retrieving sample from Mars is a long-lasting dream of planetologists and astrobiologists. NASA organized workshops as early than 1973, before the landing of the Viking spacecrafts. In the United States the National Research Council issued several reports on the handling of the samples as they arrive on Earth (National Research Council [1997](#), [2002](#)). At the end of the years 1990, NASA and CNES began preliminary discussions to develop a cooperative project named “MARS PREMIER” in France. After several joint preliminary studies, the project was considered as too difficult, risky, and expensive, and therefore it was abandoned in the early years 2000. But the conceptual development of the handling of the Martian samples led to the development of what is known as the “Draft Test Protocol” ([2002](#)). In the same time frame, several space agencies, gathered in the International Mars Exploration Working Group (IMEWG), agreed to set up a dedicated working group to study an International Mars Architecture for the Return of Samples (known as iMARS). A first report was issued in July 2008 (iMARS [2008](#)). Later it serves as a base of a second working group (iMARS2) which was chartered in 2014 with two panels devoted, respectively, to engineering on the one hand and science and earth operations on the other hand. The group issued a detailed report in 2018 (Haltigin et al. [2018](#)).

At the same time, several groups issued recommendations about the science objectives (Mars Science Planning Group- Beaty et al. [2019](#)) the handling of extraterrestrial samples (Eurocares) (Smith et al. [2021](#)), and the safety measures to take in order to comply with the planetary protection recommendations through the COSPAR planetary protection panel. All this work led to the agreement between NASA and ESA to plan

and organize a joint Mars sample mission beginning as early as 2020 with the launch of Mars 2020 and its rover named Perseverance.

Overview

Based on the former studies the mission is rather complex and challenging with a lot of interfaces between instruments and hardware developed in different countries and operations split also between various centers either in the United States and Europe.

Scientific Objectives

The more Mars is known, the more the planet is attracting planetologists and astrobiologists. The physical and geological properties of the planet are now quite well documented; thanks to several successful space missions. The former discoveries lead to questions that have to be answered by the exploration of selected Martian sites and the in-depth study of the geological record to answer the following main items:

- Has life ever arose on Mars?
- What are the processes and history of climate on Mars?
- How to determine the evolution of the surface and the interior of Mars?
- How to prepare for the future Human exploration of Mars?

To collect relevant information on these issues, a Mars Sample Return (MSR) program will offer the opportunity to answer to these items. Indeed, returning carefully selected and documented samples, for analysis in terrestrial laboratories, provides three fundamental advantages:

- Complex preparation of the samples for these analyses is feasible.
- A wide variety of instruments can be used including very large and powerful facilities.
- Adaptation of the studies to the discoveries

The selection of the returned samples is fundamental for the value of the returned samples.

These requirements impact severely the selection of the landing site, the sampling itself, the sample, and the sample preservation.

Program Layout

Based on the report of the working groups mentioned earlier and the joint work of the agency centers, a reference design was selected (Fig. 1).

The program includes at least three launches from the Earth and one launch from the surface of Mars.

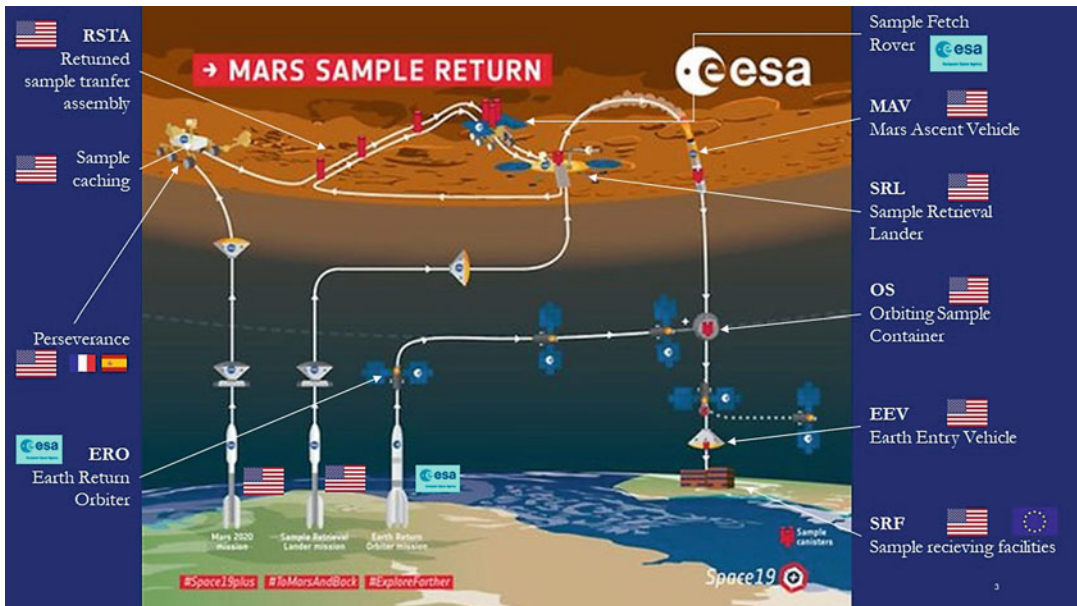
The first launch occurred on July 28, 2020, with the launch of Mars 2020 which led to the successful landing of the rover Perseverance at the surface of Mars (February 18, 2021) in the Jezero Crater.

The rover built by the JPL explores an ancient delta and have begun to collect samples (Fig. 2) encased in the RSTA. In the current version of the program, these RSTA will be dropped in different places to be collected further.

Later, a US rocket will launch the SRL with a MAV and the European SFR.

The SFR will collect the RSTA to bring them to the SRL. They will be placed in the OS which will be safely closed when the task will be completed. Note that Perseverance can collect 41 samples but that in the present configuration the OS can retrieve only 33 RSTA. The OS will be placed on top of the MAV. The MAV will be launched to put the OS (roughly the size of a basketball ball) on an appropriate Martian Orbit.

About the same time of the launch of the SRL, Europe will launch ERO to Mars to be placed in orbit. ERO will be tasked after the launch of the MAV to optically identify the OS, and to set up a rendezvous. A US built system will then capture the OS. Then this system will do operations necessary to condition this container, to place it in the EEV and to certify that it is finally tightly sealed in the EEV. At the appropriate orbital window, ERO will fire its engine to come back toward the Earth. In the vicinity of the planet, the tightness of the conditioned OS will be finally checked. The EEV will be released from ERO for a direct Earth atmospheric entry and a hard landing (planned in the Utah Test and Training Range). ERO will be



Mars Sample Return Mission, Fig. 1 Overview of the MSR program agreed between NASA and ESA. Elements shown on this diagram are abbreviated throughout this entry: *RSTA* Returned Sample Transfer Assembly, *SRL* Sample Retrieval Lander, *SFR* Sample Fetch Rover, *MAV*

Mars Ascent Vehicle, *OS* Orbiting Sample container, *ERO* Earth Return Orbiter, *EEV* Earth Entry Vehicle, *SRF* Sample Receiving Facilities. (From ESA documentation and additions from the author)

directed in a trajectory avoiding any collision with the Earth and put in a Sun centered orbit.

The story of the Martian samples on Earth will then begin under the constraints recommended by the Planetary Protection Panel of COSPAR and other dedicated scientific and institutional bodies.

Planetary Protection and Contamination Control Issues

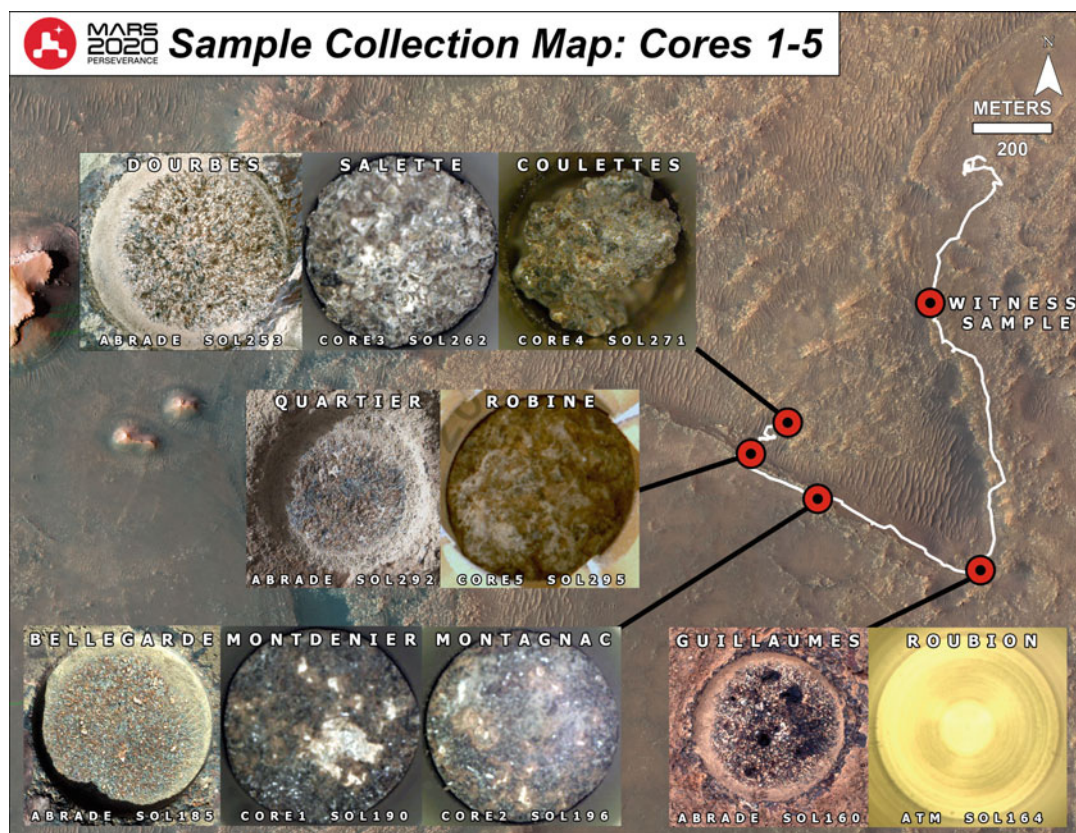
The MSR mission is facing numerous challenges in ► [planetary protection](#) (PP): (1) for protecting Mars from the possible development of viable Earth organisms; (2) for protecting Earth from potentially bio-hazardous Martian material; and (3) for preventing false-positive identification of material thought to be Mars organisms in the returned samples (but actually originating from Earth), which will affect seriously the science and PP policy in the future.

The last challenge needs to control organic and inorganic contaminants in the returned sample, in some cases to levels as low as the part-per-billion range. Both science and PP require sterilization and/or thorough cleaning of any hardware that

comes in contact with the samples and subsequent isolation from dirtier parts of the spacecraft to avoid recontamination. Both also benefit from inventory of materials and organisms on the spacecrafts before leaving Earth as an additional mean of preventing false-positives for life detection and ambiguity in science observations.

Preventing contamination of Mars by Earth organisms associated with landed spacecraft requires reduction of the ► [bioburden](#) on surface materials by cleaning, and containment or ► [sterilization](#) of internal materials. Elements expected to crash on the surface (the lander cruise, entry, and descent systems) must further reduce the bio-loads of internal hardware, since containment cannot be assured, and/or demonstrate sufficient sterilization by atmospheric entry heating.

Preventing contamination of Earth by potentially bio-hazardous Martian material requires highly reliable sample containment and ultra-safe entry and landing at Earth, as well as breaking the chain-of-contact with Mars in a way that precludes release of Mars organisms outside of sample containment.



Mars Sample Return Mission, Fig. 2 December 28, 2021, the rover Perseverance filled already 6 RSTAs. Before the coring the drill abrade few millimeters of the surface in the close vicinity of the place to be drilled and a photo taken by the camera WATSON (ABRADE). Then

after the coring a photo of the visible surface of the sample is taken by the camera CacheCam before the closure of the tube (CORE#) including the name of the sampled place and underlined with the mission sol number of the sampling. (Credit: NASA/JPL-Caltech/ASU/MSSS)

Future Directions

MSR began, actually, with the launch of Perseverance. The dream of planetologists and astrobiologists is now a perspective. Analysis is still ongoing to optimize the mission. For instance, based on the heritage of the precise landing of former NASA rovers, the MAV and SFR could be launched separately. On Earth international committees and institutions organize the arrival of the samples and prepare the plans to identify the samples, store as pristine samples a significant portion for the future generations, split the remaining portion either for life detection or bio-hazard testing under quarantine conditions and a portion for subsequent analysis in regular laboratories after the quarantine or sterilization.

The participating and associate organizations are developing consequent efforts of R&T to

welcome, store, and analyze those precious samples in the respective receiving and curation facilities in the USA and in Europe.

Cross-References

- [ExoMars](#)
- [Mars](#)
- [Mars Science Laboratory](#)
- [Planetary Protection](#)

References and Further Reading

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Mars Science Laboratory

Ashwin R. Vasavada
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Synonyms

Curiosity; Curiosity rover

Definition

Mars Science Laboratory (MSL) is a NASA mission that delivered a rover to Mars designed to

quantitatively assess past and present habitable environments within the rover’s field area. The mission’s habitability investigation is part of the overall strategy of NASA’s Mars Exploration Program to understand whether life ever was present. After a decade of development, the mission launched on November 26, 2011, and the Curiosity rover touched down at Gale crater on August 6, 2012.

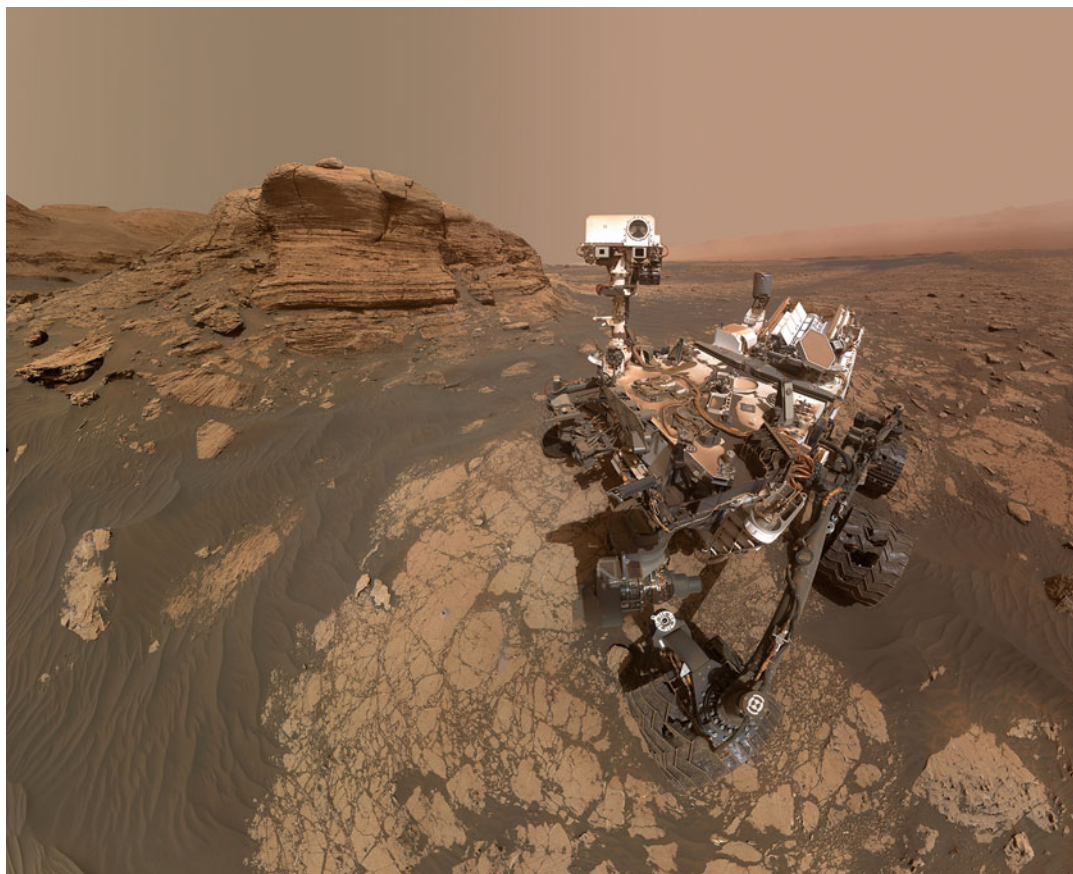
Overview

The MSL Curiosity rover (Fig. 1) was designed to be a virtual field geologist and mobile geochemical laboratory with objectives of deciphering geological history and processes, exploring major climate transitions recorded in the rock record, determining the chemical and mineralogical compositions of surface materials, including an inventory of organic molecules, assessing energy sources that could sustain biological processes, and identifying the subset of habitable environments also capable of preserving organic molecules. Additional objectives include characterizing the modern meteorological and radiation environment, and measuring the stable isotopic and noble gas compositions of the present-day atmosphere and of volatiles released from solid samples.

These science objectives are accomplished using a payload (Grotzinger et al. 2012) consisting of science cameras and a laser-induced breakdown spectrometer mounted on the rover’s mast; a camera and alpha-particle X-ray spectrometer mounted on the rover’s arm; an X-ray diffractometer and mass spectrometer, gas chromatograph, and tunable laser spectrometer suite carried within the rover chassis, an active neutron spectrometer, meteorology station, high-energy radiation detector, and descent/surface imager. Solid samples are scooped or drilled from the surface, processed, and delivered to the onboard laboratories using a sampling system on the rover’s arm (Anderson et al. 2012). A radioisotope power system and batteries provide energy.

Gale crater was selected as Curiosity’s field area because orbiter-based investigations suggested that the crater’s plains and central mound

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).



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Mars Science Laboratory, Fig. 1 Self-portrait of Curiosity on sol (mission day) 3070 in front of a 6-m outcrop called “Mont Mercou.” The mosaic is made from 60 images

taken by rover’s arm-mounted camera. (Image credit: NASA/JPL-Caltech/MSSS)

(Fig. 2) hold a diverse record of potentially habitable environments dating from the early Hesperian (Grotzinger et al. 2012; Golombek et al. 2012). The layered central mound (Aeolis Mons, or informally Mount Sharp) was interpreted as flat-lying sedimentary rock with textural and mineralogical attributes that vary with relative age, including phyllosilicate and hydrated sulfate-bearing strata that suggest aqueous interaction (Milliken et al. 2010). Plains northwest of the mound (Aeolis Palus) offered a safe landing area with alluvial fan and other stratified deposits.

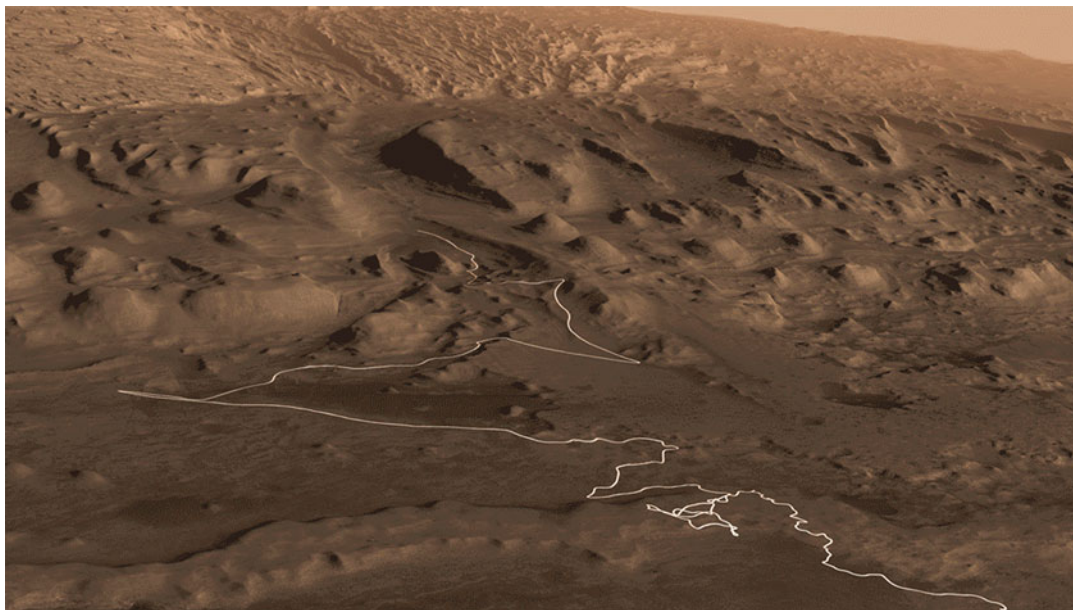
Exploration of hundreds of vertical meters of stratigraphy (Fig. 3) has revealed a succession of stream, delta, and lake depositional environments representing millions, perhaps tens of millions, of years (Grotzinger et al. 2015). Subsurface fluids

interacted with the sediments in multiple episodes after deposition, texturally and compositionally overprinting the rocks (Nachon et al. 2014; Krontyak et al. 2018; Sun et al. 2019; Achilles et al. 2020). Mast- and arm-based observations, as well as the analysis of dozens of drilled samples, show Aeolis Palus and Aeolis Mons to consist of dominantly clastic sedimentary rock composed of basaltic igneous minerals, secondary phases including hydrated phases, and X-ray amorphous materials (Rampe et al. 2020). Curiosity’s chemical and mineralogical results are consistent with surface and subsurface environments that remained within the ranges of temperature, pH, and salinity that could have supported life over much of the time that fluids were present (Grotzinger et al. 2014). A diversity



Mars Science Laboratory, Fig. 2 Panorama of Aeolis Mons (Mount Sharp) showing dark capping rocks (a) below active dark sands of the Bagnold dune field (b). Above the dune is a series of strata that include lacustrine

mudstones (c), additional planar capping units (d), rounded hills with evidence of sulfate minerals from orbiter data (e), and bright, anhydrous units (f) that form the top of the mountain. (Image credit: NASA/JPL-Caltech/MSSS)



Mars Science Laboratory, Fig. 3 Rendering of lower Aeolis Mons showing the rover's traverse path from 2017 onward, along with major geological and mineralogical units. As of July 2021, the rover has reached the transition

between the clay- and sulfate-bearing units. (Image credit: NASA/JPL-Caltech/ESA/University of Arizona/JHUAPL/MSSS/USGS Astrogeology Science Centers)

of organic molecules has been detected (<300 ppb; detections up to C₁₂ with evidence of higher molecular weights) in clay-bearing mudstones, in spite of the rocks' age and exposure to radiation (Freissinet et al. 2015; Eigenbrode et al. 2018). Igneous clasts and the mineralogy of some sedimentary samples argue for unexpectedly high magmatic diversity around Gale crater (Sautter et al. 2015; Treiman et al. 2016).

Curiosity has observed active sand transport in ripples, sand sheets, and dunes (Bridges and Ehlmann 2018; Lapotre and Rampe 2018). Analyses of atmospheric samples and water released from clay minerals indicate the preferential loss of light isotopes, consistent with atmospheric escape (Webster et al. 2013; Mahaffy et al. 2015). Atmospheric methane is found to vary diurnally and seasonally, indicating active production, likely from subsurface seepage (Webster et al. 2021). Meteorological observations over multiple Mars years have revealed the influence of the crater on wind, pressure, and atmospheric dust (Rafkin et al. 2016). Water ice clouds and hazes increase during the aphelion season, preceded by the appearance of noctilucent and iridescent high-altitude clouds. Curiosity had a unique surface vantage point for its measurements during the 2018 planet-encircling dust event (Guzewich et al. 2019). Measurements of high-energy radiation show the shielding effects of the atmosphere and topography, providing key inputs to radiation transport codes and constraints for future crewed exploration of Mars (Guo et al. 2021).

Cross-References

- [Crater Lakes \(Mars\)](#)
- [Habitability on Mars](#)
- [Mars](#)
- [Mars Stratigraphy](#)

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Mars Stratigraphy

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Keywords

Chronology · Sedimentary rocks

Definition

Stratigraphy, from Latin *stratum* (layer) and Greek *γραφειν* (to write, describe), is the description of all ► **rock** bodies forming the Earth's (or any rocky planetary body's) ► **crust** and their organization into distinctive, useful, mappable units based on their inherent properties or attributes, in order to establish their distribution and relationship in space and their succession in time, and to interpret geologic history (definition by the International Commission on Stratigraphy ICS, a scientific body within the International Union of Geological Sciences, IUGS). In a broader sense, stratigraphy is often equated with relative and absolute age determination.

Overview

The stratigraphic scheme for ► **Mars** was first outlined from photogeologic mapping of Mariner 9 data (Scott and Carr 1978) and was later refined on the basis of ► **Viking** orbiter image analysis (Tanaka 1986). It divides the history of Mars into three systems (of time-stratigraphic units) or periods (the chronologic equivalents of systems): ► **Noachian**, ► **Hesperian**, ► **Amazonian** (from lowest to highest or oldest to youngest), which are further subdivided into eight series or epochs. The Noachian System is subdivided into the Lower, Middle, and Upper Noachian Series, and the Noachian Period is subdivided into the Early, Middle, and Late Noachian Epochs, respectively. Similarly, the Hesperian is subdivided into the Lower and Upper Hesperian Series, or the Early and Late Hesperian Epochs. The Amazonian is subdivided into the Lower, Middle, and Upper Amazonian Series, or the Early, Middle, and Late Amazonian Epochs. Absolute model ages of the periods and epochs were determined on the basis of crater counting (Tanaka and Hartmann 2008; Michael 2013). Recent high-resolution images allow the establishment of detailed (but local) stratigraphic columns and mapping approaches similar to techniques used in sequence stratigraphy on Earth (Pondrelli et al. 2008).

Cross-References

- [Amazonian](#)
- [Chronostratigraphy](#)
- [Crust](#)
- [Hesperian](#)
- [Mars](#)
- [Noachian](#)
- [Rock](#)
- [Stratigraphy](#)
- [Viking](#)

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Mars, Delta

Barbara De Toffoli
German Aerospace Center, DLR, Berlin,
Germany

Keywords

Water availability · Sediment deposition · Habitability

Synonyms

[Delta deposit](#); [Delta fan](#); [Fluvial or river delta](#)

Definition

River deltas are landforms generated by deposition of fluid-carried sediments as the flow enters a slower-moving or stagnant water body. Deltas appear as fan-shaped and flat-topped deposits fed by a channel, but they may display diverse morphologies due to several factors including climate, geology, and drainage system characteristics. Well over a hundred deltas are present on Mars, mainly located close to the dichotomy boundary. These features can be indicators of past water availability and are favorable sedimentary settings for organic matter preservation. Accordingly, the Jezero crater delta has been targeted as a landing site for the Perseverance rover mission in 2021.

Overview

River deltas are landforms generated by deposition of the sediments carried by the river water as the flow enters a slower-moving or stagnant water body. When the flow enters the standing water, it is no longer con-fined to its channel and expands in width. This flow expansion results in a decrease in the flow velocity, which diminishes the ability of the flow to transport sediment. Deltas may display diverse morphologies due to several factors including climate, geology, river characteristics, basin bathymetry, and waves and tide regimes. The presence of ancient delta deposits on Mars has been thoroughly demonstrated for decades (Di Achille and Hynek 2010; Ori et al. 2000; Di Biase et al. 2013). Delta fans usually appear as fan-shaped deposits fed by a channel, characterized by either a stack of steep foresets (i.e., the sloping surface developing from the delta front due to progressive sediment deposition) of decreasing radius, or by a single steep foreset, either flat-topped or branched (De Villiers et al. 2009, 2013; Hauber et al. 2013). Deltas are distinguished from alluvial fans which differently appear gently sloping semiconical landforms associated with the discharge of water and sediments from a confined channel into an unconfined terrain characterized by the absence of a standing body of water (e.g., Moore and Howard

2005). As of today, around a hundred and sixty deltas have been identified on the Martian surface distributed on a large elevation range. Many deltas can be found in proximity of the dichotomy boundary (i.e., the boundary between the southern and the northern hemisphere of Mars characterized by a sharp elevation contrast that can be followed on a global scale), and a vast majority are located into craters or topographical depressions that could have acted as ponds/lake at the moment of the delta generation (De Toffoli et al. 2021; Wilson et al. 2021; Rivera-Hernández and Palucis 2019). Delta deposits are geological features highly relevant for astrobiology and the search for life and biosignatures on Mars due to their potential as indicators of past water availability, habitable environments, and as favorable sedimentary settings for organic matter preservation (Summons et al. 2010). In February 2021, the Perseverance rover landed in Jezero crater where an ancient river delta was detected from orbital images (e.g., Goudge et al. 2017; Mangold et al. 2020). The mission outcomes confirmed the deltaic nature of the geological formation and identified the hydrologic regime in place during sediment depositions, suggesting both a prolonged lake environment and later highly energetic paroxysmal fluvial flows (Mangold et al. 2021).

Cross-References

- Biosignature
- Crater Lakes (Mars)
- Dichotomy, Planetary
- Habitability on Mars
- Mars
- Valley Networks

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Mars, Erosion Rate

Giulia Alemanno

Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Definition

The geomorphology of a terrestrial planetary surface is characterized by erosional and depositional features. These features are produced by weathering and erosional processes. The erosion rate is the measure of the loss of soil mass over a specific time period. The study of the erosion rate of a planetary surface is a key to investigate the climatic conditions that have acted on that surface and to study its climatic evolution through time. The modification of the Martian landscape throughout erosional and depositional processes has been studied by several authors (e.g., Golombek and Bridges 2000; Kleinhans 2005; Golombek et al. 2006; Vigier et al. 2006). Estimation of erosion rates of Martian fluvial structures has been performed to study the history of water on Mars and in turn to estimate his paleo-climatic history (e.g., Hoke and Jordan 2010; Orofino et al. 2018).

Cross-References

- Mars
- Planetary Surface Ages

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Mars, Hydrated Minerals

Solmaz Adeli

Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Keywords

Alteration · Weathering · Liquid water · Early Mars · Mars climate · Sedimentary rocks

Synonyms

[Aqueous minerals](#)

Definition

Hydrated minerals are minerals that contain water or hydroxyl (OH) in their structures. They are the result of alteration and weathering processes due to surface liquid water and/or hydrothermal activities.

Overview

Hydrated minerals provide key information on Mars' past climate, climate change phase(s), and potential for habitability. Their widespread presence on the surface of Mars is an indicator of

water-bedrock interaction in a geologically long period of time. Some hydrated minerals contain bound H₂O in their structure, and others require OH. Some others can absorb water molecules and keep it in their structure. Therefore, hydrated minerals on Mars offer a wealth of information on the surface water inventory at the time of their formation and on the chemical and physical conditions of their surrounding area. The main group of hydrated minerals detected so far on Mars include phyllosilicates (e.g., kaolinite, smectite), sulfates (e.g., jarosite, kieserite, gypsum), carbonates (e.g., monohydrocalcite, artinite, hydromagnesite), ferric hydroxides (e.g., goethite, akaganéite, ferrihydrite), and other hydrated minerals (e.g., zeolite, opal). Carbonates may form in both anhydrous and hydrated conditions.

Hydrated minerals on Mars have already been detected in the spectroscopic data from Earth-based observations and early orbital instruments. Hydrated minerals such as carbonates, sulfates, phyllosilicates, and iron oxides have also been detected in Martian meteorites. More recent data (imagery and spectroscopic) from various orbiters, landers and rovers reveal a past history of liquid water activities on the Martian surface. Data from Pathfinder's Alpha Proton X-Ray Spectrometer (APXS) shows the presence of excess oxygen in form of OH or water bound in minerals. The Mars Exploration Rover (MER) Opportunity data indicates the presence of hydrated sulfates in Terra Meridiani. In Gale Crater, Mars Science Laboratory (MSL) rover data point to the presence of Gypsum (Ca-sulfate) as light-toned material filling veins in Yellowknife Bay. The Mars Express Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) infrared spectrometer and Mars Reconnaissance Orbiter's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) hyperspectral instrument have provided an extensive knowledge about the Martian surface mineralogy and the widespread distribution of various hydrated minerals. The global data shows that Mars's surface has underwent diverse and complex aqueous settings from clay-forming environments to the precipitation of evaporite minerals and to the presence of chloride and perchloride salt detected at the landers and

rovers landing site. These aqueous settings include standing bodies of water in impact craters, valley networks, outflow channels, ice-covered lakes, desiccating ponds, brines, seasonal ice/snow melt, and appearance of microscopic cryobrine on the current surface. Although hydrated minerals point clearly to a different climate during early history of the planet, it is yet unclear whether the early Mars climate was "warm and wet" or "cold and icy" with episodic warm phases. Further investigation on Early Mars mineralogy, and particularly on hydrated minerals, may hold the key to the question of Early Mars climatic conditions.

Cross-References

- [Carbonate on Mars](#)
- [Jarosite](#)
- [Mars](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)
- [Meridiani \(Mars\)](#)
- [Phyllosilicates, Extraterrestrial](#)
- [Sulfate Minerals](#)
- [Weathering](#)

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Mars, Paleo Ocean

Victor R. Baker

University of Arizona, Tucson, AZ, USA

Keywords

Mars · Ocean · Seas · Deltas

Synonyms

[Oceanus Borealis](#)

Definition

The word “ocean” derives from the Greek “okeanos” designating the great body of water that, at the time of the ancient Greeks, was believed to surround the entire landmass of the then-known world. The term subsequently came to designate the continuous body of salt water that covers approximately 71% of the surface of the planet, surrounding all the continents and containing about 97% of its surface water, while also acting as the critical reservoir for maintaining Earth’s global hydrological cycle. Where land encloses a body of surface water, smaller than an ocean, this is best termed a “sea.”

History

The idea of surface-water bodies on Mars has a very long history in human thought. However, it was not until the availability in the early 1970s of

orbital spacecraft imagery from the Mariner 9 Mission that attention became focused on the scientific significance of a great planetary dichotomy, separating heavily cratered southern and equatorial highlands from extensive northern lowlands, known as the Vastitas Borealis. By the mid-1980s, geological study of the relatively high-resolution Viking spacecraft imagery stimulated several scientific investigators to hypothesize that ancient inundations of water or mud had temporarily occupied the northern lowlands. An important observation was that of continuously traceable contacts involving topographic and/or albedo contrasts, interpreted by Parker et al. (1989, 1993) as being the shorelines of ancient seas that had formed within the Vastitas Borealis. It subsequently became clear that these seas could have constituted an Oceanus Borealis on ancient Mars that would have been a critical component for a global hydrological cycle (Baker et al. 1991), and that this paleohydrological cycle could explain the many other water-related geological features that were being discovered (Baker 1982, 2001). There followed a long period of controversy and discovery related to Oceanus Borealis, its geological history, and the implications of its presence or absence for the evolution of the planet.

Overview

Oceanus Borealis consisted of seas that, prior to about 3 billion years ago, episodically occupied Vastitas Borealis. It had at least two major phases and/or levels: Deuteronilus and Arabia (Parker and Bills 2021). Moreover, there is evidence, much degraded, for even older, higher-level seas.

The Deuteronilus phase is dated to the Hesperian time period, approximately 3.5 billion years ago. Its sea level near the Acidalia Planitia region of the northern plains is clearly expressed at about 3900 m below the mean planetary elevation, but it extends to both higher and lower elevations in other regions, mostly varying within a few hundred meters of the 3900-m level. Though the margins of the Deuteronilus Sea mostly lack morphologies indicative of wave-cut shorelines, this

can be explained because of the discovery of tsunami deposits that mantle the shoreline zones and were generated by bolide impacts into the Deuteronilus Sea (Rodriguez et al. 2016).

The Arabia Sea is older, thought to date from the Noachian time period about 4 billion years ago. The Arabia sea level is also several hundred meters higher than the Deuteronilus in the Acidalia Planitia region. However, Arabia sea levels can reach up to few thousand meters higher in other portions of the northern plains. That such immense deviations occur from what should necessarily be a uniform equipotential surface of an ocean would seem to pose a major difficulty for the Oceanus Borealis hypothesis. However, it has been found that true polar wander associated with the growth of Tharsis (Perron et al. 2007) and related tectonic deformations (Citron et al. 2018) can account for these observed deviations from an ancient equipotential surface.

The Deuteronilus Sea developed at a time when immense catastrophic flooding channels developed on Mars. Termed “outflow channels,” these features conveyed huge flows of water (megafloods) to the northern plains from the equatorial highlands, involving sources from either surface impoundments or subsurface aquifers. Sediment-charged megafloods entered the Deuteronilus Sea with such energy that their deposits were spread across the entire northern plains, constituting part of the Vastitas Borealis Formation. The Deuteronilus Sea could have held enough water to comprise a global equivalent layer 110 m deep when spread over the planetary surface (Carr and Head 2019). This value is broadly equivalent to amount of water that subsequently was lost to space, as interpreted from isotopic anomalies in the Martian atmosphere (Villanueva et al. 2015).

The Arabia Sea coincided with the extensive rainfall-induced fluvial dissection of the Martian highlands that produced widespread valley networks (Hynek et al. 2010) and associated crater lakes (Goudge et al. 2015). The valley networks and crater lakes comprise a belt that conforms to the margins of the ancient sea (Chan et al. 2018). Deltas formed along the margins of this belt

(Di Achille and Hynek 2010; Fawdon et al. 2018), and the entire system was subsequently tilted by the development of the Tharsis Bulge (Bouley et al. 2016).

The climatic system associated with Oceanus Borealis has proven difficult to reconcile with theoretical modeling (Turbet and Forget 2019), and this result has provided incentive to pose the hypothesis of a frozen northern plains ocean (Carr and Head 2019). Nevertheless, other model results indicate prevailing warm and wet conditions that are broadly consistent with the geological evidence (Ramirez et al. 2020).

That early Earth had an ocean, the existence of which coincided with the development of life, provides an incentive to pursue further understanding of Oceanus Borealis. This should occur with the 2023 Exo-Mars Mission, which will focus on Oxia Planum, an area situated on a margin of the Arabia Sea.

Cross-References

- [Aquifer \(Mars\)](#)
- [Hesperian](#)
- [Mars](#)
- [Mars, Delta](#)
- [Noachian](#)
- [Outflow Channels](#)
- [Tharsis](#)
- [Valley Networks](#)

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Mars, Paleoclimate

Vincenzo Orofino

Dipartimento di Matematica e Fisica “E. De Giorgi”, Università del Salento, Lecce, Italy

Keywords

Mars · Climate · Valley network · Volcanism · Greenhouse effect

Definition

The paleoclimate of Mars is the climate of the geological periods prior to the current era in which meteorological parameters such as temperature, atmospheric pressure, and wind speed (and direction) have been measured by the various landers that, since 1976, successfully operated on the surface of the planet. There are various indications that the Martian paleoclimate was very different from the current one, even if, due to the lack of a univocal description of the past conditions of the planet given by the paleoclimatic models, an alternative scenario, almost permanently cold and dry, has been also suggested.

Overview

Introduction

Mars is now a very cold planet with a global average annual temperature of 210 K (−63 °C) (Carr 2006). At the poles, in both hemispheres, mean diurnal temperatures are close to 150 K (−123 °C) (Carr 2006), while during summer in the southern hemisphere, they can reach 300 K (27 °C) (Carr 2006), reaching in exceptional cases up to 310 K (37 °C) (Martin 1991). Temperature falls, however, by 80 °C or more during the night, so that, even on the hottest days, its daily average values are considerably below zero centigrade.

These significant diurnal thermal variations are due to the lack of the balancing action carried out

on the Earth by the oceans and the atmosphere. The latter on Mars is made up almost exclusively of carbon dioxide, is very tenuous and exerts a pressure at the surface of less than 1/100 of that of the Earth. Also the partial pressure of the water vapor is far lower than the terrestrial one. This fact, combined with low temperatures, implies that water cannot exist in a liquid state on the Martian surface, as it solidifies and then sublimates very quickly (except at the poles where ice is relatively stable). Even rain and snow are in fact impossible. The only truly massive atmospheric events on Mars are the great dust storms, some of which affect the entire surface of the planet and have no equal on Earth (Carr 2006).

In conclusion, today Mars is extremely cold and dry by Earth standards. However, it is probable that the planet has not always been characterized by this frigid and hyperarid climate, but that in the past (around 4 billion years ago – Craddock and Howard 2002; Ramirez and Craddock 2018), the atmospheric pressure and the surface temperature were sufficiently high to allow the presence of surficial liquid water in the form of rivers, lakes, and possibly also oceans.

It is evident that this possibility would have very important astrobiological implications, since the presence of liquid water on a planet is commonly considered an essential factor for the origin and evolution of life on that body (Davis and McKay 1996; Nelson 2015). Also for this reason the study of the Martian paleoclimate is one of the most intriguing and debated issue in planetary science.

Basic Methodology

Observational Evidence

What the geological evidence clearly indicates is the presence on the Martian surface of many structures strongly suggesting fluvio-lacustrine processes. These structures include: layered deposits, alluvial fans and deltas, degraded and/or partially filled craters, putative ancient shorelines, and valley networks (see Ramirez and Craddock 2018 and references therein). The

latter are dendritic structures (recently mapped by Alemanno et al. 2018) whose morphology in most cases recalls similar terrestrial structures produced by precipitation (rain and snow), which – we have to remember – are currently impossible on Mars.

Due to this and other characteristics, valley networks are commonly considered the best evidence supporting paleoclimatic conditions substantially different from the current ones (e.g., Craddock and Howard 2002; Ramirez and Craddock 2018). Indeed, although ad hoc hypotheses have been suggested in the past to justify an origin of these structures in climatic conditions similar to the current ones (i.e., Gaidos and Marion, 2003), the hypothesis of a primitive atmosphere thick enough to allow, by means of a strong greenhouse effect, surface temperatures much higher than the current ones, seems to be able to provide a simple and unitary explanation of the origin not only of the valley networks but also of the aforementioned fluvio-lacustrine features associated with them.

The spectroscopic detection of clay deposits in many sites, where aqueous sedimentation very probably occurred, also strongly supports the notion of persistent water on ancient Mars (Bishop 2018; Ramirez and Craddock 2018), even if, according to Viennet et al. (2020), clay minerals are not always produced by aqueous alteration of preexisting silicates by surface water.

On the contrary, extensive carbonate deposits are lacking on the Martian surface (Christensen et al. 2001; Carr 2006) and this has often been cited by some authors (i.e., Christensen et al. 2001) as an evidence against a relatively warm and wet early Martian climate, since in principle, carbonates are expected to be very abundant on the surface of a planet with a CO₂-rich thick atmosphere (Carr 2006). However, more recent observations (Michalski and Niles 2010; Wray et al. 2016) have shown the widespread presence of carbonate-bearing rocks exposed from the subsurface by impact craters and troughs. According to Michalski and Niles (2010), these buried layered carbonates might be only a small part of a much more extensive ancient carbonate sedimentary record that has been buried by lava and/or airfall dust covering processes.

Key Research Findings

Results of the Paleoclimatic Models

These indications coming from geological and spectroscopic observations, substantially in support of an ancient Martian climate much less cold and dry than the present one, must be compared with those provided by paleoclimatic models. But unfortunately such models fail to give a univocal description of the past conditions of the planet.

Generally the traditional models, which assume an atmospheric composition not very dissimilar from the current one, i.e., of CO₂ and H₂O (see Wordsworth et al. 2013 and references therein), are not able to obtain surface temperatures high enough to allow fluvio-lacustrine activity. Actually, the maximum surface temperature achieved by such models for a 2 bar CO₂-H₂O atmosphere, fully saturated with water vapor, is ~250 K (Wordsworth et al. 2013), which is insufficient to support warm, wet conditions.

The only way to explain the geological/spectroscopic observations within such traditional models is to hypothesize that Mars was always cold and dry, but punctuated by short bursts of wetness, triggered by volcanism and/or meteorite impacts. In particular, according to Wordsworth et al. (2013), these two mechanisms would have caused episodic melting of glaciers located in the planet's highlands, causing the formation of the valley networks (this is the so-called “icy highlands scenario”). However, as suggested by Ramirez and Craddock (2018), these episodic warming mechanisms do not seem capable of producing the durations of warming and amounts of water necessary for the formation of the valleys and for the degradation of the ancient craters. In addition, according to the same authors, the icy highlands scenario is difficult to reconcile with a lack of evidence for widespread glaciations on the planet.

It is important to note that other “non-traditional” models have also been proposed which, under appropriate atmospheric conditions (pressure and composition) and/or surface conditions (albedo, thermal inertia), obtain global average temperatures close to zero centigrade (Mishna et al. 2013; Urata and Toon 2013; Godin et al. 2020; Kamada et al. 2020; Kite et al. 2021).

Among these models of particular interest is that of Kamada et al. (2020) which is based on an original idea of Ramirez et al. (2014) according to which the presence in the Martian atmosphere of traces of molecular hydrogen (H₂) would be able to produce an increase of the greenhouse effect due to CO₂ alone. This is because a hydrogen molecule (which is not a greenhouse gas), colliding with a carbon dioxide molecule, increases the absorption capacity in the infrared of the latter (measured by the so-called collision induced absorption cross section or CIA cross section), producing an additional heating of the atmosphere compared to the case of CO₂ alone.

The 3D model of Kamada et al. (2020) hypothesizes a planetary surface, with an ocean in the northern lowlands and some lakes in the southern highlands, below a CO₂-H₂O atmosphere with a certain additional percentage of H₂ of volcanic origin. In this partially saturated atmosphere, the water cycle is treated self-consistently by modeling the formation of H₂O clouds and their dissipation mainly due to precipitation. With this model, the Japanese team finds, for a 1.5 bar CO₂-H₂O atmosphere with 3% of H₂, an average annual temperature $T = 282$ K, while for the same atmospheric pressure and a percentage of 6% of H₂, they obtain $T = 294$ K.

To obtain these results, Kamada et al. (2020) use CIA cross sections for CO₂-H₂, theoretically derived by Wordsworth et al. (2017), which overestimate the absorption of radiation by CO₂ molecules compared to the experimental cross sections subsequently obtained by Godin et al. (2020). Consequently, the surface temperature for an atmosphere of 1.5 bar and 5% H₂ is approximately 12 K higher than that evaluated with the new CIA cross sections (Godin et al. 2020). By applying this correction to the above results, more accurate temperatures of 270 K and 282 K can be obtained in the case of a percentage respectively equal to 3% and 6% of H₂ in an atmosphere of 1.5 bar. These temperatures are easily able to support hydrological activity.

It should be noted that the values of atmospheric pressure and the percentage of H₂ that lead to this outcome appear to be consistent with the models of geological and physicochemical evolution of the

planet, in the light of what was discussed by Godin et al. (2020), about the atmospheric pressure, and by Deng et al. (2020), regarding the percentage of H_2 degassed by volcanic activity.

In conclusion, the results of this model and of all the nontraditional ones reported above suggest that around 4 billion years ago Mars was characterized by very different climatic conditions from the current ones. Compared to terrestrial standards they were, however, quite cold and also very dry, as suggested by various studies indicating an arid or semiarid Martian paleoclimate (e.g., Fukushi et al. 2019; Kamada et al. 2020). In other words, according to these scenarios, the past climatic conditions of Mars must have been similar (in terms of average temperature and precipitation) to those of the cold steppes of the Earth.

The duration of this period of mild climate experienced by Mars can be roughly estimated using as a reference the period of formation of the Martian valley networks, calculated as the difference between the age of last river activity of the oldest valley and that of the youngest valley listed by Fasset and Head (2008). The result is a mild period of 240 or 360 million years, according to the Neukum or Hartmann chronology, respectively. Obviously this is a conservative estimate, due to the relatively small number of valleys analyzed by Fasset and Head (2008). For comparison, the formation time of a single valley is of the order of tens of millions of years (Orofino et al. 2018).

This comparison suggests that the valleys were not all active at the same time. That is, in addition to the normal intermittence observed also on Earth in the individual valleys, on Mars the fluvial activity has affected the planet with a leopard spot distribution characterized by active areas that migrated on the surface as a result of roaming zones of precipitation (Hoke and Hynek 2009). It is also probable that some river systems experienced several successive episodes of water flow, interspersed with long periods of inactivity, as suggested, for example, by Jaumann et al. (2005) for an unnamed valley in the Lybia Montes region.

In any case, at some point, the declining volcanic activity was no longer able to compensate for the massive atmospheric losses measured by

the MAVEN mission (Jakosky et al. 2017). These losses, mainly due to the atmospheric sputtering by the solar wind, were caused by the disappearance of the magnetic field produced by the turning off of the planetary dynamo (Mangold et al. 2012). Therefore the planet has undergone a process of progressive cooling and drying up.

According to Rapin et al. (2021), the transition to the current frigid and hyperarid climate was not monotonic but instead it was characterized, at least locally (in the Gale crater), by a series of alternating wet and dry periods. Eventually, about 3 billion years ago, the planet stabilized in today's climatic conditions.

Future Directions

Future researches aimed to improve our knowledge on this subject should proceed in two directions: observation and modeling.

From the observational point of view, massive exposed carbonate deposits, which still escape detection, should be searched for.

On the other hand, the paleoclimate models should be improved carefully tuning the microphysics of the H_2O clouds, which are only approximately modeled. Furthermore low surface albedos, different from the present ones usually adopted in the models, should be also used to take into account the likely presence in the past of large sand-free areas composed of dark unweathered basalt (Mischna et al., 2013).

Finally, the presence of airborne dust should be included in some models, even if it is by no means certain that the dust, so important in the current paleoclimate, may have played an important role also in the ancient past of Mars.

Cross-References

- [Mars, Delta](#)
- [Mars, Hydrated Minerals](#)
- [Mars, Paleo Ocean](#)
- [Mars, Paleolakes](#)
- [Valley Networks](#)

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Mars, Paleolakes

Jules M. Goldspiel

Planetary Science Institute, Tucson, AZ, USA

George Mason University, Fairfax, VA, USA

Synonyms

[Ancient lakes](#)

Definition

A paleolake is a liquid water lake that existed in the past but no longer exists today. The existence of lakes in a previous geologic time period is known from the geologic features and geochemical signatures that are associated with the formation and maintenance of lakes. At sites of paleolakes, these features and signatures can be seen today long after the liquid water has disappeared from the surface. On Mars, there are many locations on the surface where evidence of past liquid water lakes is preserved. These locations are considered sites of Mars paleolakes. The Mars paleolakes date back to the early history of Mars, approximately 3–4 billion years ago.

History

There are numerous examples of geologic features on Mars that were created by the flow of liquid water across the surface. These geologic features include large outflow channels, small valley networks, deltas, inverted channels, conglomerates, and loose rounded gravel. These surface features seen today represent the work of liquid water flowing at different times in Mars past.

It is the small valley networks that supplied the liquid water to most of the Mars paleolakes. The direct source of the liquid water that flowed in these valleys is an area of active research. Two types of water sources are most frequently cited. These potential sources are precipitation (i.e., rain or snow) and groundwater discharge. Regardless of the source, any liquid water flowing on the

surface would have ponded, at least temporarily, in local areas of low elevation and thereby would have formed lakes.

The local topographic low points on Mars where liquid water collected and created lakes are most often ancient impact crater basins. Two of these impact craters are sites of detailed study by rover spacecraft: Gale Crater and Jezero Crater. Other paleolakes sites are not impact crater basins, but broad depressions in regions between impact craters. Most Mars paleolake sites are found at low latitudes between 30°N and 30°S, but some paleolake sites are seen at southern latitudes as high as 63°S (Goudge et al. 2012). In all cases the paleolake sites are in the oldest terrain on Mars (the ancient southern highlands). Because of the age of the Mars paleolakes and the likelihood of subsequent geologic activity, the paleolake sites in many cases may have been resurfaced since the site was a lake. The visible surface of the paleolake sites today may therefore not necessarily be the actual bed, or bottom surface, of the paleolake as it would have appeared right before the lake water was lost.

Even with the potential for resurfacing, Mars paleolakes and the geologic structures and materials they left behind are important sources of information for understanding the hydrologic and climatic history of Mars. Liquid water is generally not stable under the present environmental conditions at the surface of Mars. The small valley networks and other remnant fluvial features on the surface are therefore commonly taken as indications that the Mars paleoclimate was different from the climate of Mars today. The potential link between Mars paleoclimate and the small valley networks is intertwined with understanding the source of the water that flowed in the channels within the small valleys. Mars paleoclimate is an area of active research.

Depending on the climate of early Mars and the latitude of a given paleolake, the lake may have been an open water lake that was fully liquid, or it may have been an ice-covered lake in which liquid water existed under an ice cover that was a few meters thick (Kling et al. 2020). In either case, the paleolakes were sites where liquid water existed on the surface of Mars early in the history of the planet. The paleolake sites are therefore important

sites for astrobiological research, not just because of the singular importance of liquid water to life, but also because lake sediments not destroyed by resurfacing processes may preserve biological markers that can be used to test whether or not life ever developed on Mars.

Cross-References

- [Mars Science Laboratory](#)
- [Mars Stratigraphy](#)
- [Mars, Delta](#)
- [Mars, Paleoclimate](#)
- [Outflow Channels](#)
- [Valley Networks](#)

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Marsh

- [Palus, Paludes](#)

Martian Meteorites

- [SNC Meteorites](#)

Martian Moon Exploration

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Mars Phobos · Deimos · Sample return · Exploration

Synonyms

[MMX](#)

Definition

Mars Moon Exploration (MMX) is a planned Mission from the Japanese Exploration Agency (→ JAXA) to study, using a pseudo orbit the moons of → Mars, → Phobos and → Deimos. The mission aims at sampling the soil of Phobos and brings back these samples on Earth for future analysis. At launch the spacecraft will comprise three different modules (Kuramoto et al. 2022): the propulsion module, the exploration module, and the return module to bring the samples to Earth. For a launch in 2024, the spacecraft will stay in the Martian system for about 3 years performing close observations of Deimos and Phobos, delivering a rover on the surface of Phobos and sampling material and → regolith from that moon. Samples are supposed to arrive on Earth about 2029.

History

MMX is based on the heritage gained with the missions → Hayabusa 1 and 2. Hayabusa 1 launched in 2003, explored the asteroid → Itokawa from 2005 up to 2007 and bring sample to Earth in 2010. Hayabusa 2 was directed to the asteroid → Ryugu. Launched in 2014 it studied the asteroid from 2018 to 2019, delivering samples on Earth in December 2020. The MMX program is the continuation of the exploration, by Japanese probes, of small bodies of the solar system.

Overview

The overall objective of the mission is to understand the origin of the Martian moons (to summarize: asteroid capture or giant impact) and to explain the evolution of the habitable planets of the solar system. Phobos is presently the main target of the mission. JAXA issued a

wide list of science objectives: (i) constrain Phobos origin using in situ observations and returned sample analysis, (ii) constrain Deimos origin by remote sensing close up observations, (iii) from the samples to extract data about the transport of material between the space bodies, (iv) understand the formation process of Mars and the evolution of the Martian system including an in depth study of the impact history, (v) determine the possible presence of water in the regolith of the moons.

To achieve this large set of objectives, the science payload comprises seven instruments.

The Light Detection And Ranging altimeter LIDAR is working with a laser (1064 nm) measuring height between 100 m and 100 km. At 100 km the vertical resolution is 22 m and the swath is of 50 m. It will measure the surface morphology enlightening the geological history of the moons.

The TElescopic Nadir imager for GeOmOrphology (TENGOO) and the **Optical Radiometer composed of CHromatic Imagers** (OROCHI) are two instruments working together.

TENGOO is a telescopic camera based on a Cassegrain telescope, working in a portion of the visible wavelengths with a spatial resolution set at about 40 m at an altitude of 20 km. The high-resolution images will be used to select and to document the sampling site and detect freshly exposed surfaces (if any).

OROCHI is a wide angle multi-band imager to acquire spectral images from the Martian moon surfaces with a resolution varying with the altitude and set at 20 m for an altitude of 20 km, 10 cm for an area of $100 \times 100 \text{ m}^2$ around landing sites of the rover, 1 mm for an area of $1 \times 1 \text{ m}^2$ around sampling sites. The instrument is based on seven independent imagers equipped each with a filter (respective wavelengths: 390, 480, 550, 650, 700, 800, 950 nm) and a panchromatic camera (400–900 nm) to be used during the sampling phase. It includes also a light-emitting diode to perform measurement even in the shadow of the spacecraft during the sampling phases.

Both instruments will be dedicated to the identification of the mineral components of the

surfaces as well as the observation of water and dust circulation in the Martian climate system.

The MMX Infrared Spectrometer (MIRS) is provided by the French Space Agency ($\rightarrow$ CNES) and build by a consortium led by the “Laboratoire d’Etude Spatiale et d’Instrumentation en Astrophysique” (France) (Barucci et al. 2020), the spectrograph is working in the range of 0.9–3.6 μm (with a 10 μm spectral sampling). The spatial resolution will be better than 20 m at an altitude of 20 km.

The Mass Spectrum Analyzer (MSA) is an ion mass spectrometer to measure the ionic environment of Mars and its moons. It detects ion in the range 1–100 amu with a resolution ($M/\Delta M$) better than 100.

The Mars moons Exploration with GAMMA rays and NEutrons (MEGANE) instrument, developed in collaboration with NASA, analyzes gamma-rays in the range of 0.4–8 MeV, thermal (0.01–0.5 eV), epithermal (0.5–0.5 MeV) and fast (0.5–7 MeV) neutrons. These observations will detect the major elements of the surface and the content of the shallow regolith in hydrogen atoms.

The Circum Martian Dust Monitor (CMDM) is a dust counter which will measure the dust grains over 10–20 μm in size. The detection is performed through a set of four piezoelectric sensors on a layer of the Multi-Layer Insulator made of polyimide. The shock wave analysis will characterize the impacting grain (Kobayashi et al. 2019).

The MMX Rover, jointly provided by the German space agency ($\rightarrow$ DLR) and the French space agency (CNES) (Michel et al. 2022), is an autonomous four wheel vehicle of about 25 kg on Earth (Sedlmayr et al. 2020). This solar powered rover is equipped with a laser Raman spectrometer, a thermal radiometer, two navigation cameras to provide stereo images and two so call “wheel cameras.” It will be dropped from the mothership and will land passively.

The ultimate goal of MMX is to retrieve around 25 g of regolith from Phobos and bring them to Earth. To achieve this objective JAXA will use two sampling approach: a coring system (C-sampler) developed in house by JAXA and a pneumatic sampler (P-sampler) provided under

the auspices of → NASA. The C-sampler is mounted on the robotic arm and can sample up to 10 cm beneath the surface, the retrieved material is then translated at the appropriate container. The P-sampler, derived from the system used with → OSIRIS-Rex (Zacny et al. 2020), is based on a pneumatic circuit collecting the regolith. The C samples will give insight up to a certain depth of the moon composition as the P samples will give an insight on the surface material and its evolution.

The return will use a system similar to Hayabusa probes. The mission is categorized by → COSPAR as an Unrestricted Earth Return (Coustenis et al. 2021).

Cross-References

- CNES, France
- Deimos
- DLR, Germany
- JAXA
- Mars
- OSIRIS-Rex
- Phobos
- Regolith, Planetary
- Ryugu Asteroid

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Maser

Elizabeth Humphreys

ESO European Southern Observatory, Garching, Germany

Keywords

Active galactic nuclei · Comets · Evolved stars

Definition

An astrophysical maser (microwave amplification by stimulated emission of radiation) is a source of stimulated spectral ► [line emission](#). Maser emission is observed from circumstellar envelopes of evolved stars, ► [molecular clouds](#)/star-forming regions, active galactic nuclei, ► [supernova remnants](#), and comets and has been suggested for the Saturnian moons. It arises from molecules such as water (H₂O), hydroxyl radicals (OH), methanol (CH₃OH), formaldehyde (CH₂O), silicon monoxide (SiO), ammonia (NH₃), silicon sulfide (SiS), hydrogen cyanide (HCN), and atomic hydrogen recombination lines. Masers are compact, of high brightness temperature (see definition below), and often display narrow spectral line widths, polarized emission, and variability.

History

Astrophysical maser, or microwave laser, emission was first observed in the 1960s (Weaver et al. 1965). Initially, the nature of the emission

mechanism was not understood, and it was hypothesized that a new element, labeled “mysterium,” could be responsible. However, the spectral line was rapidly identified as a transition of the OH (hydroxyl) radical (Weinreb et al. 1965), and it was soon realized that the signal characteristics could be explained in terms of amplification by stimulated emission of radiation (e.g., Davies et al. 1967; Moran et al. 1968).

Overview

Astrophysical masers are regions of gas in which the amplification of radio or microwave radiation takes place. Maser amplification occurs at a wavelength corresponding to the energy difference between two energy states of a molecular/atomic species in the gas. In order for net stimulated emission to occur, a higher number of molecules must exist in the upper energy state than in the lower state. The populations of the levels are said to be *inverted*, and this is a prerequisite for maser action. The energy source that maintains the population inversion is known as the maser pump and can be radiative, collisional, or chemical in nature (or a combination of these processes). The radiation that stimulates maser action is amplified exponentially as a function of distance through the gas as long as the pump rate exceeds that of the maser stimulated emission rate. This is the *unsaturated* regime. As amplification continues, maser radiation may become sufficiently strong for the maser stimulated emission rate to rival that of the pump. The maser is then said to start to *saturate*, and amplification is linear as a function of distance through the source region. Maser radiation is partially coherent, highly beamed, and can display high degrees of polarization (Elitzur 1992; Gray 2011; Watson 2009; Dinh-v-Trung 2009).

Basic Methodology

Observationally, how is it possible to determine whether maser emission is being observed? One way is to measure the *brightness temperature* (the temperature of a black body in thermal

equilibrium which would produce the same intensity as that observed at the frequency of observation) of the emission. If the brightness temperature exceeds the temperature at which molecules can exist, a few thousand Kelvin, then the emission cannot derive from a thermally excited source. Masers often have brightness temperatures of $>10^9$ K and are compact compared with the scales of the astrophysical objects with which they are associated (e.g., stars, galactic nuclei). For example, masers have sizes of order 10^7 m in comets, and masers in galactic cores can have scale sizes up to 10^{19} m (Gray 2011). Other observational features that indicate maser emission are narrow, subthermal spectral line widths and time variability. Lines from different transitions of the same molecular species may also display ratios inconsistent with thermal emission. Maser polarization is typically interpreted as due to the Zeeman effect in the presence of magnetic fields.

Maser emission often involves molecular rotational transitions, with the masers typically pumped in warm, dense gas. For example, the best-studied SiO masers are those at 43 and 86 GHz ($\lambda = 7$ and 3 mm, respectively) originating from the two lowest-energy rotational transitions in each of the first and second vibrational levels. They are pumped at gas densities of $n(\text{H}_2) = 10^{10 \pm 1} \text{ cm}^{-3}$ and kinetic temperatures of $T_k \geq 1,500$ K (e.g., Elitzur 1992). The best-studied water masers are those at 22 GHz ($\lambda = 1.3$ cm) originating from the $6_{16}-5_{23}$ rotational transition. They are pumped in gas of $n(\text{H}_2) = 10^8-10^{10} \text{ cm}^{-3}$ and $T_k = 400-1,000$ K (e.g., Elitzur 1992).

When astrophysical objects associated with masers are imaged at high angular resolution, such as at submilliarcsecond resolution using very-long-baseline interferometry (VLBI), multiple maser features are often observed toward the same object. In addition, masers from multiple transitions of the same molecular species can amplify along the same regions of gas, and masers at different frequencies are often detected toward the same source. Finally, at least in the case of evolved stars and star-forming regions, masers from different molecular species are also often found toward the same object.

Key Research Findings

The circumstellar envelopes of oxygen-rich evolved low-mass and supergiant stars commonly harbor SiO, H₂O, and OH masers. Radio VLBI observations indicate that SiO masers occur close to the star, typically within about four stellar radii (Diamond et al. 1994). SiO maser emission has been detected from vibrational energy levels $v = 0-4$, up to at least the rotational transition $J = 8-7$ ($v = 344$ GHz; $\lambda \approx 1$ mm) in evolved stars, and SiO isotopologue masers are also observed (Soria-Ruiz et al. 2005). H₂O masers at 22 GHz form further from the star at a radial distance of, say, about ten stellar radii (e.g., Richards et al. 2012), with several other H₂O maser transitions also detected at frequencies up to 658 GHz. Main line (1,665 and 1,667 MHz) OH masers occur at similar radii to the 22 GHz H₂O masers but are believed to probe significantly less dense gas (Gray 2011). At much larger radii, typically 100 stellar radii, 1,612 MHz OH masers are observed. Polarized emission of the three molecular maser species has been interpreted to estimate circumstellar magnetic fields (Vlemmings 2007). ► **Proper motion** studies of the masers have been used to trace gas dynamics in the circumstellar envelope, with both outflow and infall detected in the SiO maser zone due to stellar pulsation. Toward the less common carbon-rich stars, HCN and SiS masers have been observed.

Star-forming regions in molecular clouds support a variety of maser species, with methanol, water, and OH masers the most frequently detected. Maser emission is observed from both low- and high-mass forming stars; however, stellar masses significantly $>1 M_{\text{sun}}$ are favored (Gray 2011). Water masers at 22 GHz are often seen in protostellar outflows associated with shocked gas and are more rarely thought to be associated with accretion disks. Other water masers, including those at frequencies of 183, 321, and 325 GHz, have also been detected. Methanol masers in star-forming regions are divided into two types, Class I and Class II, depending on the transitions present. Class I methanol masers are primarily collisionally pumped and may trace outflow interactions with

dense molecular gas. Class II methanol masers tend to be associated with HII regions, with the best-studied transitions occurring at frequencies of 6.7, and 12.2. GHz. Methanol, OH (mainly 1,665 and 1,667 MHz lines), and H₂O masers are often present in the same source, although water and methanol masers usually appear in different regions from each other. Again, maser polarization is used to determine magnetic field characteristics, with fields as high as 40 mG seen in OH masers (Fish 2007). Rarer masers in star-forming regions include ammonia, formaldehyde, and SiO (currently detected in three high-mass star-forming regions only).

► **Supernova remnant** (SNR)/molecular cloud interactions also give rise to maser emission. OH 1,720 MHz masers have been detected from ~ 20 galactic SNRs, that is, 10% of the galactic sources (Brogan 2007). Methanol maser emission at 95 GHz has also been detected toward one SNR. Hot stars MWC 349A and Eta Carina harbor H-atom recombination masers over a range of frequencies (see, e.g., Gray 2011).

Extragalactic maser emission, in some cases referred to as *megamaser* emission, is most commonly detected from 22 GHz H₂O and OH 1,665 and 1,667 MHz lines, although formaldehyde maser emission at 6 cm is also known. OH megamaser emission occurs from nuclear starburst activity, on scales of about 100 pc, whereas 22 GHz water maser emission is observed on (sub)parsec scales and traces the central engines of active galactic nuclei (AGN) (Pihlström 2006). Over a hundred extragalactic water maser sources are now known, including a ► **redshift** $z = 2.64$ detection magnified by gravitational lensing (Impellizzeri et al. 2008). Detections of extragalactic methanol masers are limited to the Large Magellanic Cloud and appear to be similar to Galactic methanol masers.

In the Solar System, masers have been detected from cometary comas. Cometary OH masers have a UV pumping mechanism and have been observed from at least 16 comets, including ► **Comet** Hale-Bopp. Water masers at 22 GHz have also possibly been detected. Water maser emission was detected after the impact of Comet Shoemaker-Levy 9 with Jupiter and has also been

reported from the Saturnian moons Hyperion, Titan, Enceladus, and Atlas (Pogrebenko et al. 2009). Molecular laser features from CO₂ at 10.33 μm were detected in the atmospheres of Venus and Mars. Searches have also been performed for molecular maser emission associated with exoplanets, but to date no emission sources have been reported.

Applications

Masers are used as tools to probe the physical conditions, kinematics, and magnetic fields of astrophysical sources at high angular resolution. Maser line ratios constrain radiative transfer models to determine gas temperatures and densities. ► [Proper motion](#) measurements enable tracing of gas kinematics. Maser polarization, when attributed to the Zeeman effect, can be used to determine magnetic field strength and morphology characteristics. Masers can be used to measure dynamic masses and to provide distance estimates. In the case of water masers in active galactic nuclei, this has led to their use for planned high-accuracy estimation of the Hubble constant, which may lead to constraint on the nature of dark energy (Braatz et al. 2009; Greenhill et al. 2009). OH masers are used to search for variations in the fundamental “constants” over cosmological time (Darling 2003). Galactic trigonometric parallax measurements trace the number and location of the spiral arms in the Milky Way and the distance of the Sun from the Galactic Center (Reid et al. 2009).

Future Directions

New instruments will revolutionize the use of masers as diagnostic probes. The Atacama Large Millimeter/Submillimeter Array (ALMA) will perform imaging up to about 950 GHz, enabling observation of high-frequency maser lines at angular resolutions of better than 10 mas. At low frequencies (foreseen 0.1–25 GHz), the Square Kilometre Array (SKA) will provide very high sensitivity, allowing for searches for distant masers in the early universe.

Cross-References

- [ALMA](#)
- [Circumstellar Chemistry](#)
- [Comet](#)
- [HII Region](#)
- [Linewidth](#)
- [Molecular Cloud](#)
- [Star Formation, Theory](#)
- [Supernova Remnant](#)
- [VLBI](#)

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While extinctions are quite common in nature, mass extinctions are relatively rare events. Five mass extinctions have been recorded in the last 500 Ma (Phanerozoic). It is now suggested that a sixth one, caused by increased anthropogenic pressure on the environment, is ongoing. Catastrophic agents, such as meteorite impacts, and environmental agents, volcanic eruptions, ► [glaciations](#) and global climatic changes, and variations of oxygen concentration in seawater, could explain mass extinctions, though the exact mechanisms remain relatively unknown. These biotic crises must be viewed as important steps in the evolution of life. During the post-event recovery, the vacant ecological niches are filled by new species, like the mammals that became dominant after the dinosaur extinction at the well-known ► [KT boundary](#).

Mass Extinctions

Nicholas Arndt¹ and Daniele L. Pinti²

¹ISTerre, Université Grenoble Alpes, Grenoble, France

²GEOTOP Research Center for Geochemistry and Geodynamics, Université du Québec à Montréal, QC, Canada

Keywords

Bolide impacts · Biological crisis · Chemostratigraphy · Glaciation · Life · Snowball · Volcanic traps

Synonyms

[Biotic crisis](#); [Extinction event](#); [Extinction-level event](#)

Definition

A mass extinction or extinction event refers to an abrupt decrease in the number of species in a short span of geological time. The term is different from simple *extinction* that denotes in ecology the disappearance of an organism or group of *taxa*.

Overview

Several major biotic crises or mass extinctions mark the evolution of life during the Phanerozoic (Fig. 1). During these events and over a rather short time frame, a large proportion of the existing species on land and in the oceans suddenly become extinct. A major and brutal decrease in the diversity and abundance of life characterizes these extinction levels. The development of new species follows.

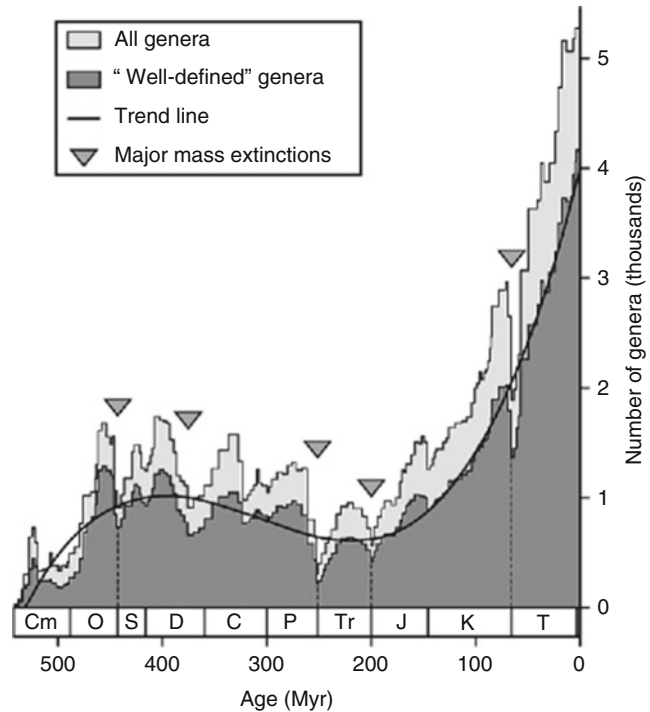
In the last 500 Ma, there have been five large mass extinctions that eliminated more than half of the species inhabiting the Earth. The five recorded mass extinction events occur at the end of the Ordovician (~444 Ma; Hirnantian stage), in the Late Devonian (~370 Ma), at the Permian-Triassic boundary (~251 Ma), at the Triassic-Jurassic boundary (~200 Ma), and at the most studied Cretaceous-Tertiary boundary (often labeled as the ► [KT boundary](#) ~65 Ma) (Raup and Sepkoski 1982; Hallam and Wignall 1997).

Late Ordovician Extinction

A major global cooling of the Earth's climate followed by rapid ► [glaciations](#) could have triggered the Late Ordovician extinction. Extinction has been linked with environmental changes

Mass Extinctions,

Fig. 1 Genus diversity in the Phanerozoic time (542–0 Ma). The *light gray* plot shows the number of known marine animal genera versus time from Sepkoski (2002), converted to the 2004 Geologic Time Scale. The *dark gray* plot shows the same data, with single occurrence and poorly dated genera removed. The trend line is a third-order polynomial fitted to the data. (After Raup and Sepkoski (1982), redrawn by M. Laithier, UQAM)



accompanying the glaciation of the supercontinent ► [Gondwana](#) that comprised most of the landmasses at that time. Sixty percent of genera disappeared from the geological record, and it is estimated that 85% of genera inhabiting the Earth became extinct. This is the second largest mass extinction after that of end-Permian. The extinction occurred as two 2 Ma-long phases, one at the beginning and the other toward the end of the Hirnantian stage. The first is associated with sea-level regression and climate deterioration at the onset of the glaciation of Gondwana, the second with sea-level transgression caused by continental flooding and accompanied by anoxia as the ice caps melted.

Late Devonian and the Permian-Triassic Extinction

The processes leading to the Late Devonian and Triassic-Jurassic biotic crises are still poorly documented. The Devonian extinction took place in the Frasnian-Famennian boundary, about 364 Ma ago and lasted 2–3 Ma. Glacial deposits in Brazil and in the Peru-Bolivia Altiplano of Devonian age suggested that another glaciation on

the Gondwana supercontinent could have triggered an episode of global cooling. This is also supported by the fact that warm water marine species were the most severely affected by this glaciation.

The greatest mass extinction at the Permian-Triassic boundary is often called the “Great Dying” because ~70% of land and more than 90% of marine species disappeared. This period is characterized by some of the best evidence recorded in the European geological record of extensive sea-level fall quickly followed by rise, and these global changes no doubt contributed to the extinction. There is no evidence of a meteorite impact, but the event was synchronous with Siberian flood volcanism, the largest-known continental volcanic province. The magmas of this province intruded carbonates and sulfate-rich sedimentary rocks, which released large amounts of CO₂ and SO₂ when heated, and the toxic cocktail of sediment- and magma-derived gases probably contributed to the extinction.

KT Boundary

The most famous ► [KT boundary](#) saw the demise of the dinosaurs on land and of the ammonites and

the marine reptiles in the oceans. Across this interval, ~60% of the fauna and flora on Earth went extinct, and in particular, the marine calcareous microplankton was drastically affected. The impact of a ~10–12 km asteroid on the Yucatan peninsula is widely accepted as one of the major causes of this mass extinction. This impact formed the ~200 km [Chicxulub crater](#) and spread ejecta material all around the globe. Worldwide, the KT boundary layer is marked by the characteristic positive iridium anomaly, generated by the presence of meteoritic material. The largest phase of Deccan flood volcanism in India erupted 67 Ma ago, synchronously with the KT event. Single lava flows extended for more than 1000 km and covered most of India of continental flood basalts, and huge emissions of greenhouse and toxic gases were associated with the eruptions. Possibly, both impact and volcanism contributed to this mass extinction (Courtillot 1999).

Precambrian Mass Extinctions

Precambrian mass extinctions have been proposed such as during the Vendian period (605–543 Ma). This extinction largely affected stromatolites and acritarchs, and it has been correlated with a large glaciation event that occurred about 600 Ma ago. This event was of such severity that almost all microorganisms were completely wiped out. Whether the Vendian event was a major extinction is currently under debate. Older extinctions are impossible to evaluate because the fossil record is less well preserved and abundant. It is likely that mass extinctions occurred during global climate events such as Snowball Earths and in earlier times during the Archean and [Hadean](#) eons, if life already inhabited the Earth. Indeed, if microorganisms were already present during the Hadean, intense meteoritic bombardment, the catastrophic volcanism, and rapid changes in the physicochemical conditions of oceans (acidity, temperature, and salinity) could have driven repeated mass extinctions.

Basic Methodology

Apparent extinction intensity, i.e., the fraction of genera going extinct at any given time, has been

reconstructed from the fossil record. Abundance and biodiversity estimates are directly related to the quantity of rock available for sampling from different time periods, and thus, this methodological approach can create artifacts. The development of the “chemostratigraphy,” i.e., the study of the variation of chemistry within sedimentary sequences, particularly the variations in the stable isotopes of C, S, and N contained in kerogens or [radiogenic isotopes](#) (Sr, Os), gives a valuable support for determining mass extinction horizons (Marshall 1992; Brenchley et al. 1994). Carbon isotope values ($\delta^{13}\text{C}$) from rocks, fossils, and biomarkers record global changes in the carbon cycle. This implies changes in carbon inputs (e.g., riverine vs. marine), outputs (e.g., methane hydrate emissions), organic productivity, and carbon burial. All five of the major Phanerozoic mass extinction events are matched by significant carbon isotopic excursions. The $\delta^{13}\text{C}$ data of both carbonate and organic carbon from numerous sections worldwide reveal a positive $\delta^{13}\text{C}$ excursion shortly after the first pulse of extinction at the end of the Ordovician. This positive $\delta^{13}\text{C}$ excursion is interpreted to have resulted from high primary productivity or from the [weathering](#) of carbonate platforms that were exposed when sea level fell during the glaciation. Negative excursions found associated with the end-Permian are interpreted to record collapse in primary productivity, massive release of methane from hydrates, or release of gases from sedimentary rocks heated by basaltic magmas (Ganino and Arndt 2009).

Future Directions

Two main questions need to be addressed:

1. Can we identify mass extinctions in the earlier geological record of the Earth?
2. Are there common or multiple causes to mass extinctions?

The first question is difficult to answer because the answers must be sought from a period when the fossil record is almost totally absent or rare. Chemostratigraphy is difficult to apply because

the diagenetic effects on the isotopic signatures and because Precambrian biogeochemical cycles of C, N, S, and other elements were possibly different than in post-Cambrian times and thus the isotopic signature rather complicated to interpret.

Several authors try to answer the second question by identifying possible periodicity in the extinction events and relate them to common geological or environmental changes. This is an old approach used since Cuvier's theory of catastrophism and still largely debated (see Hallam and Wignall 1997). Recent robust statistical estimates suggest 62 ± 3 Ma cycles (Rohde and Muller 2005). This cycle could be related to the passage of the Solar System into molecular clouds increasing meteoritic or cosmic dust showers or to perturbations of the Oort cloud increasing the risk of cometary impact on the Earth. Other theories suggest a relation with the episodic rise of the global-scale mantle plumes that cause flood basaltic volcanism. These huge basaltic volcanic eruptions are synchronous with all known mass extinction levels (except for the end-Ordovician event), within the limit of error of modern dating techniques (Courtillot 1999).

Cross-References

- Chicxulub Crater
- Deccan Trapps
- Ejecta
- Evolution, Biological
- Glaciation
- Iridium
- KT Boundary
- Mantle Plume, Planetary
- Snowball Earth
- Traps

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Mass Loss Rate

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The mass loss rate quantifies the rate at which a star loses its matter as a result of various effects. It corresponds to an ejection of matter, usually called ► [stellar wind](#), which happens all along the star's life but especially in the final stage (post-AGB phase). Massive stars exhibit very large mass loss rates. The unit is kg s^{-1} or more usually $M_{\text{sol}} \text{ year}^{-1}$, where M_{sol} is the mass of the Sun.

Cross-References

- [Stellar Evolution](#)
- [Stellar Winds](#)

Mass Spectrometry

Masamichi Yamashita

Institute of Space and Astronautical Science
(ISAS) /JAXA, Sagamihara, Kanagawa, Japan

Keywords

Electron impact · Electrospray ionization ·
GC/MS · Ion trap · Ion cyclotron resonance ·
Imaging MS · LC/MS · MSL · Quadrupole
MS · Secondary ionization MS · Soft
ionization

Synonyms

Mass spectroscopy; MS

Definition

Mass spectrometry is an analytical method used to identify and quantify chemical species based on their molecular mass. It is also widely used to determine the isotopic abundances (isotopic ratios) of various elements. The mass to charge ratio of ionized molecules is determined by their motion traveling through electromagnetic fields. Elemental composition and chemical structure of molecules are also estimated using the higher mass-resolving power of the system and interpretation of the mass spectrum of fragment ions. By choosing appropriate ionization methods, mass spectrometry provides information other than mass, such as the polarity of molecules. Imaging capability and chiral identification are promising features of mass spectrometry for astrobiology.

Overview

Mass spectrometry (MS) is capable of analyzing any substance, once sample molecules are ionized. By this generic feature, which is superior to other methods of chemical analysis, MS has

become a common instrument for astrobiology. Ordinary MS requires a volatilization process prior to analysis. However, many bio-associated molecules are hard to volatilize even at relatively high temperature. The strong intermolecular interaction of biomolecules, originating in their strong polarity, tends to produce charring, not volatilization, at high temperature. The innovation of soft ionization, appropriate for such substances in principle, leads MS to be a highly powerful tool for astrobiology with many new applications, both on the ground and in space.

The most common use of MS is to detect and characterize organic substances of astrobiology interest. It is essential for understanding prebiotic chemical evolution and ultimately for getting direct evidence of extraterrestrial life, if any. Analysis of the isotopic composition of substances is a unique capability of MS. The isotopic composition of bioelements in fossils can provide evidence of activities of extinct living organisms, based on the isotope effects on biochemical reaction rates. Spatially resolved MS techniques have been developed recently. This also opens new horizons for astrobiology.

Basic Methodology

Mass spectrometry consists of three steps, i.e., ionization, mass separation, and ion detection.

Electron impact (EI) is a common ionization method. Electrons, with energies at 50–100 eV, hit sample molecules to ionize them. Molecules should be volatilized before EI. Most biogenic molecules are hard to volatilize and require chemical modification to increase vapor pressure. Thermal ionization, inductively coupled plasmas (ICP), and sputtering sources are also widely used to determine isotopic abundances.

Another approach for biomolecules is soft ionization. Electrospray ionization (ESI) and matrix-assisted laser desorption/ionization (MALDI) are typical soft ionization methods. ESI ionizes molecules by spraying finely charged droplets in a strong electric field. Desorption electrospray (DESI), a derived method of soft ionization,

produces ions directly from a surface. MALDI ionizes biological substances through desorption of molecules after energy deposition by a laser to the matrix.

► **Photoionization** can provide highly selective ionization, useful in case the ionization potential of the target molecule is lower than the energy of the irradiating photon, while that of other molecules is higher than the photon energy. Because aromatic compounds have low ionization potentials, poly-aromatic hydrocarbons (PAHs) are selectively ionized by ultraviolet lasers in this way.

An imaging capability of MS has been developed for several ionization methods. Secondary ionization MS (SIMS) is based on excitation of sample molecules by the incidence of primary ion beams. Scanning of the primary beam on the substrate creates spatially resolved MS. Ionization methods employing lasers are capable of imaging. DESI can analyze the spatial distribution of substances at less resolving power.

In the second step of MS analysis, charged molecules can be separated by the electromagnetic force. In the early era of MS, deflection of traveling ions in a magnetic field has been the common principle of MS (magnetic sector MS). The trajectory of ions in a quadrupole electric field, either two dimensional (quadrupole MS) or three dimensional (ion trap and orbitrap), stays within a defined space, if the operational parameters of the quadrupole field are tuned to a specific m/z . Time-of-flight MS (TOF MS) generates a mass spectrum by measuring the traveling time of ions after pulsed acceleration. Ion cyclotron resonance (ICR) is based on the cyclotron motion of charged particles in magnetic fields and its dependence on m/z .

Tandem MS (MS/MS) is a popular configuration to obtain the spectrum of fragment ions. The fragmentation spectrum provides information about chemical structure, mostly the sequence of monomers.

Ion detection is the final stage of mass analysis. A resonance method such as ICR detects ions by their image current, which is induced by the motion of the ions. Another type of mass analyzer uses a secondary electron multiplying device to gain high sensitivity for the detection of ions.

Key Research Findings

Mass spectrometry in ground-based astrobiological studies:

The organic substances found in a Martian meteorite, ALH84001, marked the first direct evidence of organic molecules brought from an extraterrestrial planet. It was analyzed by a combination of infrared and ultraviolet lasers. Evaporation of the sample was made by infrared radiation, and successive shots of UV laser light produced photoionized PAHs. It has been proposed that the aliphatic side chains of the PAHs suggest a biological origin of these PAHs, although others have claimed these are in fact contaminants introduced from Antarctic ice.

An extraterrestrial amino acid, glycine, was found in the captured dust of a comet by gas chromatography/mass spectrometry (GC/MS). The Stardust sample was hydrolyzed and chemically derivatized in order to increase the vapor pressure for GC/MS analysis. The isotopic abundance of ^{13}C in the glycine supports its extraterrestrial origin. This result bears on the understanding of the chemical evolution in our solar system and the possible contribution of comets in supplying prebiotic organics to initiate life on Earth.

Mass spectrometry employed in space astrobiology missions is summarized below.

- **Mars:** The two ► **Viking** landers (1976) had MS to analyze the Martian atmosphere and its isotopic composition. Even though the composition of the atmosphere can be estimated remotely from Earth, on-site MS analysis is essential to provide isotopic information. The observed data was also used to determine the origin of some Martian meteorites, which contain trapped samples of the Martian atmosphere. The history of Mars' lost atmosphere can be elucidated from measured isotopic ratios. GC/MS also performed a biological experiment on Viking.
- **Phoenix** landed on a polar region of Mars in 2008. A Thermal and Evolved Gas Analyzer (TEGA) was included in the scientific payload of Phoenix. A surface sample was heated in its

oven up to 1000 °C, and volatiles from the sample were analyzed by a magnetic sector MS. The dynamic range of this system would have been able to detect organic molecules at 10 ppb level.

- Mars Science Laboratory (MSL) is exploring habitability of Mars since landing of the Curiosity rover in 2012. Quadrupole MS with GC is a part of the Sample Analysis at Mars (SAM) instrument. Analysis of gas released from heated rock samples suggests a chemical environment in the past related to potential habitability.
- ► [Titan](#): The Cassini-Huygens mission to Saturn included the Huygens probe that descended to Titan in 2005. The GC/MS on the Huygens probe analyzed the atmospheric composition of Titan, which is dominated by CH₄ and N₂. The isotopic ratios were analyzed for those atmospheric species.
- Comets: Giotto explored ► [Comet Halley](#) with MS in 1986. Chemical species, both neutral molecules and ions, were analyzed during its flyby. Comets are considered to be a source of prebiotic molecules. Other than the major components H₂O, CO, and CO₂, both H₂CO and HCN were found.

Applications

Mass spectrometry is a powerful tool to detect and characterize biogenic and prebiotic substances and thus to find signatures of life on extraterrestrial bodies and to elucidate their environmental factors. The generic features and high sensitivity of MS make it a common science payload of many space missions. Isotopic information available by MS is essential to differentiate biotic or abiotic origin and to understand a planetary environment and its history for astrobiology.

Future Directions

The following space missions with MS instrument are now ongoing or in preparation.

A part of the ► [ExoMars](#) mission will be launched in 2022. The Mars Organic Molecule

Analyzer (MOMA) is a scientific payload of this portion of ExoMars. It aims to detect organic substances in deep (2 m) drilled samples. Ion trap MS with a laser desorption ion source enables detection of biogenic or prebiotic organics without the heating and charring of samples experienced in former missions.

Mass spectrometry can be further adapted for astrobiology in several ways.

To gain higher sensitivity to detect biogenic and prebiotic substances is essential for astrobiology. Even if organics will not be found at all, the extended limit of detection will contribute to assessing working hypotheses for the origin of life. Choosing proper soft ionization processes for biogenic and prebiotic molecules will bring new findings through the high signal-to-noise ratio and increased sensitivity.

In addition to the choice of ionization, preprocessing of samples is an important step in astrobiology MS. One solution is direct ionization from a substrate surface. Another approach is preprocessing to convert complex sample substances to their constituent molecules. ExoMars implements a payload, Urey, to detect organics on the Martian surface. The sample will be exposed to subcritical (near the critical point) aqueous extraction. Organics are leached out from the solid sample, and macromolecules are hydrolyzed to constituent molecules. Digested smaller molecules, if similarly processed, keep information specific to the original biological system and can be mass analyzed by soft ionization. For astrobiology, a combination of liquid chromatography and MS (LC/MS) is by its nature a more suitable approach compared to GC/MS.

The imaging capability of MS enforces its strength by high sensitivity. Compared to the ordinary bulk analysis, spatial information from MS provides structural information on biological forms at scales from the microscopic cellular level to mesoscopic systems.

The homochirality of amino acids and sugars, if found on extraterrestrial bodies, is a factor that would distinguish biogenic origin from abiogenic substance. Even separation of optical isomers can be made by liquid chromatography/MS.

Mass spectrometry continues to be a powerful tool for astrobiology.

Cross-References

- ▶ [Cassini-Huygens Space Mission](#)
- ▶ [Comet Halley](#)
- ▶ [ExoMars](#)
- ▶ [Gas Chromatography](#)
- ▶ [GC/MS](#)
- ▶ [Giotto Spacecraft](#)
- ▶ [Isotopic Ratio](#)
- ▶ [Liquid Chromatography-Mass Spectrometry](#)
- ▶ [Mars](#)
- ▶ [Mars Science Laboratory](#)
- ▶ [Molecular Weight](#)
- ▶ [Photoionization](#)
- ▶ [Rosetta Spacecraft](#)
- ▶ [Stardust Mission](#)
- ▶ [Titan](#)
- ▶ [Viking](#)

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Mass Spectroscopy

- ▶ [Mass Spectrometry](#)

Mass-Luminosity Relation

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

The mass-luminosity relation for ▶ [stars](#) is an empirical correlation observed between the mass M and the luminosity L of stars on the ▶ [main sequence](#) of the ▶ [Hertzsprung-Russell](#) diagram. It has the form $L \propto M^K$, with $K \sim 3.5$ as an average value. The lowest mass stars ($0.1 M_{\odot}$) are about 2,000 times less luminous than the Sun, whereas the most massive ones ($100 M_{\odot}$) are 1,000,000 times more luminous. The relation is due to the fact that stars in hydrostatic equilibrium – supported against self-gravity by their internal pressure – are hotter when they are more massive; therefore, their material radiates more strongly than in the case of lower mass stars.

Cross-References

- ▶ [Hertzsprung-Russell Diagram](#)
- ▶ [Main Sequence, Star](#)
- ▶ [Stars](#)
- ▶ [Stellar Evolution](#)

Master Equation Models

Eric Herbst

University of Virginia, Charlottesville, VA, USA

Definition

Master equation models can be employed for interstellar grain surface chemistry when there are few reactive species on individual grains. For example, if there are fewer than 2 hydrogen atoms on a grain, reactions to form molecular hydrogen are impossible yet are included in rate equation

treatments when not modified. Instead of normal rate equations, which include only one time derivative per species, master equation treatments include different equations for the time derivatives of the probabilities of specific numbers of species per grain. For example, consider a grain surface with initial probabilities $p(n_H)$ for n_H hydrogen atoms. The differential equations for the time derivatives of the $p(n_H)$ values equate the derivatives to the sum of positive (gain) and negative (loss) terms. Consider a specific number of hydrogen atoms n_H' . Positive terms enhance the probability $p(n_H')$ by adding H atoms to a grain with fewer atoms or by reducing the number of H atoms on a grain with initially more than n_H' atoms, while negative terms do the opposite. Summing over the solutions of the equations for each $p(n_H)$ and $p^2(n_H)$ as a function of time leads to an average value $\langle n(H) \rangle$ and its fluctuation, which can be compared with the concentration of the rate equation method (Biham et al. 2005).

With more than one species on a grain, however, the probabilities become joint probabilities which include numbers of each species, i.e., $p(n_H, n_O, n_{CO}, \dots)$. The large number of different probabilities leads to a large number of equations (strictly infinite) which requires approximations such as only using the master equation treatment on species of low abundance but important reactivity and/or setting an upper limit on n for either the total number of reactive species or for specific species (Stantcheva and Herbst 2004; Le Petit et al. 2009). Another approximation, known as the moment approach, in which the master equation is expanded in a series based on moments, has also been used. In general, the master equation technique for problems, in which small numbers of reactive adsorbates such as atomic hydrogen exist per grain, has been replaced by Monte Carlo techniques, in which similar results are obtained but by a very different technique. Here pseudo-random numbers from 0 to 1 are called to choose a process and its rate involving individual species, which occurs in a given time based on a distribution. (See entries for macroscopic Monte Carlo models and microscopic Monte Carlo models.) It should be noted that mixed gas-grain simulations can contain the master equation approach for the

granular chemistry and a deterministic rate equation approach for the gas-phase chemistry. If, on the other hand, a Monte Carlo approach is used for the granular chemistry, such an approach must also be used for the gas-phase chemistry.

Cross-References

- [Abundances](#)
- [Cosmic Ray, Ionization Rate](#)
- [Cosmic-Ray-Induced Desorption](#)
- [Gas-Grain Chemistry](#)
- [Hydrogen](#)
- [Interstellar Chemical Processes](#)
- [Macro Monte Carlo Models](#)
- [Micro-Monte-Carlo Models](#)
- [Molecular Cloud](#)
- [Physisorption](#)
- [Rate Equation Models](#)
- [Reaction Rate Coefficient](#)

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Mated Bioburden

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In ► [planetary protection](#), the term “mated ► [bioburden](#)” is used to indicate the viable

microorganisms that are carried on spacecraft surfaces that are in contact with each other (mated) and joined by fasteners (e.g., bolt, screw, rivet, clip, and clamp) rather than by adhesives (surfaces joined by adhesives would result in ► [Encapsulated bioburden](#)).

Location of a microorganism on a mated surface is thought to reduce the rate of water loss during heat sterilization processes (relative to surface bioburden) that is one of the causative factors for cell death during ► [DHMR](#). The lethality of DHMR processes on mated bioburden is taken as half the lethality for bioburden on exposed surfaces.

Cross-References

- [Bioburden](#)
- [DHMR](#)
- [Encapsulated Bioburden](#)
- [Planetary Protection](#)

Materialism

Christophe Malaterre

XInstitut d'Histoire et Philosophie des Sciences et Techniques (IHPST), Université Paris 1-Panthéon Sorbonne, Paris, France

Keywords

Dialectical materialism · Ethical materialism · Historical materialism · Matter · Metaphysical materialism · Substance

Synonyms

[Physicalism](#)

Definition

In philosophy, materialism is most often taken as a metaphysical thesis according to which everything that exists is matter or results from matter (including life and consciousness); this thesis offers a monist ontology that typically contrasts with idealism, dualism, and ► [vitalism](#). Materialism also refers to an ethical doctrine according to which the material well-being (including wealth, health or pleasure) is to be sought after. In social sciences, historical materialism is the Marxian thesis that historical and social phenomena are determined by economic facts; it is a particular case of dialectical materialism that construes the universe as a whole within which objects cannot be understood in isolation of one another.

Overview

The nature of what exists is an old question that goes back to ancient Greek philosophers such as Thales or Lucretius. In the seventeenth century, Hobbes and Gassendi typically represented the materialist tradition, in clear opposition to Descartes' dualism. The word "materialism" is said to have appeared for the first time in writings of Boyle. The doctrine is further developed in the eighteenth century by several French enlightenment thinkers (e.g., Meslier, de la Mettrie, Baron d' Holbach, Diderot). Broadly, materialism holds that "everything is matter," and that, as a consequence, all phenomena, including life and consciousness, result from matter and material interactions. Materialism offers a monist ontology in which matter is the only substance, in contrast with idealism or spiritualism, and with pluralist ontologies such as dualism or vitalism.

The metaphysical thesis of materialism raises interpretation and truth questions: what does it mean to say that *everything* is matter? What is *matter*? Is materialism *true*? The nature and

definition of matter, in particular, have been much controversial. Traditionally referring to the type of tangible substance that we are broadly familiar with, the concept of matter has considerably evolved with the physical sciences, in particular relativity and quantum field theory, possibly including “dark matter” and “dark energy.” Some prefer now to use the term ► **“physicalism”** instead of “materialism,” as exemplified by much of the contemporary debate in analytic philosophy, also linked to questions of supervenience, emergence, and ► **reductionism**, especially in philosophy of mind and philosophy of biology.

In moral philosophy, materialism refers to a practical doctrine according to which material considerations are the most worthy in one’s life: material well-being, wealth, health, or pleasure. Such an ethical materialism is present in Baron d’Holbach’s *System of Nature* and Haeckel’s *Natürliche Schöpfungsgeschichte*, and can be traced back to Epicurus.

The concept of historical materialism, first articulated by Engels and Marx, refers to the thesis that change in human societies originates in the economic means of production of the necessities of life; social classes, political structures, and other noneconomic elements of a society are seen as an outgrowth of the economic activity. Historical materialism fits as a particular case of dialectical materialism, a doctrine that construes the universe as a whole, constituted by matter in movement and within which qualitative transitions result from quantitative changes and from interactions of objects with one another. Evolutionary biologists such as Gould and Lewontin have defended dialectical materialism as a heuristic methodology.

Cross-References

- **Chance and Randomness**
- **Physicalism**
- **Reductionism**
- **Vitalism**

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Mathilde

Stefano Mottola

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

(253) Mathilde is a dark, primitive Main Belt asteroid classified as a C type. The body, which is approximately 50 km in size, was the third asteroid to be visited by spacecraft when the Discovery space probe NEAR Shoemaker flew by in 1997 on its route to NEA Eros. Pre-encounter ground-based observations performed during the 1995 apparition have allowed an unusually long rotation period in excess of 17 days to be determined. In addition, those observations have detected multiple periodicities in the body’s lightcurve, which have been interpreted as the signature of free precession. Although NEAR Shoemaker could only image one hemisphere of the body, due to its slow rotation and to the fast flyby geometry, the bulk density of the body could be estimated to 1.3 g/cm³. This value, which is lower than the density of analog carbonaceous chondritic meteorites, implies comparatively

high porosity. The visible surface of the body is characterized by several very large impact craters, two of which have diameters comparable to the object's radius. The very fact that the body escaped destruction as a consequence of such large impact events, in addition to its low bulk density, is interpreted as Mathilde having the structure of a rubble pile.

Mean Free Path

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The mean free path is the mean travel length of an elementary particle (photon, atom, molecule, ion) between two successive interactions with other particles of another or of the same type.
 ► [Scattering](#) of photons in a dusty medium and
 ► [diffusion](#) of molecules are examples of phenomena where the notion applies. Unit: m.

Cross-References

- [Diffusion](#)
- [Radiative Transfer](#)
- [Scattering](#)

Mean Motion Resonance

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planetary dynamics, a mean motion resonance refers to a commensurability between orbital

frequencies. If the ratio of the orbital periods of two (or more) planets or satellites is close to the ratio of two small integers, mutual perturbations may cause the orbits to evolve in ways not expected from secular evolution. Mean motion resonances have the potential to be protective or destructive, depending on the relative orientation of the orbits. For example, Neptune and Pluto's orbital period ratio is close to $2/3$, and the orbits actually cross, but resonance forbids the two planets from ever meeting at this crossing. Note that mean motion resonances do not depend solely on the orbital period ratio of two objects but also on their orbital alignment and phase.

Cross-References

- [Apsidal Angle](#)
- [Orbit](#)
- [Planetary Migration](#)

MEarth

Emeline Bolmont
Observatoire de Genève, Université de Genève,
Chemin Pegasi 51, 1290, Sauverny, Switzerland

Definition

The MEarth project (Nutzman and Charbonneau 2008) is an all-sky transit survey done using small 40 cm robotic telescopes, located in the northern hemisphere at the Fred Lawrence Whipple Observatory in Arizona (USA) and in the southern hemisphere at the Cerro Tololo Inter-American Observatory, just east of La Serena (Chile). MEarth was built to find planets in the habitable zone of very low-mass stars (M-stars, the "M" of MEarth). The first MEarth planet, GJ 1214b, was detected in 2009 (Charbonneau et al. 2009). To date, the most remarkable discovery of MEarth is one of a super-Earth planet of 1.7 Earth radius:

LHS-1140b (Dittmann et al. 2017). It sits comfortably in the habitable zone of its star.

Thanks to the groundbreaking MEarth project, other surveys targeting very low-mass stars have started. In particular, SPECULOOS, whose prototype TRAPPIST allowed the discovery of the TRAPPIST-1 system, which hosts three small planets in the habitable zone of a very low-mass star.

Cross-References

- ▶ [LHS-1140b](#)
- ▶ [SPECULOOS](#)
- ▶ [Super-Earths](#)
- ▶ [Transit](#)
- ▶ [Transiting Planets](#)
- ▶ [TRAPPIST-1 System](#)

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Medicean Stars

- ▶ [Galilean Satellites](#)

Mediocrity Principle

- ▶ [Copernican Principle](#)

MEED

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Synonyms

[Microbial Ecology Evaluation Device](#)

Definition

The Microbial Ecology Evaluation Device (MEED) is a device to expose different biological systems to selected parameters of outer space (space vacuum, solar UV radiation, and/or cosmic radiation).

Overview

The Microbial Ecology Evaluation Device (MEED) is an exposure facility for a variety of ▶ [microorganisms](#) (Table 1) that were transported with the Apollo 16 spacecraft to the Moon and back to the Earth. It is, so far, the only device that has exposed microorganisms to the outer space conditions beyond the Earth's magnetic field. During the extravehicular activity phase of the transearth coast, that is, return trip to the Earth, MEED was deployed outside the Apollo 16 capsule on the distal end of a television boom, opened, and oriented perpendicular to the Sun's rays. After 10 min of Sun exposure, the MEED was closed again and returned back to the Command Module for return to Earth. MEED was also equipped with UV dosimeters, and passive nuclear track detectors, and thermoluminescent dosimeters for monitoring cosmic rays.

MEED, Table 1 Biological assay systems of MEED (Taylor 1975)

Biological system	Phenomenon studied	Assay system
<i>Bacillus subtilis</i> spores	Genome alteration	Spore production
<i>Bacillus subtilis</i> spores	UV- and vacuum-sensitivity	Colony formation
<i>Bacillus thuringiensis</i>	α , β , and δ toxin production	<i>Sarcina flava</i> , house fly, silk worm, and crystal assay
<i>Aeromonas proteolytica</i>	Hemorrhagic factor production	Guinea pig and hemoglobin
<i>Escherichia coli</i> (T7 phage)	Bacteriophage infectivity	Host lysis
<i>Chaetomium globosum</i>	Cellulolytic activity	Cloth fibers
<i>Trichophyton terrestre</i>	Animal tissue invasion	Human hair
<i>Rodoturula rubra</i>	Drug sensitivity	Antibiotic sensitivity in agar
<i>Saccharomyces cerevisiae</i>		

Cross-References

- [Apollo Mission](#)
- [Cosmic Rays in the Heliosphere](#)
- [Exposure Facilities](#)
- [Microorganism](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Vacuum Effects](#)

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Mega-Annum

- [Ma](#)

Megayear

- [Ma](#)

Melanins

Marco d’Ischia and Paola Manini
Department of Chemical Sciences, University of Napoli Federico II, Naples, Italy

Keywords

Eumelanins · Pheomelanins · Allomelanin · Neuromelanin · Pyomelanins · Polyphenols · Tyrosine · Tyrosinase · DOPA · 5,6-Dihydroxyindole · 5,6-Dihydroxyindole-2-carboxylic acid · 5-S-CysteinylDopa · 1,8-Dihydroxynaphthalene · Homogentisic acid

Definition

“Melanins” is a generic term commonly used to define dark and insoluble pigments found in living organisms, including animals, plants, and microorganisms (fungi and bacteria), arising biosynthetically from the oxidative polymerization of L-tyrosine or other phenolic substrates. A recent classification of melanins includes the black-to-dark brown eumelanins and the reddish-brown sulfur-containing pheomelanins (in animals), neuromelanin (in catecholaminergic regions of the brain), allomelanins (in plants and fungi), and pyomelanin (in bacteria). Melanins display a peculiar set of physicochemical properties that have been implicated as underlying most of their biological roles including photoprotection, camouflage, and virulence, denoting per se a melanin-like pigment.

Overview

The origin of the term “Melanins” (from μέλας, black) is attributed to the Swedish chemist Berzelius (1840) with reference to the dark pigment found in eye membranes and was initially used to denote the major dark pigments present in surface structures of vertebrates, including man (Prota 1992; Riley 1997). Sometimes, however, the term has been used fairly indiscriminately to mean any dark pigment without specific biosynthetic or functional implications.

The basic classification of melanins is due to Nicolaus (1968), who divided these natural pigments into three main groups: eumelanins, pheomelanins, and allomelanins. The former two groups comprise animal pigments while the latter group refers to the broad collection of dark non-nitrogenous pigments of plant, fungal, and bacterial origin (Glagoleva et al. 2020).

Later, Prota proposed a more restrictive usage of the term “melanin” to include only those pigments that are formed intracellularly by the oxidation of L-tyrosine and related metabolites (Prota 1992), thus taking both the biogenetic origin from L-tyrosine and the metabolic activity of melanocytes and other pigment cells as key requisites for a pigment to be classified as a melanin.

Recently, as knowledge on melanin occurrence and distribution in nature has increased, an improved consensus definition and classification of melanins *sensu stricto* has been proposed, as *pigments of diverse structure and origin derived by the oxidation and polymerization of tyrosine in animals or phenolic compounds in lower organisms* (d’Ischia et al. 2013). This definition allows to set the modern classification of melanins into five main groups (Fig. 1):

Eumelanins (εὖ = good, true): *Black-to-brown insoluble subgroup of melanin pigments derived at least in part from the oxidative polymerization of L-DOPA via 5,6-dihydroxyindole intermediates.* Typical eumelanins are found in the skin, hair, and eyes of dark-complexioned phenotypes, as well as in bird feathers, amphibians, reptiles, fish (zebrafish is an established model for studies of melanoma), and cephalopod ink.

Pheomelanins (φαιος = gray): *Yellow-to-reddish brown, alkali-soluble, sulfur-containing subgroup of melanin pigments derived from the oxidation of cysteinyl-dopa precursors via benzothiazine and benzothiazole intermediates.* Typical pheomelanins include red human and mammalian hair and hen feather pigments (although red hair pigment is rarely pure pheomelanin).

Neuromelanins: *Dark pigments produced within neurons by the oxidation of dopamine and other catecholamine precursors.* The typical example of this class of melanins is the pigment from human *Substantia nigra*.

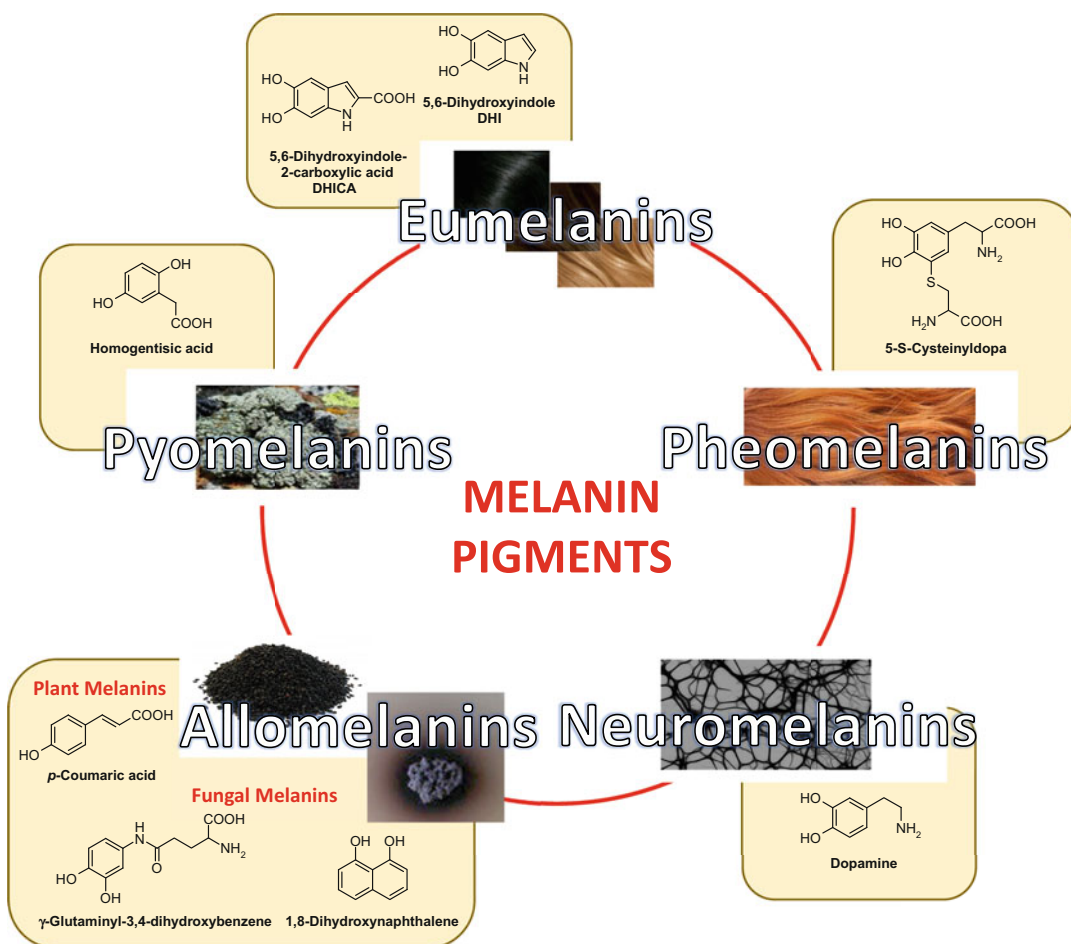
Allomelanins (ἄλλος = other): All other melanins like the dark non-nitrogenous phenolic pigments from plants and lower organisms, which cannot be classified as eumelanins, pheomelanins, or neuromelanins. Typical allomelanins are fungal melanins and the pigments found in some black seeds like black sesame.

Pyomelanin (πύον = pus): A eumelanin-like pigment produced by *Pseudomonas* and *Aspergillus fumigatus* in the presence of L-tyrosine via homogentisic acid (Schmaler-Ripcke et al. 2009).

It is worth noting that in several instances two or more different types of pigments are co-produced by the same organism. For example, pheomelanin in red hair and feathers is usually found mixed with eumelanin in variable proportions.

When seen from an evolutionary perspective, melanin distribution across the phylogenetic tree suggests that the appearance of nitrogen-containing units in melanin pigments marks the passage from lower organisms and plants to the animal kingdom. Moreover, the presence of a mutated phenotype with reddish sulfur-containing cysteine-derived melanin pigments, the pheomelanins, seems to be associated with higher levels of evolution (the red-haired phenotypes in man and mammals).

An evolutionarily preserved primitive role of melanin pigments is documented by their identification in various fossils (see e.g. Negro et al. 2018; Lindgren et al. 2015; Rossi et al. 2019). Melanin and melanosomes have been detected in diverse fossils leading to inferences about the



Melanins, Fig. 1 Modern classification of melanin pigments. The monomer precursors are highlighted in the boxes

adaptive coloration and behavior of extinct taxa (Vinther et al. 2016; Hu et al. 2018).

Evidence for non-integumentary melanin (extracutaneous, i.e., from internal tissues, excluding the eyes) in extant vertebrates and fossil amphibians (Dubey and Roulin 2014; McNamara et al. 2018) supported the possibility that these pigments played broader functions exceeding the mere integumentary coloration (Vinther 2015).

Records of melanin pigments in fossils include organosulfur-Zn complexes as indicators of pheomelanin in extant and fossil soft tissue of a three-million-year-old mammal species (*Apodemus atavus*) (Manning et al. 2019) and the presence of eumelanin in the soft tissue headcrest of the pterosaur *Tupandactylus imperator* (Pinheiro et al. 2019).

Basic Methodology

Animal melanins arise biosynthetically from the metabolic activity of highly specialized cells, the melanocytes, via the oxidative conversion of L-tyrosine catalyzed by the copper enzyme tyrosinase. The pathway leading to the synthesis and deposition of eumelanins involves the following key steps:

1. Tyrosinase-catalyzed conversion of L-tyrosine to DOPAquinone
2. Intramolecular cyclization of DOPAquinone and oxidation to DOPAchrome
3. Rearrangement/isomerization of DOPAchrome with/without decarboxylation to give 5,6-dihydroxyindole (DHI) and/or 5,6-dihydroxyindole-2-carboxylic acid (DHICA)

4. Oxidative polymerization of DHI and DHICA to eumelanin

Following mutation at *mc1r*, a critical gene for the eumelanin pathway, the formation of the dark pigments is partially inhibited and a switch occurs from eumelanin to pheomelanin synthesis following the intervention of L-cysteine.

Key steps in pheomelanin synthesis are:

1. Addition of L-cysteine to DOPAquinone to give 5-S-cysteinylDOPA as the main conjugation product
2. Oxidation of 5-S-cysteinylDOPA to its quinone followed by intramolecular cyclization to give dihydro-1,4-benzothiazine derivatives
3. Oxidation of dihydro-1,4-benzothiazine derivatives to give pheomelanin via partial isomerization to benzothiazole derivatives

In the dopaminergic neurons of *Substantia nigra pars compacta*, neuromelanin formation seems to proceed without enzymatic assistance due to a failure of the antioxidant defense system to control catecholamine autoxidation. This latter process involves the following steps:

1. Oxidation of dopamine to dopaminoquinone
2. Intramolecular cyclization of dopaminoquinone and oxidation to dopaminochrome
3. Isomerization of dopaminochrome to DHI
4. Oxidative polymerization of DHI to neuromelanin

The pathway represented by the above steps appears to be intermeshed with a pheomelanin-type reaction channel derived from the partial entrapment of dopaminoquinone by L-cysteine leading to give benzothiazine intermediates that are eventually incorporated into the neuromelanin polymer.

Allomelanin synthesis in plants may involve different phenolic substrates including catechol, caffeic, chlorogenic, protocatechuic, and gallic acids (Lyakh 1981; Bell and Wheeler 1986; Glagoleva et al. 2020). The biosynthetic process consists in the oxidative polymerization of the phenolic/catecholic substrates assisted by enzymes such as polyphenol oxidase.

Fungal melanins can be formed from gamma-glutaminy-3,4-dihydroxybenzene, L-DOPA, and 1,8-dihydroxynaphthalene. *Aspergillus fumigatus* can synthesize melanin-type pigments from 1,8-dihydroxynaphthalene, while *Serratia marcescens* (Trias et al. 1989) or the pathological fungus *Cryptococcus neoformans* (Feldmesser et al. 2000) can produce similar pigments from alternate pathways.

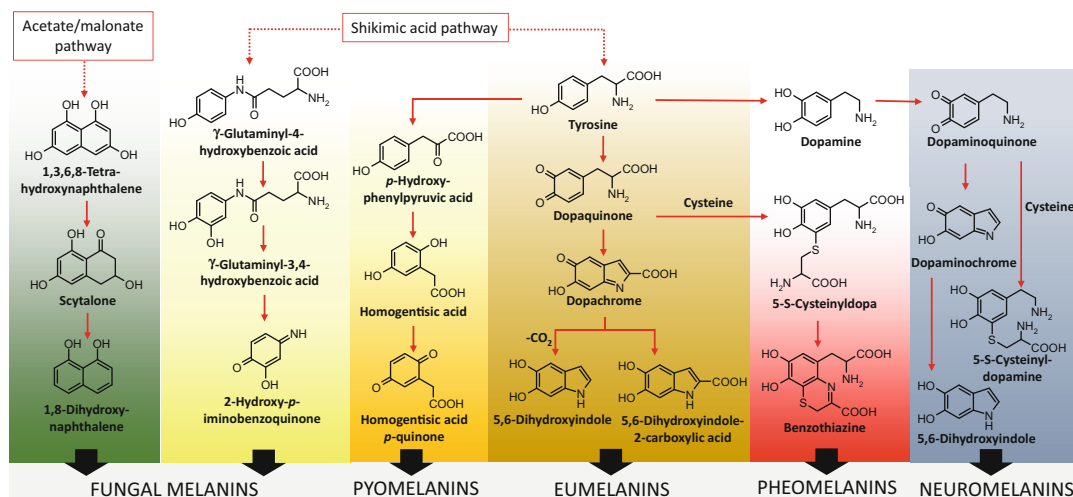
The biosynthetic pathway of bacterial pyromelanins starts from homogentisic acid, a metabolite deriving from L-tyrosine, involves the intermediate formation of the corresponding *p*-quinone derivative, and proceeds through an oxidative polymerization process.

A schematic outline of the biosynthetic pathways is reported in Fig. 2.

Key Research Findings

Production of melanin is now recognized as a universal adaptive behavior of living organisms to variable environmental conditions and cues. The presence of various types of melanins throughout the phylogenetic scale underscores the potential evolutionary importance of melanogenesis, which could be rooted in the peculiar physical and chemical characteristics of its products. Although the subject of multidisciplinary investigations since time immemorial, the biological roles of melanins are still a matter of debate. Besides photoprotection in human skin and exposed organs, accepted melanin functions include camouflage, antioxidant and free radical scavenger defense, UV dissipation, ionic conductor behavior, and de-toxication via binding of metals and xenobiotics.

At the lowest evolutionary levels, which may be of closer relevance to prebiotic processes, the ability to produce melanin from various phenolic substrates is typical of various microorganisms. Thus, the possible scenario of evolution of melanogenesis would include extracellular oxidative polymerization of phenolic compounds to active secretion of substrates and enzymes supporting this process, followed by a gradual adaptation to the intracellular control of the process and delivery of melanin to the surrounding.



Melanins, Fig. 2 Schematic outline of the biosynthesis of eumelanins, pheomelanins, neuromelanins, pyromelanins, and fungal melanins

In fungi, melanins are believed to offer protection from UV light and ionizing radiation as well as resistance to heat or cold (Wang and Casadevall 1994; Malo and Dadachova 2019). The ability of melanized fungi to survive high doses of ionizing radiation and the associated extreme environments is a particular example of radioresistance in which melanin provides not only physical resistance to ionizing radiation but also the ability to dynamically respond to such conditions. This latter can be related to the phenomenon of radiotropism, that is, the ability to grow toward a radiation source, as reported for melanized fungi such as *Aspergillus versicolor* and *Cladosporium cladosporioides* isolated from the Chernobyl reactor (Zhdanova et al. 1991). The growth of these strains toward radioactive particles and the capacity to adsorb them was observed to correlate with the degree of pigmentation.

In addition to protection from radiation, melanins in microbial organisms may serve as electron acceptors or carriers to produce energy under anaerobic conditions, may help maintain ion balance via electron exchange with insoluble compounds of iron (Menter and Willis 1997), and may be a factor of virulence in pathogenic microorganisms by lowering the vulnerability to the defense mechanisms of the hosts. In the case of eukaryotic microbial enzymes melanin

production is normally associated to modification of the cellular wall. Several reviews collect current knowledge about melanin roles and functions in low organisms (Tran-Ly et al. 2020).

Melanins, regardless of, and despite structural and biosynthetic differences, display a common set of physicochemical properties that can be taken as a useful criterion to classify a complex organic polymer as a melanin. These properties include, among others, (a) almost complete insolubility in water and organic solvents; (b) a black or dark coloration due to broadband, often featureless absorption spectra covering the entire UV-visible range; (c) an intrinsic paramagnetic character responsible for a broad stable EPR signal; (d) semiconductor-type electrical conductivity properties; (e) efficient non-radiative excited state deactivation; (f) a redox behavior associated with a marked antioxidant activity; and (g) a strong metal cation binding and drug affinity.

These and other properties have been recently reviewed in terms of the marked structural heterogeneity of melanins. Such a heterogeneity derives in part from the participation of different monomer units in the growing polymer backbone and in part from post-synthetic modifications, and accounts for a high level of chemical complexity stemming from various interrelated levels of structural disorder (d'Ischia et al. 2020).

Future Directions

Melanin pigmentation is an adaptive phenomenon widespread in living organisms from man to bacteria and extensively documented in fossil records. It occurred very early in all living organisms and that can be probably traced back to the earliest forms of life or even to the origin of life itself (Zhang et al. 2010; Glass et al. 2012). Melanin is a multifunctional polymer-like complex chemical system displaying the ability to absorb a wide range of radiations (Brenner and Hearing 2008; Liu et al. 2013), to serve as an antioxidant and radical scavenger (Ju et al. 2011), to chelate metals and bind organic compounds (Tran-Ly et al. 2020), and to transduce redox signals. Melanogenesis may thus have developed as a survival strategy for many organisms suffering extreme or unfavorable environmental conditions. Starting from these evidences, future perspectives will concern the exploitation of the properties of melanins to design a set of innovative and high-performing materials for applications in different fields.

Cross-References

- Bacteria
- Cysteine
- Fungi
- Polymer
- Tyrosine
- UV Radiation

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Membrane

Irma Marín
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Ciudad
Universitaria de Cantoblanco, Madrid, Spain

Keywords

Bilayer · Energy conservation · Glycerol-ester lipids · Glycerol-ether lipids · Lipids · Proton-motive force · Transmembrane proteins · Transport

Synonyms

Cell membrane; Cytoplasmic membrane; Plasma membrane

Definition

A membrane is a fine structure that encloses the ► [cell](#) and separates the cytoplasm from the environment. In eukaryotic cells, membranes compartmentalize organelles to segregate processes and components.

Overview

The cell membrane is a thin bilayer (5–8 nm) of complex lipids embedded with proteins as depicted in the Fluid Mosaic Model. The bilayer is arranged so that the polar ends of the lipids form the outermost surface of the membrane while the nonpolar ends form the center of the membrane bilayer. ► [Bacteria](#) and ► [Eukarya](#) have membranes composed mainly of glycerol-ester lipids, whereas ► [Archaea](#) have membranes composed of glycerol-ether lipids. Archaeal lipids are based upon nonpolar isoprenoid side chains. The proteins of the membrane can be of two different types: transmembrane or integral membrane proteins, which are inserted into the ► [lipid bilayer](#) and in some cases bound to the lipids; and peripheral membrane proteins, which are usually attached by ionic bonding to the protruding portion of some integral membrane proteins.

Membrane structure and composition make them selectively permeable, allowing only certain substances to enter or leave the cell. Dissolved gases and lipid soluble molecules simply diffuse passively across the bilayer but all other molecules require carrier molecules to transport them through the membrane by active transport. In transport processes, cells use transport membrane proteins and metabolic energy to transport substances across the membrane against concentration gradients. Depending on the carrier protein, the energy is provided by proton-motive force, the hydrolysis of ATP, the breakdown of some other

high-energy compound, or other substance concentration gradients.

A number of functions associated with the internal membranes of eukaryotic organelles are carried out in bacteria by the cell membrane as well as some other functions of bacterial membranes including energy production, motility, ► [endospores](#) formation, binary fission, cell adhesion, cell signaling, and attachment point for cytoskeleton.

The ► [gram-negative bacteria](#) cell envelope contains an additional outer membrane, the lipopolysaccharide (LPS) layer, composed of phospholipids and lipopolysaccharides, which face the external environment.

Psychrophilic and psychrotolerant bacteria have different strategies to adapt to low temperature, one of which is the ability of the cell to modulate the fluidity of the membrane by altering the fatty acid composition by including high concentrations of lipids with unsaturated fatty acids in their membranes. Similarly, highly saturated fatty acids in the cell membrane of thermophiles maintain their integrity even at high temperatures. Hyperthermophilic Archaea have side chains of covalently bonded glycerol tetraethers forming a lipid monolayer that resist melting at the high temperatures at which they grow.

Some compounds can alter microbial cell membranes and are used to control bacterial infections.

The formation of membranes to separate the contents of the cell from the environment is considered an important event in the early steps of the origin of life.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Bioenergetics](#)
- [Cell](#)
- [Cell Membrane](#)
- [Cell Wall](#)
- [Endospore](#)
- [Eukarya](#)
- [Extremophiles](#)
- [Gram-Negative Bacteria](#)

- [Hyperthermophile](#)
- [Lipid Bilayer](#)
- [Proton Motive Force](#)

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Membrane Potential

David Deamer

Department of Chemistry, University of California, Santa Cruz, Santa Cruz, CA, USA

Keywords

Concentration gradient · Nernst equation · Polarization · Selective permeability

Synonyms

[Diffusion potential](#); [Nernst potential](#)

Definition

Membrane potential is the difference in electric potential produced across membranes by ionic ► [concentration gradients](#), if the membrane barrier contains channels that preferentially allow either cationic or anionic solutes to flow through. Membrane potential is measured in units of volts or millivolts.

Overview

Living cells today have evolved a variety of trans-membrane channel proteins that allow sodium or potassium ions to pass through the ► [lipid bilayer](#) barrier of membranes. Gradients of these ions are

produced and maintained by the action of ion transport enzymes that use ► [ATP](#) as an energy source. Potassium ions, carrying a positive charge, tend to diffuse down their concentration through the ion specific channel, while sodium and chloride ions cannot. As a result, the membrane becomes polarized, positive outside and negative inside, and the polarization is measured as a membrane potential. The voltage is described by the Nernst equation, a simplified form of which is:

$$V = 0.059 \log \left(\frac{C_o}{C_i} \right) \quad (1)$$

where C_o and C_i are the external and internal concentrations of an ion such as potassium. Typical gradients are approximately tenfold, and from the Nernst equation, a tenfold gradient produces a membrane potential of 0.059 V, or 59 mV.

Membrane potentials can also be produced by the active transport of protons. The electron transport systems of bacteria are capable of pumping 1,000-fold gradients of protons, equivalent to 180 mV. Mitochondria and ► [chloroplasts](#) are evolutionary descendents of bacteria and also pump protons. According to the chemiosmotic theory, a membrane potential of protons is the essential energy source for ATP synthesis. The relation to early forms of life is that at some point the membranes of primitive bacteria were able to generate and maintain a membrane potential, so that chemiosmotic ATP synthesis could occur. How this could happen remains an open question for research on the origin of life.

Cross-References

- [Bioenergetics](#)
- [Cell Membrane](#)
- [Concentration Gradients](#)
- [Lipid Bilayer](#)
- [Permeability](#)

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Mensa/Mensae

Daniela Tirsch

German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

Synonyms

[Table mountain](#)

Definition

The term mensa, meaning table or plate, is used for a flat-topped rise with cliff-like edges on ► [Mars](#) and ► [Jupiter's](#) moon ► [Io](#). These topographic features can be built by the action of fluids or lava resulting from the erosion of adjacent, less resistant material. On Mars the term mensae is also used for long scarps along the highland–lowland boundary as well as for flat-topped deposits of layered sediments (i.e., Interior Layered Deposits, ILDs) located in the chasmata of ► [Valles Marineris](#).

Cross-References

- [Io](#)
- [Jupiter](#)
- [Mars](#)
- [Valles Marineris](#)

MER, Spirit, and Opportunity (Mars)

Claude D’Uston

Géophysique Planétaire & Plasmas Spatiaux, Institut de Recherche Astrophysique et Planétologique, Toulouse, France

Keywords

Mars

Synonyms

Mars exploration rovers

Definition

Mars Exploration Rover (MER) is a ► [NASA](#) mission composed of two identical robot geologists, SPIRIT and OPPORTUNITY, which were launched separately in June and July 2003, respectively. After their successful landing on the surface of ► [Mars](#) in January 2004, in areas near the equator, they started exploring their landing sites, searching for clues of past water activity on Mars. Both Mars Exploration Rovers were designed to last 90 ► [sol](#) (a Martian day = 1.027491 Earth days). SPIRIT has been operating for 6 years 2 months and 25 days; it drove 7.73 km. OPPORTUNITY is still functioning more than 11 years after landing and with an odometry of more 42 km.

Overview

The MER mission is part of the Mars exploration program that NASA has conducted regularly to decipher the history of this planet, to find whether life ever existed there, and to prepare a future human visit.

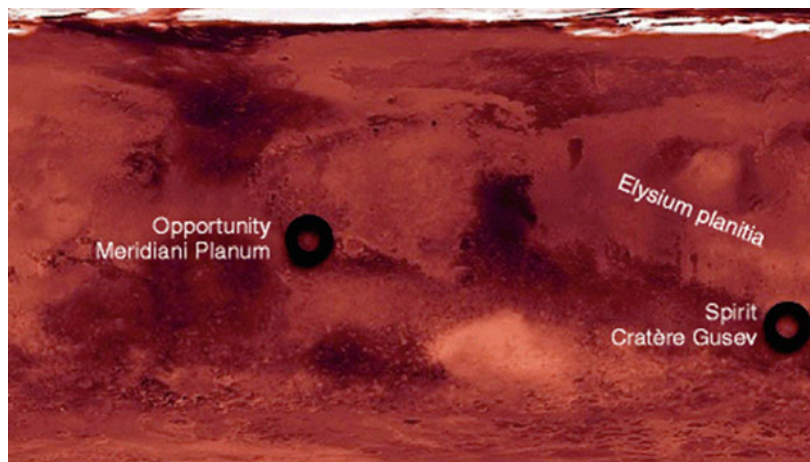
After the previous missions, both in orbit (► [Mars Global Surveyor](#) [MGS], ► [Mars Odyssey](#)) and on the surface of Mars (Viking 1 & 2, ► [Mars Pathfinder](#)), it appeared likely that liquid water had been present in the past on the surface of Mars. Then, the questions were when in the history of Mars, and how long were those periods of liquid water.

The MER mission consisted in sending to Mars two identical robotic rovers to explore areas of Mars that were selected because they presented likely indications of past activity of water. These landing sites were chosen among areas that satisfied the engineering constraints for a safe landing (Fig. 1). One is within the flat-floored Gusev crater (14.57°S, 175.47°E) at the end of the large valley Ma'adim Vallis, suggesting that the materials inside were deposited in a crater lake. The second one is in Meridiani Planum (354.47 E, 1.95°S), composed of basaltic sand and sparse outcroppings, where the identification of coarse-grained hematite in MGS Thermal Emission Spectrometer (TES) spectra and the geologic setting from Thermal Emission Imaging System (THEMIS) data could arguably indicate the influence of liquid water.

Within just a few months of arriving on Mars, both Spirit and Opportunity fulfilled their mission objectives and discovered evidence that large quantities of water used to be on the surface of Mars. Spirit discovered hints that water had acted on a ► [rock](#) called Humphrey, while Opportunity

M

MER, Spirit, and Opportunity (Mars),
Fig. 1 Location of the
landing sites (Credit:
NASA/JPL)



found layers of sedimentary rock that would have been formed by deposits in water. Both rovers continued to find additional evidence for the presence of water.

Over the course of their mission on the surface of Mars, both rovers traveled several kilometers. Spirit climbed a small mountain, and Opportunity crawled into a large crater to sample the walls for evidence of past water. And both rovers continued to perform quite well, for many years beyond their originally estimated life spans. In total, Spirit traveled 7.76 km and survived three martian winters, while OPPORTUNITY covered more than 42 km, and is still progressing, and has survived six martian winters.

Basic Methodology

The rovers and their operational capacities were designed according to the scientific objectives of the mission, which were defined following the general motto “Follow the water.” Its main objectives are to search for and characterize a variety of rocks and soils, in particular, samples that could have minerals deposited by water-related processes and to determine their distribution in the surroundings of the landing sites in order to determine what geologic processes have shaped the local terrain and influenced the chemistry. The rovers should also search for geological clues to the environmental conditions that existed when liquid water was present, in order to assess whether those environments were conducive to life.

Consequently, each rover is equipped with a suite of science instruments to read the geologic record at each site, to investigate what role water played there, and to determine how suitable the conditions would have been for life.

The scientific instrument suite consists of the following:

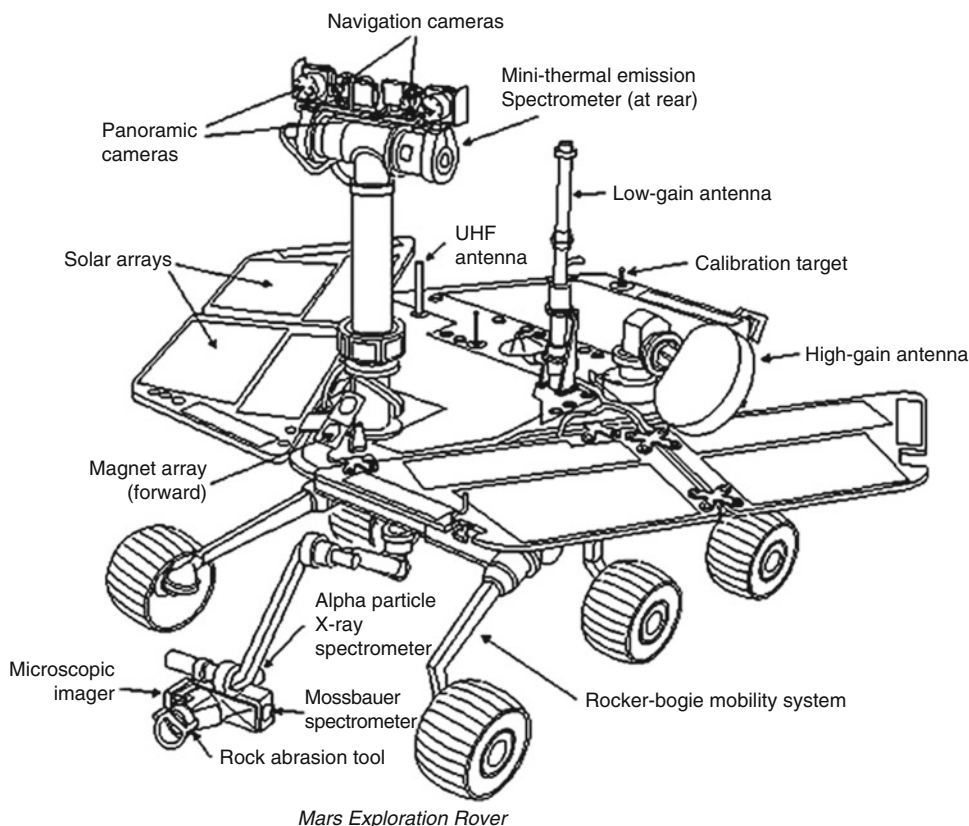
1. A panoramic Camera (PANCAM) mounted 1.5 m high on the Pancam Mast Assembly, for characterizing the local terrains; it is a stereo pair with eight possible filters for each eye.

2. A miniature infrared spectrometer for the thermal emission (miniTES) whose mirror is also mounted on the mast near the PANCAM, to determine the mineral composition of rocks and soil.
3. A microscope camera imager (MI) at the end of the robotic arm to obtain close-up high-resolution macroscopic images of target rocks and soil.
4. An alpha particle and X-ray fluorescence Spectrometer (APXS), for close-up analysis of the abundances of elements that make up rocks and soils.
5. A Mössbauer spectrometer (MB) for close-up investigations of the mineralogy of iron-bearing rocks and soils.
6. A rock abrasion tool (RAT) for removing dusty and weathered rock surfaces and exposing fresh material for examination by the suite of instruments.
7. Three sets of magnets for collecting magnetic dust particles. The particles are analyzed by the Mössbauer spectrometer and x-ray spectrometer to help determine the ratio of magnetic particles to nonmagnetic particles and the composition of magnetic material.

The two rovers are identical six-wheeled, solar-powered robots with a mass of 180 kg (Fig. 2). Each Mars rover communicates with Earth using antennas that transmit information to either Deep Space Network (DSN) antennas on Earth or to any spacecraft orbiting Mars, which in turn relays the information to land-based stations on Earth.

To move autonomously on the uneven surface of Mars, the rovers use three pairs of monochromatic cameras and navigation software which identifies obstacles; the pairs of cameras allow for 3D vision and are located at the front and at the rear under the solar panel deck, and on top of the mast to allow for a larger view used for planning the displacements.

They are also equipped with a robotic arm called the instrument deployment device (IDD), which holds a grinding tool (RAT) and in situ instruments (MI, APXS, and MB).

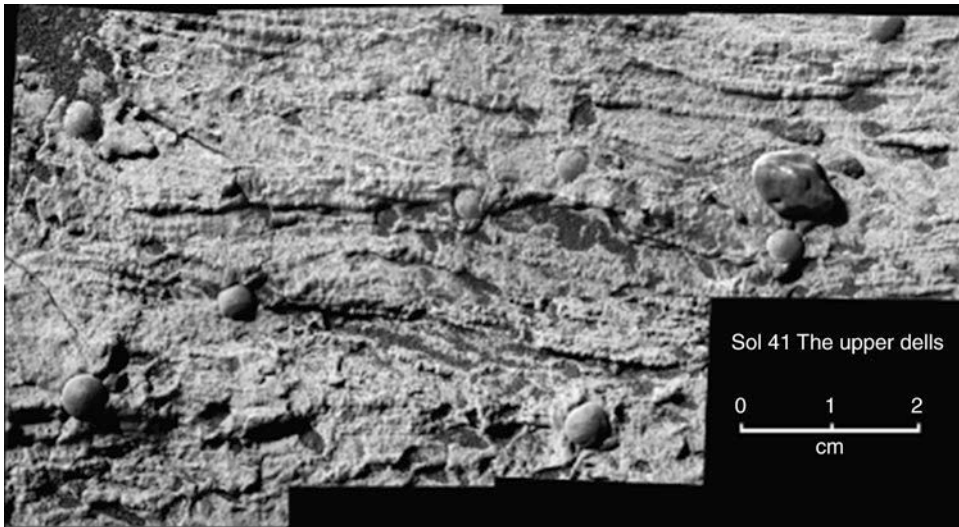


MER, Spirit, and Opportunity (Mars), Fig. 2 Description of the main elements of the MER rover

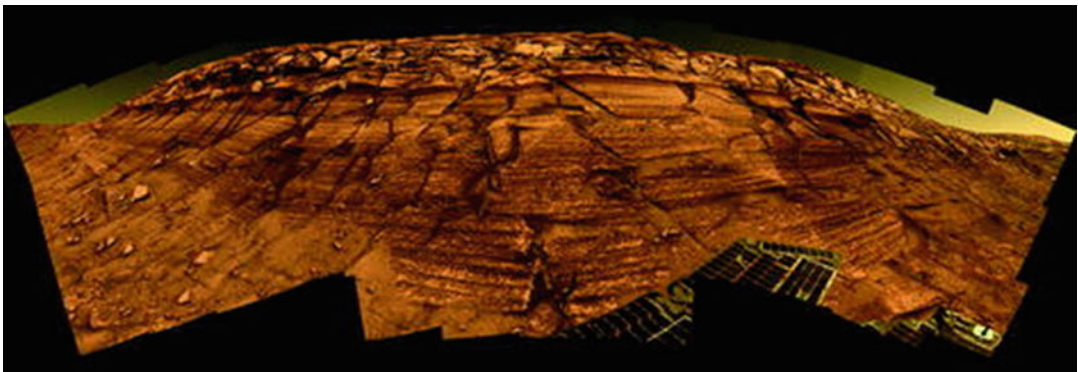
Story Board of the Mission

The main events that marked the exploration of either rover are listed below:

- Landings occurred on January 4 for SPIRIT and on January 25, 2004, for OPPORTUNITY. At first, the Gusev area appeared as dry and devoid of past water activity, similar to Mars Pathfinder or Viking landing sites. On the other side of the planet, OPPORTUNITY found itself in the middle of a small depression caused by impact, the Eagle crater, which revealed rock outcrops showing layering and composition that could be sediments deposited by water (Fig. 3).
- On March 11, 2004, Spirit reached Bonneville crater hoping for a view of underlying bedrock, but none was visible and it was decided to continue toward the Columbia hills.
- On April 30, 2004, OPPORTUNITY arrived at Endurance crater and started to explore its inner slope until it exited on September 22 (Fig. 4).
- On June 15, 2004, SPIRIT arrived at the foot of the Columbia Hills and started observing very different rocks that suggested that they had undergone water alteration (Fig. 5). Then, while climbing, several dust devils were observed, some of them cleaning the solar panels, thus allowing for a supplement of electric power.
- On August 21, 2005, SPIRIT reached the summit of Husband Hill. It then went on downhill, making more analyses of the different outcrops and soils.
- On February 7, 2006, SPIRIT reached the semicircular rock formation known as Home Plate. It is a layered rock outcrop, and it is



MER, Spirit, and Opportunity (Mars), Fig. 3 Magnified view of a portion of outcrop rock seen in Eagle crater, which is interpreted as sediments that were laid down in flowing water (Credit: NASA/JPL)



MER, Spirit, and Opportunity (Mars), Fig. 4 View of the “burncliff” formation within Endurance crater that shows stratification that was analyzed to decipher the emplacement history (Credit: NASA/JPL)

thought that its rocks are explosive volcanic deposits, though other possibilities exist, including impact deposits or wind/waterborne sediment.

- OPPORTUNITY arrived at Victoria crater on September 27, 2006, and started to observe from around its rim. After a large dust storm faded away, OPPORTUNITY entered Victoria crater in September 2007 and analyzed the rock layers until exiting on August 29, 2008.
- OPPORTUNITY continued its way toward the very large Endeavour crater 12 km further

south; it is progressing through sand dunes fields, making detours to avoid the most risky paths.

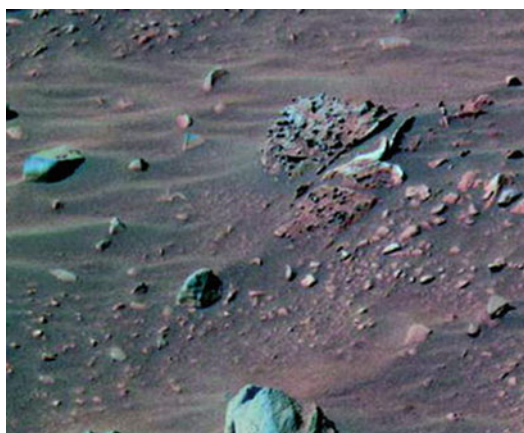
- Since May 2009, SPIRIT had been stopped with its wheels sunk in very loose sand on the west of Home Plate. After unsuccessful attempts to extricate the rover from this trap, NASA redefined the robot mission as a stationary research platform.
- End of March 2010, SPIRIT went into hibernation at her location on the west side of Home Plate due to low electric power production

during Martian winter. Next Martian spring started in November 2010. When Martian spring and then summer passed without receiving any signal from SPIRIT, the enduring rover mission had been declared over in May 2011.

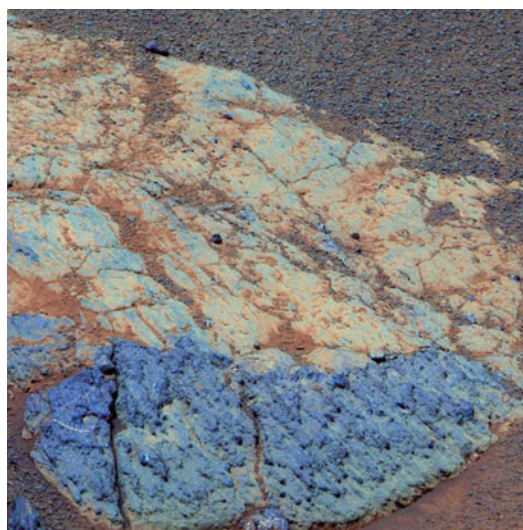
- On its way to the large crater Endeavour, OPPORTUNITY stopped on December 16, 2010, by a fresh crater named Santa Maria, and it stayed there during conjunction and analyzed a piece of outcrop in which the MRO CRISM instrument had identified kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$), a hydrated mineral not seen before by OPPORTUNITY.
- OPPORTUNITY entered the western rim of Endeavour crater on August 9 after a total drive of ~ 33.5 km. This crater is a Noachian period impact, and the largest visited by the rover with a diameter of about 22 km.
- In a thorough examination of a part of the western rim called Cape York, OPPORTUNITY spent almost 2 years including its fifth winter campaign. It made a stratigraphy analysis of this ridged hill.
- From May 2012 to April 2013, the robot field geologist has been on an excursion, traveling back in geologic time on Matijevic Hill, located along the inboard side of the Cape York segment of Endeavour's rim. It has found mystery "newberries," and veins of

gypsum, large and small, running through bedrock and ancient soft rocks, the residual signs of clay minerals of which OPPORTUNITY observations support the identification of smectite as derived from MRO CRISM data. These findings bring solid evidence that once, long, long ago, lots of flowing water, kind of like water on Earth, created a habitat there suitable for the emergence of life.

- OPPORTUNITY continued then its route along the western rim of Endeavour's crater toward Solander point where it has found a larger set of strata and stayed during its sixth Martian winter (Fig. 6).
- In the course of its exploration along the western rim of Endeavour, OPPORTUNITY went up and down through hills, craters and valleys looking for more hints of the liquid water history of Mars.
- At some point in 2015, it's flash memory couldn't anymore keep the files over sleeping times and the onboard software had to be



MER, Spirit, and Opportunity (Mars), Fig. 5 False-color image taken by the panoramic camera on the Mars Exploration Rover Spirit shows the rock dubbed "Pot of Gold" located near the base of the Columbia Hills in Gusev Crater (Credit: NASA/JPL)



MER, Spirit, and Opportunity (Mars), Fig. 6 This picture shows one of the light-tone, flat Whitewater Lake rocks that are harboring the smectite clay minerals the MER team came looking for at Endeavour Crater. The rover saw these flat, light-tone rocks all around her in mid-November as she completed her survey Matijevic Hill. The Pancam team processed this picture in false color to better show the dark coating or rind that immediately set these stones apart (Credit: NASA/JPL-Caltech/Cornell/UA)

modified so that the rover could continue its operational capabilities.

- In 2016, while looking down the Marathon Valley, OPPORTUNITY recorded an image of a Martian dust devil (Fig. 7); such phenom-



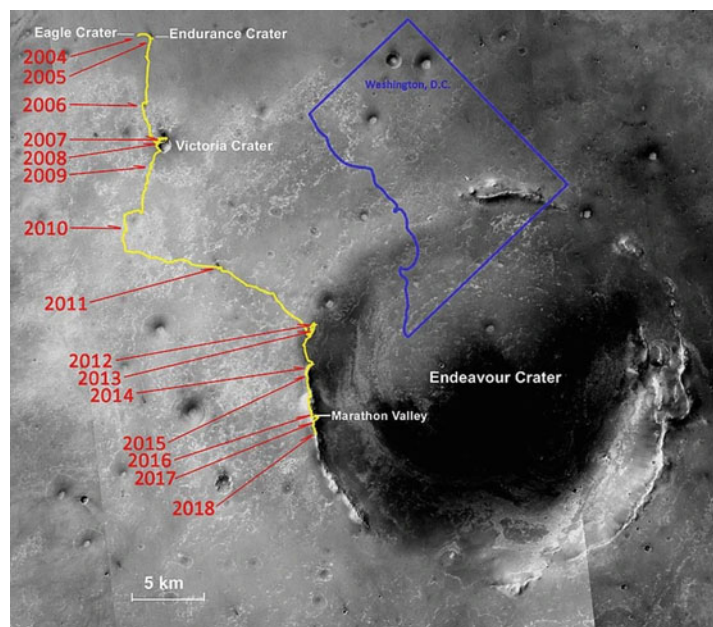
MER, Spirit, and Opportunity (Mars), Fig. 7 From the height of the Marathon Valley, OPPORTUNITY caught this picture of a dust devil twirling within Endeavour crater. (Credit: NASA/JPL-Caltech/MSSS)

ena have been commonly observed by SPIRIT in the Gusev crater, but were rare over Meridiani planum.

- In early June 2018, while in the flank of Perseverance Valley, one of the most intense ever observed dust storm covered a large part of the Martian surface. It has effectively blocked the sunlight preventing OPPORTUNITY of receiving enough energy and sent the rover into hibernation on sol 5111 (June 10, 2018); on this date OPPORTUNITY had sent his last message. After this massive storm had last until August, many attempts were made to recover any contact with the rover until February 13, 2019, when NASA declared that the mission had come to an end.

Beyond its exceptional duration, OPPORTUNITY had traveled a record distance of 45.16 km (Fig. 8), transmitted 217,594 images of Mars, exposed the surfaces of 52 rocks to reveal fresh mineral surfaces for analysis and cleared 72 additional targets with a brush to prepare them for inspection with spectrometers and a microscopic imager.

MER, Spirit, and Opportunity (Mars), Fig. 8 OPPORTUNITY lifetime progress year after year; Washington DC is superimposed for size comparison (credit: James919 — Travail personnel, CC BY-SA 4.0)



Key Research Findings

Signs of the past presence of water indicated that there has been liquid water in large quantities and for long periods of time. Little spherules that contain ► **hematite** (Fe_2O_3), called “blueberries,” have been found by OPPORTUNITY everywhere on the Meridiani Planum; they are considered as an indicator of a long presence of liquid water. There have been also other signs in the fine outcrop layering, or in the presence of vugs (small to medium-sized cavities inside rocks) in the bedrock, and with the identification of ► **Jarosite**, a basic hydrous sulfate of potassium and iron. In the Columbia Hills, Spirit found also very typical minerals, in particular, pure silica, and also ► **goethite** ($\text{FeO}(\text{OH})$), and for the first time some long-sought-after carbonate.

All those observations indicate that the past environment at these locations was wet, possibly favorable to life. Furthermore, the variety of such places in which life could have found a way to emerge demonstrates that there are more places on Mars where conditions were good for a long period of time than previously imagined.

The atmospheric temperature variations through several Martian years have been recorded; density and composition of atmospheric dust and water ice ► **aerosols**, together with the obscuring of solar light, have been observed by both rovers. Numerous dust devils were seen during spring and at the beginning of summer.

Cross-References

- **Basalt**
- **Hematite**
- **Jarosite**
- **Landing Site**
- **Life in the Solar System (History)**
- **Mars**
- **Mars Global Surveyor**
- **Mars Pathfinder**
- **Meridiani (Mars)**
- **Rock**
- **Sol**
- **Sulfate Minerals**
- **Water Activity**

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Mercapto Radical

► Sulfur Hydrides in the Interstellar Medium

Mercaptomethane

► Methanethiol (CH₃SH)

Mercury

Jörn Helbert
DLR, Institut für Planetenforschung, Berlin,
Germany

Keywords

Core · Exosphere · NASA mission Mariner 10 · NASA mission Messenger

Definition

Mercury is the innermost ► [planet](#) and the smallest of the four ► [terrestrial planets](#). It is the only terrestrial planet except Earth to have a global magnetic field. Mercury shows the most extreme surface temperature variations of all terrestrial planets. The average surface temperature is 442.5 K, with dayside temperatures up to 700 K and nightside temperatures down to 80 K. Mercury has a tenuous exosphere containing hydrogen, helium, oxygen, sodium, calcium, and potassium. This exosphere

is not stable – atoms are continuously lost and replenished from a variety of sources.

Overview

So far, only two spacecrafts have visited Mercury. The NASA mission Mariner 10 made 3 flybys in 1974 and 1975. The NASA mission MESSENGER made three flybys between 2007 and 2009 and has entered orbit around the planet in March 2011. The ESA mission BepiColombo will observe the planet from orbit starting 2019. Observing Mercury from ► [Earth](#) is challenging. While it is bright, ranging from –2.3 to 5.7 in apparent magnitude, the greatest angular separation from the Sun is only 28.3°. Since Mercury is normally lost in the glare of the Sun, unless there is a solar eclipse, Mercury can only be viewed in morning or evening twilight.

With a radius of 2,439.7 km, Mercury is the smallest of the terrestrial planets and its evolution and formation can provide important clues to the formation of planetary systems in general.

With 5.427 g/cm³, Mercury has the second highest density of all terrestrial planets (Earth: 5.515 g/cm³). It has the highest metal-to-silica ratio of all planets or satellites. The surface mineralogy seems to be dominated by plagioclase. The ► [magnetic field](#) of Mercury has about 1.1% of the strength of the Earth's magnetic field. Observations by the NASA spacecrafts Mariner 10 and MESSENGER have indicated that the strength and shape of the magnetic field are stable. The high density and the magnetic field combined lead to the assumption that Mercury has a large iron core occupying about 42% of its volume, compared to 17% for Earth. There are several competing theories for the origin of this large core during the formation of Mercury, ranging from a giant impact that striped the planet of its crust to inhomogeneities in the early solar nebular leading to an enrichment of proto-Mercury in iron.

Mercury has a mean heliocentric distance of 0.3871 AU. One orbit around the Sun takes 87.969 days; in this time, the planet performs 1.5 rotations. This 3:2 spin-orbit coupling has been explained by Giuseppe Colombo. Given the eccentricity of Mercury's orbit, the 3:2 coupling

minimizes the tidal torque (see tides) on the planet during perihelion passage.

The exosphere of Mercury is formed by thermal desorption and sputtering of surface material, as well as captured solar wind particles. The NASA MESSENGER spacecraft detected indications for water in the exosphere, most likely formed from solar hydrogen and oxygen sputtered off the planet's surface.

Radar observation from Earth show bright regions close to Mercury's poles. This could be an indication for water ice deposits in permanently shadowed craters.

Cross-References

- [Core, Planetary](#)
- [Crater, Impact](#)
- [Earth](#)
- [Magnetic Field](#)
- [Planet](#)
- [Satellite or Moon](#)
- [Sun \(and Young Sun\)](#)
- [Terrestrial Planet](#)
- [Tides, Planetary](#)

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Meridiani (Mars)

Ralf Jaumann
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

Meridiani Planum is an extended plain on ► [Mars](#) centered at 357.5°E/0.2°N in the western part of

an ► [albedo feature](#) called Sinus Meridiani. Meridiani Planum was the landing site of the ► [Mars Exploration Rover Opportunity \(MER\)](#) in 2004. In Meridiani Planum cross-bedded sedimentary rocks are exposed that contain crystalline ► [hematite](#) (Fe₂O₃) and sulfate-rich ► [minerals](#) such as ► [jarosite](#). The presence of the latter mineral indicates an acid and saline environment and a soil saturated with liquid water during a considerable period of time. Airy-0, a small crater of 0.5 km in diameter at 0°E/5.1°S, defines the prime meridian of Mars. It is located within the larger (40 km) crater Airy in southern Meridiani Planum.

Cross-References

- [Albedo Feature](#)
- [Crater, Impact](#)
- [Hematite](#)
- [Jarosite](#)
- [Mars](#)
- [MER, Spirit, and Opportunity \(Mars\)](#)
- [Mineral](#)
- [Planum](#)
- [Water Activity](#)

Mesophile

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

The term mesophile is mainly applied to ► [micro-organisms](#), and it refers to microbes whose optimal development temperatures are moderate, ranging from 15 °C to 45 °C. They are probably the most abundant and conspicuous group of microbes and their habitats are widely distributed, from soils to water to animal niches. Most of the pathogens for humans (bacteria and viruses) belong to this group.

Cross-References

- ▶ [Bacteria](#)
- ▶ [Microorganism](#)
- ▶ [Prokaryote](#)

Mesosphere

Sébastien Lebonnois
Laboratoire de Météorologie Dynamique
(LMD/IPSL), Sorbonne Université, CNRS, Paris,
France

Definition

In this region, as in the stratosphere (located below when existing), the dominant mode of energy transfer is radiation, with a balance between the energy absorbed from the stellar irradiation by gaseous components and particles when present, and the energy reemitted by these components at infrared wavelengths. This balance in these regions is characterized by local thermodynamic equilibrium, which means that the energy distributions of the molecules are in equilibrium and follow the Boltzmann distribution.

The mesosphere is characterized by a temperature that is either constant or decreasing with altitude. In Venus and Mars, the mesosphere is mostly isothermal and located immediately above the tropopause.

The upper boundary of the mesosphere is called the mesopause (at roughly 85 km altitude for the Earth). The thermosphere is the region above the mesopause.

Cross-References

- ▶ [Atmosphere, Structure](#)
- ▶ [Giant Planets](#)
- ▶ [Stratosphere](#)
- ▶ [Terrestrial Planet](#)
- ▶ [Thermosphere](#)
- ▶ [Troposphere](#)

Messenger

Johannes Benkhoff
ESA-ESTEC, Noordwijk, The Netherlands

Keywords

Space mission · NASA discovery program · Planet Mercury · Evolution of the Solar System

Definition

MESSENGER (MERcury Surface, Space Environment, GEOchemistry, and Ranging) is a NASA (Discovery class) space mission which flew by Mercury three times in 2008/2009 before going in an orbit around our innermost planet in March 2011. It stayed in orbit for over 4 years before it intentionally crashed on the surface on 30 April 2015. Until that MESSENGER orbited Mercury more than 4100 times, its camera system took more than 290,000 images, and its instruments have made many unique and sometimes also surprising measurements which largely increased our knowledge about Mercury.

History

The spacecraft was designed and built by the Johns Hopkins University Applied Physics Laboratory – with contributions from research institutions and companies around the world (McNutt et al. 2006; Solomon et al. 2001). The spacecraft's graphite composite structure was integrated with a low-mass propulsion system. The spacecraft was protected behind a 2.5-meter by 2-meter sunshade to keep temperatures low and enabling the spacecraft and instruments to operate in the harsh environment around Mercury. The spacecraft was launched aboard a Delta II rocket on 3 August 2004. The journey took more than six and a half years. MESSENGER used six gravity-assists one at Earth, two at Venus, and three at Mercury

before it could be inserted into orbit around Mercury.

During its three Mercury flybys, it provided first close-up looks of the surface of Mercury in more than 30 years (after NASA's Mariner 10 spacecraft flew by Mercury in 1974/1975). At that time, MESSENGER photographed also areas of Mercury not imaged during the Mariner 10 encounters.

The science goal of MESSENGER was to contribute to the understanding of Mercury, the smallest, densest, and least explored of the terrestrial planets.

The science payload onboard MESSENGER consist of the following instruments:

- **Mercury Dual Imaging System (MDIS)** – detailed color and monochrome images of Mercury's surface.
- **Gamma-Ray and Neutron Spectrometer (GRNS)** – element composition of the planet including the polar areas.
- **X-Ray Spectrometer (XRS)** – elements in Mercury's crust.
- **Magnetometer (MAG)** – Mercury's magnetic field investigations.
- **Mercury Atmospheric and Surface Composition Spectrometer (MASCS)** – atmospheric species and surface composition.
- **Energetic Particle and Plasma Spectrometer (EPPS)** – charged particles in Mercury's magnetosphere.
- **Mercury Laser Altimeter (MLA)** – topography of surface features; determines whether Mercury has a fluid core.
- **Radio Science uses Doppler tracking** – Mercury's mass distribution.

Measurements performed by MESSENGER have shown that volcanism has played a critical role in shaping Mercury's surface. Mercury is abundant in volatile elements, which was not expected for such a small planet and has changed our view about the formation and early history of the innermost planet. Results have further shown that Mercury contracted by as much as 7 km in radius. MESSENGER discovered a geologic landform called Hollows. These shallow,

irregular depressions are some of the brightest and youngest features on the surface of Mercury and have not yet been seen on other planets. It could be demonstrated that Mercury's polar regions very likely host water ice. Illumination models of these regions derived from the topography show that the radar-bright deposits measured from ground and indicate the presence of water are located in regions of permanent shadow. The existence of an Earth like magnetic field, but 100 times weaker, was confirmed. However, in addition, it was found that magnetic field is offset along the planetary spin axis by about 400 km to the north. Mercury's magnetosphere is highly dynamic because of the weak magnetic field and proximity to the Sun. The solar wind interacts with the magnetosphere and generates waves in particles and fields, reconnection of interplanetary and planetary magnetic field lines. MESSENGER detected electrons which seem an almost permanent part of Mercury's magnetosphere. Mercury's tenuous atmosphere scatters sunlight, and the emission brightness is proportional to its content (Solomon et al. 2018).

More information about the mission and images of the spacecraft and the instruments can be found in Solomon et al. (2018) and on the JHU/APL website (Johns Hopkins Applied Physics Lab (1999–2016)).

Cross-References

- [BepiColombo](#)
- [Mercury](#)
- [NASA](#)
- [Planetary Evolution](#)
- [Solar System, Inner](#)
- [Terrestrial Planet](#)

References and Further Reading

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Metabolic Diversity

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Metabolic diversity mainly refers to the different metabolic strategies that organisms have evolved to obtain energy. Metabolic pathways evolved among prokaryotes before eukaryotes arose as the result of their interaction and coevolution with changing physicochemical environmental conditions. Metabolic diversity is life's evolutive response enabling it to adapt to and use all available energy and organic and inorganic matter sources. Life, as we know it, follows common nutritional patterns that can be subdivided depending on energy or carbon requirements. Organisms can be classified according to their energy requirements as phototrophs, if energy comes from solar radiation, or chemotrophs, if the energy source is inorganic (► [chemolithotroph](#)) or organic (► [chemoorganotroph](#)) reduced compounds. According to the mechanism used, they can be classified as photosynthetic (oxygenic and anoxygenic), respirers (aerobic and anaerobic), and fermentors. Depending on the carbon source, organisms can be autotrophs or self-feeders, if carbon is fixed from CO₂ by the organisms, or heterotrophs or consumers, if the carbon source is already existing organic matter. Combining energy and carbon sources, organisms can be classified

into four groups: photoautotrophs (green plants, algae, and cyanobacteria), photoheterotrophs (some ► [Bacteria](#)), chemoautotrophs (some *Bacteria* and ► [Archaea](#), such as methanogens), and chemoheterotrophs (animals, fungi, protists, and most bacteria). Due to this adaptative response, metabolic diversity has tremendous astrobiological implications since such wide diversity could cover life's adaptation to other planetary conditions, especially the photoautotrophy or chemolithoautotrophy. An interesting property of some microorganisms is their metabolic versatility, which enables them to select their metabolic mode according to environmental conditions. The most versatile microorganisms known so far are the purple nonsulfur bacteria, a group of anoxygenic photosynthetic microorganisms that in the absence of light can employ aerobic and ► [anaerobic respiration](#) and ► [fermentation](#).

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Anoxygenic Photosynthesis](#)
- [Autotroph](#)
- [Bioenergetics](#)
- [Biosynthesis](#)
- [Chemoautotroph](#)
- [Chemolithotroph](#)
- [Chemoorganotroph](#)
- [Chemotroph](#)
- [Energy Conservation](#)
- [Fermentation](#)
- [Lithotroph](#)
- [Metabolism](#)
- [Oxygenic Photosynthesis](#)
- [Photosynthesis](#)
- [Phototroph](#)
- [Respiration](#)

Metabolic Networks

- [Biological Networks](#)
- [Metabolism](#)

Metabolic Organization

► [Autopoiesis](#)

Metabolic Zone

► [Redox Zonation](#)

Metabolism

María Luz Cárdenas and Athel Cornish-Bowden
Unité de Bioénergétique et Ingénierie des
Protéines, Centre National de la Recherche
Scientifique, Aix-Marseille Université, Marseille,
France

Keywords

Compartmentation · Enzymes · Metabolic
cascades · Metabolic flux · Organization ·
Pathway · Regulation

Synonyms

[Metabolic networks](#); [Minimal metabolism](#)

Definition

Metabolism is the collection of chemical reactions that define a living organism and allow it to make its components and obtain the energy required for staying alive.

History

Recognition that the processes occurring in a living organism are fundamentally chemical reactions came progressively with the decline in *vitalism* in the nineteenth century. The discovery of cell-free fermentation by Eduard Buchner sounded the death knell of vitalism and the beginning of the

unraveling of the major metabolic pathways that constitute metabolism. This process began with the understanding of ► [fermentation](#) and ► [glycolysis](#), and by the end of the 1950s, virtually all the major pathways were known.

Overview

Although a living organism is identified and recognized by its physical appearance and hence by its structure, its status as living is defined by its chemistry and thus by its *metabolism*. This is a network of reactions that is responsible for synthesizing all of the molecules needed for the organism to survive, apart from those directly available from its environment, and for disposing of molecules that are harmful or no longer required. The entire network consists of thousands of connected reactions, and as many of these need to be maintained far from equilibrium, all organisms require and consume energy.

To a first approximation, the metabolism of all organisms is the same, but there are important differences that depend on whether it is *aerobic*, requiring ► [dioxygen](#) as the ultimate electron acceptor, or *anaerobic*, which can be *facultative*, with dioxygen tolerated, or *obligate*, with dioxygen completely avoided. Some organisms, including plants and some bacteria and archaea, are ► [autotrophs](#) that produce organic compounds from inorganic precursors (CO₂ and carbonates being considered inorganic), whereas others, including all animals, fungi, and some bacteria and archaea, are *heterotrophs*, depending on other organisms as primary sources of organic materials. Aerobes use dioxygen as their primary source of oxidizing power, but anaerobes also need oxidizing precursors, such as sulfates, and can obtain oxygen from these. Heterotrophs use organic compounds ingested as food as their primary source of reducing power, but autotrophs do not require organic food. As they exist in an oxidizing environment, they cannot use inorganic reducing agents but depend on ► [photosynthesis](#) for reducing power.

Oxidation and reduction inevitably conflict with one another, and so metabolism is only

possible with a very high degree of *regulation*, preventing the terminal oxidizing and reducing agents from reacting directly with one another and similarly allowing synthesis (► *anabolism*) and degradation (► *catabolism*) to proceed without interference. Essentially no reactions must occur without *catalysis*, therefore, and the catalysts should be highly specific. With no thermodynamic prohibition of unwanted reactions, they can only be avoided by the absence of active catalysts, which is achieved by ► *enzyme* regulation and to some degree by *compartmentation* (Ginger et al. 2010), with physical barriers separating reactions that might conflict with one another: a cell is not just a bag of catalysts.

Only proteins (and to a much more limited extent RNA) can provide the necessary specificity that allows efficient catalytic activity in very mild conditions, and virtually all the catalysts of metabolism are protein-based *enzymes*. These cannot be harvested by an organism from its environment, but must be synthesized by the organism itself. Thus, although enzymes are conventionally regarded as different from *metabolites*, the chemical intermediates of metabolism, there is no fundamental distinction between them, both being produced internally from the same precursors, used internally, and broken down to the same end products.

During the course of evolution, several mechanisms have appeared that allow fine regulation of metabolism, such as *allosteric* and *cooperative* interaction of effectors with appropriate enzymes, chemical modification of enzymes (*metabolic cascades*), and compartmentation. Although cyclic pathways, such as the tricarboxylate (Krebs) cycle, have sometimes been claimed to be too complex to be the result of natural selection, a convincing analysis of the steps that could produce such a cycle has been given (Meléndez-Hevia et al. 1996).

Cross-References

- [Anabolism](#)
- [Autotroph](#)
- [Bioenergetics](#)
- [Catabolism](#)

- [Chemotroph](#)
- [Citric Acid Cycle](#)
- [Dioxygen](#)
- [Enzyme](#)
- [Fermentation](#)
- [Glycolysis](#)
- [Photosynthesis](#)
- [Respiration](#)

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Metabolism, Prebiotic

Harold Morowitz

George Mason University, Fairfax, VA, USA

Definition

Metabolism in contemporary biology and biochemistry refers to the aggregate of chemical transformations taking place in living organisms or in ecosystems. It consists of ► *anabolism*, the buildup of compounds, catabolism, the breakdown of compounds, and the alteration of compounds for energy transformation or usage. The word itself comes from Hellenic Greek, where it refers to change.

Overview

The contemporary usage seems to go back to the 1870s where it occurs in physiology books in the

sense of chemical change. In present day ecological systems, the overall metabolic activity consists of the incorporation of carbon, hydrogen, nitrogen, phosphorous, and sulfur driven by photosynthesis or chemosynthesis, the transformation of the inputs into metabolites, the buildup of these small molecules into macromolecules and other cell structures; and, ultimately, loss due to ► [respiration](#), predation, and decay. There are common features of metabolism across all taxa: the same amino acids, the same sugars, the same ► [nucleotides](#), and the same cofactors are used. These are matched even to the level of ► [chirality](#) and the universality of the ► [genetic code](#). Many of these intertaxonomic features were gathered together in the 1950s by Donald E. Nicholson in a chart of intermediary metabolism. This material was organized and codified in 1970, in the book “*An Introduction to Metabolic Pathways*” by S. Dagley and Donald E. Nicholson. What is striking is the universality of adenosine triphosphate and its hydrolysis in bioenergy transfer processes, the universality of macromolecule synthesis, and the universality of the citric acid cycle in both energy utilization and anabolism. All anabolism comes from five compounds in the citric acid cycle and the anaplerotic loop. A number of cofactors are essential and are either synthesized or obtained as vitamins. The enormous overlap in all metabolisms indicates it is a rare accident, it is the best solution to biochemistry, or it is the only solution to biochemistry.

The overlap of metabolic intermediates is a necessity for trophic ecology, for otherwise the predator or grazer would find its food indigestible or unusable. The universality question can potentially be answered by experimental astrobiology or a theory of living systems subject to experimental test. In any case, metabolism may be regarded as a feature of an organism or an ecosystem. Indeed, the failure to grow many of the microbes of an ecosystem in pure culture suggests difficulties in defining species metabolism and questions regarding the meaning of species at the microbial level.

Energy for metabolism is derived from mineral energy sources in the environment, photoautotrophy, or oxidative heterotrophy. Biogenesis

would require one of the first two. All metabolisms require the flow of energy from a high quantum-size source to a low quantum-size sink, making metabolism consistent with the laws of thermodynamics. Complete genome sequencing allows the construction of the metabolic chart in toto, since almost all reactions require enzymes that are encoded in the genome. This has led to a common autotrophic metabolic chart, most reactions of which are universal, again suggesting universal laws of metabolism.

One way to search for microbial life on other astronomical objects is to search for core molecules of metabolism. The total absence of such molecules would indicate no life or a life so metabolically different from terrestrial life that a reframing of the question of what life is might be required. For example, it is extremely unlikely that organisms metabolically different from those on Earth could be pathogenic. In any case, the full consequence of cross-contamination of spatial bodies should be viewed in terms of metabolism.

The laws of metabolism are a necessary feature of the laws of life on Earth and must form a central feature of astrobiology.

Cross-References

- [Chirality](#)
- [Genetic Code](#)
- [Nucleotide](#)
- [Respiration](#)

Metabolism, Secondary

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Secondary ► [metabolism](#) is the subset of metabolic networks not directly involved in the

production of the essential cell components and, thus, not playing any part in cell growth and development. Secondary metabolites include chemical species with ecological functions (e.g., antibiotics) and are more or less elaborated derivatives from metabolites involved in central pathways. Thus, secondary metabolism occupies a peripheral position in metabolic networks.

Cross-References

► [Metabolism](#)

Metagenome

Víctor Parro

Molecular Evolution Department, Centro de Astrobiología (INTA-CSIC), Madrid, Spain

Keywords

Bioinformatics · Ecogenomics ·
Environmental microbiology · Metabolic
diversity · Metabolic networks ·
Metabolomics · Metaproteomics ·
Metatranscriptomics · Microbial diversity

Synonyms

[Community genome](#); [Environmental genome](#);
[Population genome](#)

Definition

The metagenome is the genetic content of a biological community. The term is mainly applied to microbial communities which can be somehow considered as a whole entity and, consequently, treated and studied as a single “meta-organism” with a single ► [genome](#). It can also be applied to subpopulations like a viral population isolated from a whole microbial community. In such case, it is called the ► [metavirome](#) (the genome

of the virome). The term “meta” comes from Greek and means “next to” or “related to.”

History

Phylogenetic studies with the DNA ► [sequence](#) of environmental rRNA genes revealed that most of the microbial diversity (up to 99 %) remained unexplored when only culturing techniques were applied. This was one of the main conclusions after the pioneering work conducted by Norman R. Pace and colleagues, who used the amplification technique called ► [polymerase chain reaction](#) to explore the diversity of ribosomal RNA sequences (Lane et al. [1985](#); Pace et al. [1985](#)). It was Jo Handelsman who in 1998 first suggested the term “metagenomics” for naming the idea that a set of ► [gene](#) sequences obtained from environmental samples could be analyzed as if they came from a single genome (Handelsman et al. [1998](#)). Since then many works have been reported where the whole genetic content of a microbial community (the metagenome) has been used either for gene sequencing and screening for novel enzymatic activities (Healy et al. [1995](#)), or for whole genome DNA sequencing (Tyson et al. [2004](#); Venter et al. [2004](#)).

Overview

The exploration of metagenomes has been tightly bound to the improvement and development of new cloning and amplification strategies and sequencing techniques, as well as advances in bioinformatics for sequence analysis. From the analysis of metagenomes, important information can be obtained about microbial and metabolic diversity as well as the versatility of natural populations. Some applications include: environmental monitoring either to follow the effect of pollutants or bioremediation technologies; monitoring of industrial processes conducted by microbial consortia; gene inventory of a microbial community either for the search of new enzymatic activities (Zhang et al. [2009](#)) or to explore the potential metabolic networks in the

community; sequencing single genomes from uncultivable microorganisms (Tyson et al. 2004); exploring potential pathogens in the microbial flora of humans and animals (Sommer et al. 2009); exploring the genetic wealth of environmental viruses from extreme environments (López-Bueno et al. 2009); exploration of the preferential gene expression in extremophilic communities for astrobiology purposes (Parro et al. 2007).

Cross-References

- [Amplification \(Genetics\)](#)
- [Biodiversity](#)
- [Bioinformatics](#)
- [Gene](#)
- [Genetics](#)
- [Genome](#)
- [Metavirome](#)
- [Polymerase Chain Reaction](#)
- [Sequence](#)

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Metal Compounds in Circumstellar Envelopes

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Definition

A number of metal (in the chemical sense, rather than the astronomical sense in which all elements heavier than He are labeled “metals”) cyanides, isocyanides, oxides, chlorides, fluorides, and hydrides have been found by radio astronomers in the circumstellar envelopes of evolved stars, predominantly in carbon-rich stars (see ► [Molecules in Space](#) and ► [Circumstellar Chemistry](#)). The observed metals include Fe, K, Mg, Na, Al, Ca, and Ti.

History

The first metal-bearing species NaCl, KCl, AlCl, and AlF were detected by Cernicharo and Guélin in 1987 toward CW Leo. Subsequent detections have included FeCN (Zack et al. 2011), KCN (Pulliam et al. 2010), HMgNC (Cabezas et al. 2013), TiO, TiO₂, and CaNC (Cernicharo et al. (2019). In the ► [interstellar medium](#), as opposed to the circumstellar environment, metals in the

chemical sense are mostly incorporated into the ► [interstellar dust](#) grains.

Cross-References

- [Circumstellar Chemistry](#)
- [Interstellar Dust](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)

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Metallicity

Nikos Prantzos
Institut d’Astrophysique de Paris, Paris, France

Definition

Metallicity specifies the relative amount of elements heavier than helium (collectively called *metals* by astronomers) in a star, galaxy, or some part of the interstellar medium. The metallicity of the Sun is $Z_{\odot} = 1.5\%$ by mass. The most metal rich ► [stars](#) in the inner Galaxy have two or three times that figure, whereas the most metal poor halo stars of the Milky Way have metallicities as

low as $0.0001 Z_{\odot}$. Usually, the abundance of some key element (like Fe or O) is used as a proxy for metallicity. Host stars of extrasolar giant planets (observed in the solar neighborhood) are more metallic than non-planet hosting stars.

Cross-References

- [Abundances of Elements](#)
- [Heavy Element](#)
- [Stars](#)

Metamorphic Rock

Jean-Emmanuel Martelat
Université Claude Bernard Lyon 1, Grenoble, France

Keywords

Metamorphic facies · Mineral assemblages · Protolith · Rock texture

Definition

A metamorphic rock forms when igneous, sedimentary, or older metamorphic rocks are subjected to heat, pressure, and strain that result in changes of their texture and mineral assemblage. The new texture, commonly characterized by aligned mineral grains and the new mineral assemblage reveals the metamorphic origin.

Overview

Characteristic metamorphic minerals are mica, garnet, aluminosilicates, chlorite, and serpentine. To give the proper name of a metamorphic rock, the petrologist refers to the nature of protolith, i.e., the rock prior to ► [metamorphism](#). Most metamorphism is isochemical, except for the gain or loss of water and other volatile components, that is, the metamorphic rock usually retains the chemical

composition of its precursor. When shale, a sediment rich in Aluminum, is metamorphosed, clay minerals are converted to aluminous minerals such as micas to produce a schist or metapelite. As metamorphic conditions increase, a part of the micas converts to feldspar and other minerals. When limestone is metamorphosed, it is transformed to marble. Schist, some types of gneiss, and marble are examples of metasedimentary rocks. Metamorphism of basalt produces amphibolite; metamorphism of granite produces orthogneiss.

The structure (shape, size, and spatial arrangement of minerals in the rock) is an essential characteristic of metamorphic rocks. Minerals may be distributed randomly, but commonly show a preferred orientation. When platy minerals such as micas are well aligned, the rock will show a planar structure or schistosity. At high metamorphic grades and with increasing strain, minerals segregate into bands to produce a gneissic texture. Elongated minerals such as sillimanite needles or strained minerals can then underline a linear feature named mineral lineation. The size and shape of grains can be used to identify the strain intensity and preferential direction of strain (finite strain ellipsoid). In some cases, the mineral association of a metamorphic rock is restricted to a specific pressure-temperature (P-T) domain or metamorphic facies. A small number of metamorphic facies, about 10, have been related to the wide range of P-T conditions that occur in the crust and uppermost mantle. Consequently, a metamorphic rock is named using the type of protolith and the metamorphic facies recorded by a specific set of minerals, for example, “blueschist-facies metapelite.” The metamorphic facies may be related to a specific geodynamic context: ► [subduction](#) results in high P-low T metamorphism (blueschist-facies). Another example, contact metamorphism, results when a shallow magmatic intrusion produces low P-high T metamorphism (hornfels metamorphic facies).

Cross-References

- [Geothermobarometers](#)
- [Greenschist Facies](#)

- [Igneous Rock](#)
- [Mafic and Felsic](#)
- [Metamorphism](#)
- [Metasediment](#)
- [Plate Tectonics](#)
- [Sedimentary Rock](#)
- [Subduction](#)

References and Further Reading

IUGS Subcommittee on the Systematics of Metamorphic Rocks (SCMR). <http://www.bgs.ac.uk/scmr/products.html>

Metamorphism

Jean-Emmanuel Martelat
Université Claude Bernard Lyon 1, Grenoble,
France

Keywords

Geotherm · Metamorphic reactions · Pressure · Temperature

Definition

Metamorphism is the process that modifies the texture, chemistry and/or mineralogy of a rock subjected to a change of physical conditions, usually an increase in temperature and pressure. Metamorphism is by definition a dominantly solid-state process, operating at all scales, from regional to micrometric, and within all types of rocks.

Overview

The field of metamorphism begins somewhat arbitrarily when diagenesis (the lithification and alteration of sediment) ends. This differs widely for different rock types (such as salt vs. a quartzose sandstone). A good criterion is whether

primary volcanic or depositional textures are still recognizable. For many rock types, metamorphism begins at a temperature around 150 °C. It ends when the rock becomes largely molten. The transition from metamorphism to magmatism is not straightforward; a rock is said to be metamorphic even when it contains a molten fraction if this fraction is localized and in a sufficiently small amount that the rock as a whole behaves as a solid. When material transfer is important (driven by melt, volatiles, or diffusion at high temperature), the system is chemically open and the bulk rock composition may be modified. This process is called ► [metasomatism](#). ► [Hydrothermal alteration](#) is considered a part of metamorphism (e.g., hydrothermalism of ► [Oceanic Crust](#)). In contrast, low-temperature weathering at the Earth's surface is considered a sedimentary process.

The changes induced by metamorphism are visible in the textures and types of rock-forming minerals. Prolonged heating induces crystal growth with the consequence that grain size increases systematically with increasing metamorphic grade. Deviatoric stress produces strain. As strain increases, the mineral grains become more elongated and commonly acquire a preferred orientation.

As pressure increases with depth, minerals like quartz (density = 2.66 g/cm³) may be transformed into high-pressure polymorphs such as coesite (density = 3.0 g/cm³). This metamorphic reaction results in a volume decrease. The time needed for such a change is relatively long and controlled by fluid, strain, or temperature. At room temperature and atmospheric pressure, the reaction coesite-to-quartz operates as well but is extremely slow. Because the stable mineral under these low P-T conditions is quartz, any coesite formed is metastable. Thus, metastable mineral assemblages that are preserved in metamorphic rocks on Earth surface can record earlier temperatures and pressures. They can help to define old geotherms (paleogeotherms), the record of how temperature varies with depth in the Earth's crust and mantle. On Earth, the rate and manner of temperature changes largely depends on the tectonic setting. The geotherm varies with the type of crust (continental or oceanic) and with the geodynamic

activity (stable craton, subduction, collision, or extension). Thus, metamorphic rocks are sources of information about specific geodynamic contexts. In some cases, metamorphic rocks record a series of metamorphic conditions through time, defining what is called a P-T-t (pressure-temperature-time) path.

Cross-References

- [Geothermobarometers](#)
- [Greenschist Facies](#)
- [Heat Flow, Planetary](#)
- [Metamorphic Rock](#)
- [Metasediment](#)
- [Metasomatism](#)
- [Plate Tectonics](#)

Metasediment

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble, France

Definition

A metasediment is a rock of sedimentary origin that has been subjected to metamorphism. When the protolith (the sedimentary rock before metamorphism) is shale, metamorphism produces first schist and then paragneiss as temperature and pressure increase. As grain size increases, the rock acquires first a foliation (alignment of mineral grains), then a banding (alternating, thin layers of different mineral compositions), and the mineral assemblage changes to include minerals such as mica, garnet, and aluminosilicates. Metamorphism of pure limestone produces marble; that of chert quartzite, and that of banded-iron formation a magnetite-garnet rock. Metamorphism of impure silica or clay-rich limestone produces calc-silicate rocks. Sandstone is transformed into quartzite. Most Archean terranes contain metasediments which have been affected by at least low-grade metamorphism

(prehnite-pumpellyite facies: 250–350 °C and 2–7 kbars) which has either completely or partially reset most of the isotope systems.

Cross-References

- ▶ [Archean Eon](#)
- ▶ [Banded Iron Formation](#)
- ▶ [Chert](#)
- ▶ [Metamorphic Rock](#)
- ▶ [Metamorphism](#)
- ▶ [Sedimentary Rock](#)
- ▶ [Shale](#)

Metasomatism

Bruce Yardley
School of Earth and Environment, University of
Leeds, Leeds, UK

Keywords

Chemical change · Metamorphism · Aqueous processes

Synonyms

[Metasomatosis](#)

Definition

Metasomatism is a group of processes by which a rock can change chemical composition while it recrystallises, remaining a coherent solid throughout. It is closely related to ▶ [metamorphism](#), which, however, is isochemical, apart from the loss of volatiles. Metasomatism can be subdivided into diffusion metasomatism, observed at the interface between contrasting rock types, and infiltration metasomatism, in which material is introduced in a fluid phase infiltrated from a remote source. Infiltration metasomatism is normally meant in general use of the term.

History

The term Metasomatism has been used in its general modern sense for terrestrial rocks since the nineteenth century, although some historical examples of metasomatic rocks are now interpreted differently. Metasomatism has been recognized in meteorites, primarily chondrites, since the end of the twentieth century, and is now recognized as an important process, at least locally, in the early Solar System.

Overview

The most widespread metasomatism on Earth occurs in permeable rocks, often at relatively shallow depths in the crust. This includes the modification of sandstones by formation waters, notably albitization of plagioclase feldspar, albitization of fractured crystalline basement rocks as they return to the surface, and the alteration of basalts to spilites (metabasalts which have anomalously high Mg-contents) at mid-ocean ridges. At greater crustal depths, metasomatism of limestones or marbles intruded by granite results in the formation of skarns, while metasomatism has been invoked to account for the composition of some mantle rocks, especially potassic xenoliths (xenolith = a deep-seated rock fragment transported to surface during magma emplacement and eruption), where it may be ascribed to melt migration.

A theoretical understanding of metasomatism was developed by D.S. Korzhinskii in the 1930s. The Korzhinskii Phase Rule relates the number of phases and independent degrees of freedom in a system to the number of immobile chemical components, rather than the total number of components. As a result, a rock which has experienced substantive chemical change by migrating fluids has a relatively small number of phases while solid solution minerals in metasomatic rocks have rather uniform compositions, despite the potential for variation. Despite the essential role of water in metasomatism, many metasomatic minerals do not contain water in their structure.

The presence of hydrous minerals in chondritic meteorites has been known for many years, but metasomatism, implying chemical transport

through the medium of water, has only been recognized over the past quarter century. CV chondrites show a range of metasomatic minerals, mainly rich in Fe and/or Ca, alkalis or halogens, and these are consistent with subsolidus growth in an aqueous environment. CO chondrites show a more restricted range of secondary minerals. In both cases, metasomatism is believed to have occurred predominantly in an asteroidal environment, although some meteorites show evidence for later metasomatic effects also. The case for metasomatism of some Martian meteorites is based on the presence of REE-enriched minerals which are out of equilibrium with the major silicate phases, suggesting that they grew subsequently as REE were introduced.

Cross-References

- [Hydrothermal Alteration](#)
- [Hydrothermal Environments](#)
- [Metamorphic Rock](#)
- [Metamorphism](#)
- [Rare Earth Elements](#)

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Metatranscriptome

Víctor Parro and Mercedes Moreno Paz
Molecular Evolution Department, Centro de Astrobiología (INTA-CSIC), Torrejón de Ardoz, Madrid, Spain

Keywords

Transcription · Gene expression · Microbial diversity · Environmental microbiology · Complex microbial communities

Synonyms

[Environmental transcriptome](#); [Microbial community gene expression profile](#); [Microbial community RNAs](#); [Whole community transcripts](#)

Definition

Metatranscriptome refers to the total content of gene transcripts (RNA copies of the genes) in a community, considered as a unique entity, at a specific moment of sampling. Metatranscriptome varies with time and environmental changes. The techniques applied to obtain the whole expression profile in a community and to follow the dynamics of gene expression patterns over time or environmental parameters are known as metatranscriptomics. It improves our understanding of the structure, function, and adaptive mechanisms in complex communities and, together with other “omics,” is applied to fields such as medicine, biotechnology, and, particularly, in microbial ecology.

History

The study of the total expressed genes in a cell or organism at a certain moment started in the 1980s using techniques such as northern blot and reverse transcription coupled to polymerase chain

Metasomatosis

- [Metasomatism](#)

reaction amplification (RT-PCR). The development of microarrays technology in the 1990s (Schena et al. 1995) enabled the characterization of gene expression for hundreds or thousands of genes at once, thus opening the door to the study of single transcriptomes (Zhou et al. 2003) and complex environmental transcriptomes (Parro et al. 2007). It was Leininger et al. (2006) who reported the first metatranscriptome from an ammonia-oxidizing prokaryote community in soils, thanks to the development of massive sequencing platforms. Since then, metatranscriptomic analysis has revolutionized the field of gene expression profiling, extending its scope of application to the analyses to small non-coding RNAs (Shi et al. 2009; Herbig and Nieselt 2011).

Overview

Metatranscriptomics provides insights into the metabolic activities, functions, and regulation in environmental microbial communities. This powerful tool is crucial to investigate the metabolic traits of environmental communities as a whole, where unculturable microorganisms constitute the vast majority of the population (Bailly et al. 2007; Embree et al. 2013). The first attempts to characterize complex communities by sequencing their mRNAs led to the discovery that Archaea were the most predominant ammonia oxidizers in soils (Leininger et al. 2006). Since then, this technique has been applied to typify many ecosystems including soils, marine, and freshwater as well as the human microflora, making it possible to determine the composition of complex microbial communities, the function of individual microorganisms in the environment, and the role of microbial interactions in global biogeochemical cycles (Embree et al. 2013). In addition, *scientists* are using metatranscriptomics to explore the human microbiome, in order to shed light on its role in the human physiology (Gosalbes et al. 2011). Some studies have shown the microbiome interaction with the immune and nervous systems to be also related to obesity, cardiovascular risk, and diseases such as the inflammatory bowel disease (Clemente et al. 2012).

The understanding of the role played by the human microbiota in its host, through metatranscriptomic approaches, could contribute to develop new therapeutic strategies in the near future.

Cross-References

- DNA
- Metagenome
- RNA
- Transcription

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Metavirome

Josefa Anton

Department of Physiology, Genetics and Microbiology, University of Alicante, Alicante, Spain

Keywords

Virus · Metagenome · Environmental sample

Synonyms

[Viral metagenome](#)

Definition

The metavirome is the ► [metagenome](#) (sum of genomes) of the viruses present in a sample, obtained by the extraction and sequencing of the viral genetic material present in the analyzed sample. It can also be defined as the metagenome of a viral assemblage.

History

This term was coined by J. H. Paul and M. B. Sullivan in 2005 to refer to the studies on the uncultivated marine ► [virus](#) community ► [genome](#) (Paul and Sullivan 2005).

Overview

The first study on an environmental metavirome was published in 2002 (Breitbart et al. 2002), which analyzed the metagenome of uncultured marine virus communities. Since then, studies on the metaviromes from different environments, such as human feces, rice paddy soil, solar salterns, marine water and sediments, coral, freshwater, microbialites, hot springs, Antarctic lakes, fish, mosquitoes, reclaimed water, and grapevine, among others, have been carried out by several authors. Most of the studies have been focused on dsDNA metaviromes, although ssDNA and RNA

viruses have also been analyzed using this approach. The analysis of metaviromes allows for the direct study of natural virus communities and circumvents the problems derived of the fact that the majority of viruses cannot be cultured because their hosts cannot be readily isolated.

There are several protocols for constructing metaviromes that normally follow this scheme: first, cells are removed, and the viral assemblage is concentrated by tangential filtration and/or ultracentrifugation; then viral nucleic acids are extracted by means of different protocols (Thurber et al. 2009; Santos et al. 2010) and sequenced. In some cases, nucleic acids are cloned into plasmids and/or fosmids (cloning vectors that allow for the cloning of large DNA fragments) prior to sequencing, or amplified using different protocols (Paul and Sullivan 2005; Thurber et al. 2009) and directly sequenced using high-throughput sequencing methods. Pros and cons of every approach are discussed in Thurber et al. (2009). Once the metaviromic sequences are available, they can be analyzed and compared with databases using several bioinformatic tools.

Metavirome characterization allows the cataloging of the viruses present in a given environment as well as the descriptions of relative abundance of different virus types. Thus, the analysis of metaviromes, in addition of ascertaining the viral diversity in a sample, makes it possible to reconstruct the structure of uncultured viral communities (Edwards and Rohwer 2005), and also to identify viral encoded functions. However, it has the main drawback of the high number of unknown genes found when trying to identify the protein-coding regions or open reading frames (ORFs) present in the metaviromes. For this reason, methods for metavirome analysis (Angly et al. 2005; Willner et al. 2009) have been developed that do not depend on gene annotation and allow for the comparison of different viral metagenomes corresponding to different environments, as well as for functional metagenomic approaches (McDaniel et al. 2009).

Cross-References

- [Biodiversity](#)
- [Bioinformatics](#)

- [Genetics](#)
- [Genome](#)
- [Metagenome](#)
- [Sequence](#)
- [Virology](#)
- [Virus](#)

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Meteor

Alessandro Airo

Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Synonyms

[Shooting star](#)

Definition

A meteor is a visible streak of light caused by the entry of an extraterrestrial solid object with high velocity (few km/s) into the atmosphere. The generation of a streak of light is due to frictional heating and atmospheric ram pressure during atmospheric entry, resulting in the shedding of glowing material. Depending on the composition of the bolide, the colour of the meteor can be different. Most meteors are caused by pebble size ► [meteoroids](#) that entirely disintegrate before reaching the surface, however, if parts reach the surface they are called ► [meteorites](#).

Cross-References

- [Asteroid](#)
- [Meteorites](#)
- [Meteoroid](#)

Meteorite, Allende

Matthieu Gounelle

Laboratoire de Minéralogie et Cosmochimie du Muséum (LMCM) MNHN USM 0205 – CNRS UMR 7202, Muséum National d'Histoire Naturelle, Paris, France

Keywords

CAIs · Chondrite · Meteorite · Protoplanetary disk

Definition

Allende is a meteorite that fell in Mexico in 1969. Roughly 2 t of that CV3 ► [carbonaceous chondrite](#) were found. Allende is one of the most studied meteorites, because it contains abundant and large ► [CAIs](#), which are believed to be the first solids to have formed in the solar system.

Overview

The Allende meteorite fell early in the morning of Saturday, February 8, 1969, 7 months before the fall of ► [Murchison](#) (CM2 chondrite rich in amino acid) and 4 months before the return of 22 kg of Moon rocks by the Apollo 11 crew. After a bright fireball that was seen in Texas and New Mexico, thousands of stones fell near the small village (pueblito) of Allende, south of Chihuahua, in northern Mexico.

A large stone (15 kg) fell near a house and some pieces were brought to the office of the newspaper *El correo de Parral* the same day. News of the meteorite fall was published the same evening. Mexican and US scientists collected rocks the next weeks. Eight months after the fall, a 110-kg sample was found. In total, 2 t of rocks were recovered (see Fig. 1).

Allende belongs to the class of CV3 chondrites, an important group of carbonaceous chondrites, which represent roughly 0.6% of the meteorite falls.

The fall of Allende was a landmark in ► [cosmochemistry](#), because it led to the rediscovery of calcium-, aluminum-rich inclusions (CAIs). These white inclusions were first reported and described in 1968 by Mireille Christophe Michel-Lévy in a French journal, which did not receive the attention it deserved (Christophe Michel-Lévy 1968). The abundance of CAIs in Allende is



Meteorite, Allende, Fig. 1 A piece of the Allende meteorite kept at the Muséum National d'Histoire Naturelle in Paris (sample 2870, 144 g). The nearest face is still covered by the fusion crust (see entry “► [Cosmochemistry](#)”). The white inclusion is a calcium-, aluminum-rich inclusion (see entry “► [CAIs](#)”). (Picture C. Fiéni [MNH])

roughly 10%, while the mean abundance in CV3 chondrites is 4.8%, explaining why CAIs had been overlooked until Allende fell, though ten other meteorites of that kind were known in 1969.

CAIs' mineralogy indicates that they were the first solids to form in the protoplanetary disk. This is confirmed by their old Pb-Pb age and their high abundance of short-lived radionuclides. CAIs can potentially reveal the physicochemical conditions in the protoplanetary disk, 4567 Gyr ago (see ► [“CAIs”](#)).

The high abundance as well as the large size (millimeter objects are common, centimeter objects are not rare) of Allende CAIs explain why the study of these key objects has been dominated by samples coming from the Allende chondrite for at least 30 years. In addition, it was widely believed that CAIs within Allende did not suffer any secondary event in its parent-body and that the record of the protoplanetary disk was kept intact within these samples. Numerous chemical, mineralogic, and isotopic studies were made over the last 30 years on these objects.

In the mid-1990s, Sasha Krot and collaborators demonstrated, however, that Allende endured metamorphism and metasomatism in its parent-asteroid. This means that Allende CAIs are not as pristine as it was thought. Furthermore, it appears that many of the CAIs studied within Allende (type B CAIs) are absent from other chondrites and that most of our knowledge on CAIs is based on unrepresentative samples.

Cross-References

- [CAIs](#)
- [Cosmochemistry](#)
- [Geochronology](#)
- [Meteorite, Murchison](#)
- [Meteorites](#)
- [Micrometeorites](#)

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Meteorite, Murchison

Laurent Remusat and François Robert
Institut de Minéralogie, de Physique des
Matériaux et de Cosmochimie, Muséum National
d'Histoire Naturelle, Sorbonne Université, UMR
CNRS 7590, Paris, France

Keywords

Extraterrestrial matter · Meteorites · Organic matter · Prebiotic molecules · Presolar grains

Synonyms

[Carbonaceous meteorite](#); [Murchison](#)

Definition

The Murchison meteorite is a carbonaceous chondrite belonging to the CM group (Mighei like). It was formed 4.56 billion years ago and has remained undifferentiated since then, although it is classified as a CM2 chondrite, meaning it shows signs of aqueous alteration. This meteorite contains about 30% of chondrules, in volume, and 70% of a fine-grained matrix. This matrix hosts a diverse suite of organic compounds, some of them being considered as potential prebiotic molecules.

History

On 28 September 1969, at about 10:58 a.m., near the town of Murchison, Victoria, in Australia, a bright fireball was observed that broke into three distinct fragments. About 30 s later, a tremor was

heard. Many specimens of this Murchison meteorite were found over an area larger than 13 km², and the total-collected mass exceeds 100 kg. This meteorite has since been the reference material to investigate extraterrestrial organic matter.

Overview

The Murchison meteorite belongs to the CM group of carbonaceous chondrites. These chondrites are rich in volatiles, including carbon, and are among the most chemically primitive meteorites. Murchison contains presolar grains including silicon carbides that are 7 billion years old (Heck et al. 2020). Like most other CM chondrites, Murchison contains centimeter-size inclusions of refractory oxides and silicates (calcium-aluminum-rich inclusions; the CAIs). These inclusions were condensed from a gas of solar composition at high temperature and are interpreted as the first stages of the cooling of the protosolar disk that eventually led to the planets of the solar system. Murchison exhibits features related to extensive alteration by water-rich fluids on its parent body, few million years after its formation 4.56 billion years ago.

Basic Methodology

Since its discovery, the Murchison meteorite has been studied using a large range of analytical techniques, from electron microscopy to investigate its petrographic and mineralogic properties, to isotope ratio mass spectrometry to determine the age and the origin of its components. Studies have been performed in situ on intact pieces, on polished preparation of sections and by applying chemical treatments (including acid leaching) to separate its organic and inorganic constituents. As it happens to be rich in well-preserved organic matter, Murchison has been and remains the prime target for organic analysis of extraterrestrial compounds. At every major improvement in analytical chemistry, new discoveries are made about the organic composition of the Murchison meteorite.

Key Research Findings

The Murchison meteorite, as other CM chondrites, contains organic molecules formed at low temperatures (i.e., between 30 and 300 K). Several lines of evidence indicate that the interior portions of Murchison are well-preserved and are indigenous to the meteorite, that is, not modified or contaminated on Earth. A 2010 study using very high mass-resolution mass spectrometer has reported more than 14,000 different molecular compositions in a methanol extract of the Murchison meteorite (Schmitt-Kopplin et al. 2010). This represents a huge molecular diversity of organic molecules formed by abiotic processes. The Murchison meteorite contains various organic molecules that are involved in life forms on Earth: amino acids, as well as nucleobases or sugar-related molecules (Callahan et al. 2011; Cooper and Rios 2016; Koga and Naraoaka 2017). They represent a potential molecular source for the chemistry that led to the origin of life. The main organic component is recovered as an insoluble organic macromolecule, constituted by small aromatic units connected by short and branched aliphatic chains. The aromatic units host N- and S-moieties (pyrroles and thiophenes group), whereas O groups (ester or ether functions) can be found in aliphatic chains (Alexander et al. 2017).

Judging from the numerous interpretations on the origin of these organic compounds that can be found in the literature, it can be considered that the organic matter of Murchison reflects a mixture of different origins (Remusat et al. 2016). While some precursor compounds of the insoluble organic matter may have been formed in the protoplanetary disk or the parent molecular cloud by photochemical reactions (such as the polycyclic aromatic hydrocarbons), others – the small and soluble molecules – were likely processed inside the parent body of the meteorite itself. The pre-accretionary origin is supported by significant enrichments in heavy isotopes of H and N, likely related to synthesis occurring at low temperature under irradiation. Ion-molecule reactions are often involved to account for large D/H ratios in the insoluble organic matter, for instance, which exhibits numerous D-rich hotspots and organic

radicals. Nevertheless, the extent of the alteration of the D/H signature of organic molecules by the aqueous alteration on the parent body remains discussed, making it dubious to determine the exact origin of organic precursors.

The emblematic example of low-temperature molecules is the amino acids that are often considered as prebiotic components of life, as well as nucleobases or sugar-related molecules. More than 92 amino acids have been identified in Murchison including 12 actually involved in the living-protein world. For example, glycine, α -alanine, and glutamic acid, as well as unusual ones like isovaline and β -alanine are present in Murchison. It is usually assumed that a large part of amino acids was formed on the parent body of carbonaceous chondrites during aqueous alteration, most probably by the Strecker cyanohydrin synthetic mechanism. Michael addition, reductive amination, and CO₂ addition are additional mechanisms proposed to account for non α -amino acids. Laboratory data on the deuterium retention of amino acids during Strecker synthesis indicates that, with the exception of glycine, meteoritic amino acids can be formed by this mechanism from highly deuterated precursors. The origin of these deuterium-rich precursors (solar or interstellar) is still in debate. In addition, the isotopic fractionation of carbon and nitrogen occurring during Strecker synthesis does not account for the large enrichment in ¹³C and ¹⁵N observed among several families of organic molecules; the possible – and proposed – interpretations of such a huge fractionation have not been experimentally substantiated.

In the 1970s, several studies reported that amino acids were racemic (i.e., the chirality of their enantiomers are equally left and right handed), indicating that they are not terrestrial contamination. However, refinements of analytical chromatographic techniques have shown that enantiomeric excesses do exist in some amino acids. This finding has reopened Pandora's box of possible terrestrial contaminants. The debate was finally closed owing to an outstanding high-tech analytical technique where the nitrogen isotopic compositions of each enantiomer were measured individually. These isotopic compositions are out of the terrestrial range, and the two

enantiomers are equally enriched in ^{15}N relative to their terrestrial counterparts (Engel and Macko 1997). Since the terrestrial contamination would have left its isotopic signature on the L-enantiomer, indubitably an extraterrestrial source favored L-enantiomers in the early Solar System. Furthermore, L-excess has also been reported for non-protein amino acids, for example, isovaline (Glavin et al. 2020). Interestingly, some sugar derivative molecules detected in Murchison exhibits excess in the right-handed form (Cooper and Rios 2016). It is possible that the origin of the homochirality of life (i.e., the occurrence of only the left-handed amino acids and right-handed sugars) was triggered on Earth by the deposition of chiral molecules contained in meteorites. The origin of these enantiomeric excesses has been related to irradiation by circular polarized UV-light of ices where organic precursors were formed and that would be accreted on parent bodies (de Marcellus et al. 2011), or to the occurrence of chemical reactions at the surface of minerals having capabilities to sort enantiomers during aqueous alteration (Glavin et al. 2020).

Meteorites resembling Murchison may have delivered molecules that have influenced the origin of life on Earth (d'Ischia et al. 2021). Although it is difficult to estimate the flux of extraterrestrial carbon to the early Earth from the present-day observations, it has been calculated that around 10^9 kg of organic carbon could have been delivered to the planet per year in the first billion years of its existence, mostly incorporated in dusty particles like interplanetary dust particles (IDPs) or micrometeorites (Rojas et al. 2021). This flux is two to three orders of magnitude higher than nowadays. While organic compounds delivered by small particles may suffer from atmospheric entry, delivery by larger bodies like the Murchison meteorite brings intact prebiotic molecules on the surface of Earth.

Future Directions

The discussion about the input of extraterrestrial organic molecules on Earth has several ramifications. Even if it can be demonstrated that amino

acids or nucleobases can “safely” land on the primitive Earth, would that prove the origin of the world of left-handed amino acids in which we live? What is the amount – or the concentration in a sterile ocean – of prebiotic molecules necessary for a life ancestor to be assembled? Are high concentrations and a large molecular diversity of organic molecules required for life to emerge? The answers to these questions are largely unknown; they are related to a credible model of the chemical pathways that gave rise to life.

Cross-References

- ▶ Amino Acid
- ▶ CAIs
- ▶ Carbonaceous Chondrite
- ▶ Carbonaceous Chondrites, Organic Chemistry of
- ▶ Chirality
- ▶ Meteorite, Allende
- ▶ Meteorite, Orgueil
- ▶ Meteorites
- ▶ Nonprotein Amino Acids
- ▶ Organic Dust, Influence on the Origin of Life
- ▶ Parent Body
- ▶ System Solar Formation, Chronology of

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- sample of the CI ► [Carbonaceous Chondrite](#) group, which represents the most primitive bodies of the solar system. Its composition is identical to that of the solar photosphere, except for the lightest elements (roughly from hydrogen to nitrogen). An important discovery was the detection of a high abundance of isotopically anomalous xenon, which could be the signature of presolar material. The absence of high-temperature components within the Orgueil meteorite is explained by an important aqueous alteration of its parent body. The Orgueil meteorite also contains amino acids (a few ppm), although this abundance is below what can be observed in CM meteorites such as Murchison. Interestingly, a significant L-enantiomeric excess of isovaline (a non-biological amino acid) is measured in the meteorite Orgueil (enantiomeric excess of about 15%). Some studies have suggested that Orgueil could have a cometary origin, although this hypothesis remains quite uncertain.

Cross-References

- [Amino Acid](#)
- [Chondrite](#)
- [Enantiomeric Excess](#)
- [Isovaline](#)
- [Meteorite, Allende](#)
- [Meteorite, Murchison](#)
- [Meteorites](#)

Meteorite, Orgueil

Therese Encrenaz¹ and Hervé Cottin²

¹Observatoire de Paris, PSL Université, CNRS, Sorbonne Université, Université Paris Cité, Meudon, France

²Univ Paris Est Creteil and Université Paris Cité, CNRS, LISA, Créteil, France

Definition

The Orgueil meteorite fell on May 14, 1864, near the village of the same name, in the south of France. With a mass of 14 kg, it is the biggest

Meteorites

Emmanuel Jacquet

Institut de Minéralogie, Physique des Matériaux et Cosmochimie (IMPMC), Sorbonne Université et Muséum National d'Histoire Naturelle, UMR 7590 CNRS, Paris, France

Keywords

Extraterrestrial matter

Definition

A meteorite is a macroscopic rock originating from interplanetary space and which has naturally landed on a planetary surface (e.g., Earth).

History

A few metallic artifacts predating the Iron Age, such as Tutankhamun's dagger, show an iron-nickel composition characteristic of iron meteorites. Meteorite falls have been reported since the earliest Antiquity and some of them have been worshipped as baetyls, such as the Elagabal stone in Emesa, whose eponymous priest achieved temporary fame as a Roman Emperor in 218–222 A.D. These meteorites are however lost, and the oldest falls with preserved samples date back to 861 (Nogata, Japan) and 1492 (Ensisheim, then a part of the Holy Roman Empire and now France).

While some Greek philosophers entertained a cosmic origin of those objects, others, starting with Aristotle, envisioned a formation within the atmosphere. With the advent of the Enlightenment, the very reality of meteorite falls was questioned, as many objects held by folklore to be of celestial origin turned out to be fossils or prehistoric artifacts. Nonetheless, the scientific community accepted the existence of meteorites (as extraterrestrial objects) at the end of the eighteenth century, in a process which roughly started with the 1794 publication of Ernst Florens Friedrich Chladni's book on the cosmic origin of bolides and concluded with the 1803 meteorite shower near L'Aigle in Normandy, which was extensively studied by Jean-Baptiste Biot (Jacquet 2017).

Chemical analyses had just started to be routinely applied to meteorites (which had rapidly revealed iron-nickel alloys as a diagnostic of most meteoritic material; Jacquet 2017). Over the next century, the various classes of meteorites would gradually be recognized, in tandem with the development of geology and mineralogy (Jacquet 2017). The discovery of asteroids

starting with Ceres in 1801 paved the way for the recognition of the parent bodies of most meteorites, though it would take the installation of dedicated camera networks to confirm, from orbital reconstruction, that these originated from the asteroid main belt between Mars and Jupiter (starting with the Pribram fall in 1959; Jacquet 2017). The advent of the Space Age (inaugurated by Sputnik 1 in 1957) and microanalytical techniques meant a boost in the understanding of meteorites as remnants of the early Solar System. Meteorite finds also began to pour from hot and cold deserts. Starting at the turn of the millennium, space probes were sent to study asteroids and comets, and even returned first-hand samples thereof, which allowed direct linking of meteorites with spectroscopic taxa of these minor solar system bodies (Jacquet 2017).

Overview

Fall Phenomena

A meteorite (or, strictly speaking, a *meteoroid* so long it has not reached the ground) enters the Earth atmosphere at a (“cosmic”) velocity between 11 and 72 km/s (corresponding to Earth's escape velocity and the relative speed of a meteoroid on an hyperbolic orbit meeting Earth head-on, respectively). Such a supersonic velocity entails the formation of a bow shock, where air compressed and heated in the vicinity of the rock glows and gives rise to a visible light phenomenon called a *meteor* (or “bolide”). The hot air also melts and partly vaporizes the surface of the meteorite, which thereby loses mass in a process called *ablation*, and may entirely destroy meteoroids smaller than about 10 cm in diameter (unless in the micrometeorite size range). The drag due to the ram pressure (i.e., the pressure of the compressed gas in front) usually removes all the cosmic velocity at ~20 km altitude (the *retardation point*), and the meteor goes extinct and the meteorite falls at terminal velocity (*dark flight*). Most of the time, before the retardation point, the ram pressure overcomes the tensile strength of the meteorite and causes its explosion – adding to the sonic booms accompanying the

meteoroid – forming a *meteorite shower*. The individual meteorites then distribute themselves on the ground over an elliptical area called a *strewn field*, with the heaviest usually travelling furthest due to their inertia. Freshly fallen meteorites are covered by a thin (~mm thickness), usually black *fusion crust* which is the quenched remnant of the melted surface during ablation.

Meteoroids larger than about 10 m in size are not efficiently slowed by atmospheric drag and thus impact the ground at close to their initial (cosmic) velocity. Such hypervelocity impacts generate explosion craters, which may attain 20 times the impactor diameter. Depending on the energy of the impact and distance from the epicenter, the substratum (and the impactor) may be fractured, melted, or vaporized, generating a suite of impact-created rocks called *impactites*. These include shatter cones, lithic breccias, suevites (breccias with melt inclusions), and impact melt rocks, and sometimes even impact glasses. Some melted ejecta may travel far from the impact before landing as glasses called *tektites*; such as the moldavites mostly found in the Czech Republic and formed by the impact at Nördlinger Ries in Bavaria (Germany), or the australasites which scattered over Southeast Asia and Oceania, but whose source crater, presumably in Indochina, has not yet been identified (Jacquet 2017). Only ~200 impact craters are known worldwide because geological activity on Earth has erased most others. The oldest impacts may be then only manifest by impact spherule deposits (microtektites (crystal-free), microkrystites (crystal-bearing)) in the sedimentary record. Most meteorite craters formed in prehistoric times and lack any surviving meteorite (either because of weathering or vaporization upon impact), so their recognition depends essentially on the aforementioned impactites. The largest (but heavily eroded) impact craters are Vredefort (South Africa, 300 km diameter) and Sudbury (Canada, 250 km), both about 2 Ga in age. Next comes the Chicxulub crater in the Yucatan peninsula (Mexico, 200 km) which has notoriously attracted attention since its formation coincides with, and may be the cause of, the extinction of non-avian dinosaurs 66 Ma ago (Jacquet 2017).

Meteorites are named after the place they were found, under the auspices of the Nomenclature Committee of the Meteoritical Society (Jacquet 2017). A meteorite whose fall has been witnessed is called a *fall* (or an “observed fall”); other meteorites are simply *finds*. Falls are often favored by meteoriticists because of their minimal weathering, but nowadays, they are greatly outnumbered by finds (by a factor of ~50) which may be the only form in which some rare types are known. Finds are especially numerous in deserts, where dryness and/or cold may allow preservation for tens of millennia, and, if the soil is light-colored, dark (fusion-crust) rocks may be more conspicuous (although desert varnish may partly mimic fusion crusts). Numbers need to be added to the names of the associated dense collection areas to distinguish different meteorites found there, for example, “Dar al Gani 400” refers to the 400th find of the Dar al Gani area (in Libya). Some differently numbered meteorites may be actually *paired*, that is, associated with the same meteorite shower. In Antarctica, where the wind-driven erosion of glaciers at the base of mountains chains has generated considerable accumulations of exposed meteorites, the numbering rewinds at each new field season, with the year being indicated by the first two digits. For example, Allan Hill 84001 (or ALH 84001) is the first find of the 1984–1985 search campaign at Allan Hill. While meteorite collection in Antarctica is exclusively performed by scientists, hot desert finds are mostly made by private meteorite hunters, which may result in the lack of available find coordinates (critical for pairing assessments). Such data are missing for the many “Northwest Africa” (shorthand: “NWA”) meteorites (Jacquet 2017).

Meteorite Parent Bodies

The *parent body* of a meteorite is its celestial body of origin. If the immediate parent body of a meteorite is itself a fragment of some prior object, it is worthwhile to distinguish between *primary* (i.e., as originally formed at the beginning of the Solar System) and *secondary* parent bodies. Usually, discussions on the parent body of some meteorite group refer to the primary parent body (Greenwood et al. 2020).

The orbits of most falls captured on cameras have their aphelia in the main belt of asteroids, between Mars and Jupiter, which must be the source of the vast majority of meteorites (Jacquet 2017). A meteoroid, in essence, is simply a small asteroid, and there is no sharp size limit between “meteoroids” and “asteroids.” An *asteroid* should certainly be big enough to be telescopically observable, but meter-size objects can be observed if they approach Earth sufficiently closely. For instance, asteroid 2008 TC₃, 2–5 m across, was discovered hours before actually hitting Earth in 2008 – it ended as a meteorite shower over Sudan, whose remnants have subsequently been recovered and named Almahatta Sitta (Jacquet 2017).

A designation such as “2008 TC₃” above is in principle only provisional; once the orbit of a newly discovered asteroid is sufficiently well-determined, it may be assigned a number and a name (different from that of the discoverer, unlike for comets). The first discovered (and largest, with 950 km diameter) asteroid is 1 Ceres (or simply “Ceres”), the second 2 Pallas, etc. Over a million asteroids have been observed to date.

Most meteoroids are liberated from their parent asteroids through impacts. Many meteorites retain evidence of shock effects such as brecciation or shock veins. Many asteroids are merely rubble piles of material reaccumulated after catastrophic collisions. Some asteroids are binary (i.e., comprise two objects orbiting around each other), such as Didymos whose satellite Dimorphos will be impacted by the DART probe to test near-Earth asteroid deflection strategies. Others, while free of each other’s gravity, may still form a cluster in orbital element space which is called an asteroid “family.” The Gefion family (named after its main member, 1272 Gefion), for example, may have formed 470 Ma ago, as evidenced by an overabundance of fossil meteorites in the corresponding (Ordovician) sedimentary strata on Earth (Jacquet 2017).

Impact ejection by itself will not send a meteoroid into an Earth-crossing orbit (Jacquet 2017). However, a meter-size meteoroid is prone to orbit alteration via the Yarkovsky effect. The Yarkosky effect is the recoil in the orthoradial direction that a rotating object may undergo from delayed

reemission of sunlight. So significant specific angular momentum may be gained or lost because of its large surface/volume ratio, and the meteoroid may drift and eventually reach resonances where gravitational interactions with Jupiter will rapidly increase the eccentricity of the orbit, which may cross those of inner planets.

During its interplanetary transit, a meteoroid is exposed to galactic cosmic rays (energetic charged particles) which entail spallation reactions and the synthesis of new (*cosmogenic*) nuclides. This ceases after impact on Earth which is shielded by its atmosphere. The measurement of such nuclides (especially for noble gases, e.g., neon-21, which are depleted in the starting rock; Turekian and Holland 2014) can allow the duration of the interplanetary transit (the *cosmic ray exposure age*) to be calculated (Turekian and Holland 2014). Measurement of those cosmogenic isotopes which are also radioactive – and whose decay is not compensated by production after reaching our atmosphere – also allow estimation of the *terrestrial age* of a find (which is usually much shorter than the exposure age). For stony meteorites, the cosmic ray exposure age does not exceed 104 Ma, and is generally much less, but for irons, older ages up to 2.2 Ga (for the Deep Springs meteorite) are known. Clusters of exposure ages for a given meteorite group (e.g., around 7 Ma for H ordinary chondrites) provide evidence for a common ejection event of the associated meteorites, and thus a common parent body of origin.

While, historically, asteroids have been envisioned as debris of a former planet missing between Mars and Jupiter, the main belt currently only comprises a total mass of 3×10^{21} kg (with a third locked up in Ceres), not even a 20th part of the Moon. The diversity and primitivity of most asteroids are also inconsistent with derivation from a former planet. Rather, the region between Mars and Jupiter may not have harbored enough mass to ever build a planet, which may also explain the mass of Mars, whose mass is an order of magnitude below that of Earth and Venus. It is possible that inward-then-outward migration of Jupiter largely emptied that area (see the “Grand Tack” scenario in ► “Planet

Formation”), but other scenarios are conceivable. Whatever that may be, the asteroid main belt is essentially a repository of planetesimals left over from planetary accretion 4.5 Ga ago (Jacquet 2017).

Asteroid classification is based on reflectance spectra. To a first approximation, the main asteroid belt consists of an inner region (<2.6 AU, where the Astronomical Unit (AU) refers to the Earth-Sun distance, about 1.5×10^{11} m) dominated by dry silicate asteroids grouped in the S taxonomic class, and an outer region dominated by the “C complex,” whose members have a low albedo suggestive of a carbonaceous composition. The link between S type asteroids and ordinary chondrites has been confirmed by the sample-return mission Hayabusa 1 on asteroid Itokawa (Nakamura et al. 2011). The comparison between C-complex asteroids and carbonaceous chondrites will be informed by the study of samples returned by Hayabusa 2 (see ► “Hayabusa Missions”) and Osiris-Rex from asteroids Ryugu and Bennu, respectively (Jacquet 2017).

Some meteorites may actually derive from comets (as entertained for Orgueil based on reconstruction of its orbit; Gounelle et al. 2006). Dust returned from comet Wild 2 by the Stardust mission in 2006, as well as micrometeorites, suggests kinship to carbonaceous chondrites, so the difference may not be readily recognizable, and there must essentially be a continuum between (C complex) asteroids and comets in the outer solar system (Gounelle et al. 2006). The Grand Tack scenario even considers C complex asteroids as imported from the outer disk. Some main belt asteroids may be in fact dormant comets, as sometimes suggested by episodic activity, which may be due to recent impacts exposing the icy subsurface.

A small minority of meteorites have planetary origins. Lunar meteorites have been recognized based on comparison with samples returned by the Apollo and Luna missions. Other meteorites, long referred to as SNC meteorites (after Shergotty, Nakhla, and Chassigny which were the prototypes of the main varieties), are considered to be of Martian origin, chiefly because of their young crystallization age (mostly a few hundreds of Ma, although some, such as the “Black Beauty”

NWA 7034, may date back up to 4.4 Ga), which is inconsistent with an asteroidal origin, and the correspondence between gases trapped in impact glasses and Martian atmosphere analyses by the Viking landers (e.g., Turekian and Holland 2014).

Basic Methodology

The Petrological Classification of Meteorites

The classification of meteorites developed in the nineteenth century and, after some simplifications by Prior (1920), achieved more or less its contemporaneous form in the 1960s–1970s (e.g., Van Schmus and Wood 1967). Nowadays, meteoritists distinguish two overarching petrological categories: *primitive* meteorites (or *chondrites*) which have undergone little change since their parent bodies accreted, and *differentiated* meteorites, which have undergone melting and igneous fractionation. The difference in the fate of the planetesimals in this respect was dictated by the size of the planetesimal (i.e., its surface/volume ratio controlling cooling) and the abundance of short-lived radionuclides present at the time of accretion. The chief heat source was aluminum-26 (half-life: 0.7 Ma), whose past existence is evidenced by excesses in its daughter isotope magnesium-26 correlated with the Al/Mg ratio in meteoritic material; iron-60 (half-life: 2.6 Ma), once considered an important contributor, is now deemed to have been too low in abundance. Impacts may have also locally contributed to heating on planetesimals. Since ^{26}Al was most abundant in the earliest first million years of the protoplanetary disk (with original $^{26}\text{Al}/^{27}\text{Al}$ ratio of $\sim 5 \times 10^{-5}$), the earliest formed planetesimals tended to differentiate more easily, as confirmed by Hf-W dating of iron meteorites. Paradoxical as it may seem, the parent bodies of differentiated meteorites thus accreted earlier than those of chondrites (accreted ~ 2 – 3 Ma after the formation of the Solar System), even though only the latter retain the oldest solids of the Solar System.

Primitive Meteorites and Their Components

Chondrites make up 86% of falls. Their primitivity is evinced by the close correspondence of the

nonvolatile elements with the (spectroscopically measured) solar photosphere (with the exception of lithium, underrepresented in the Sun because of its destruction in an early stage of its nuclear history), especially for the carbonaceous chondrite Orgueil, which may serve as a reference material for solar abundances. Chondrites are basically conglomerates of the diverse mm-size solids that populated the solar protoplanetary disk during its few million years of lifetime (before dissipation), cemented by a fine-grained matrix, and such have been aptly termed “cosmic sediments” (McSween 1999).

Chief among them are the eponymous *chondrules* (from the Greek for “granule”) which are mm-size silicate spheroids which show evidence of formation as solidified droplets. Most of them exhibit porphyritic textures, with randomly oriented olivine and pyroxene crystals set in a glassy (or devitrified) mesostasis, a texture indicative of extensive but incomplete melting, with sometimes identifiable relicts of precursor material. Others have been entirely melted and undercooled before crystal nucleation, hence spectacular barred or radial textures. Chondrules may also contain metal and sulfide grains and may be the source of those found outside them as well. Some chondrules collided while hot and formed “compound chondrules.” The nature of chondrule-forming episodes, which may have lasted minutes, hours, or days, is arguably the deepest mystery of cosmochemistry. Two broad categories of scenarios are still contending for the favors of the community: “Planetary scenarios” form chondrules on an early generation of planetesimals, for example, in impact plumes (whether the melting is due to the energy of the impact itself, or in a preexisting magma ocean). “Nebular scenarios” have them formed in the general protoplanetary disk (also called “the solar nebula”), by melting of “nebular” (i.e., preaccretionary) precursors, for example, during the passage of shock waves (e.g., such as attend planetary embryos on eccentric or inclined orbits). Nebular scenarios were preferred from the 1980s through the 2000s, for example, because of the occurrence of nebular relict grains. However, planetary scenarios have regained momentum following evidence (e.g., from FeO or volatile

contents, or compound chondrule frequencies) that chondrule-forming regions were enriched in solids by orders of magnitude compared to the expected average background disk.

Refractory inclusions are a minor component of chondrites, but are the oldest dated solids of the Solar System, predating the chondrules by typically 1–3 Ma, with a Pb-Pb age of 4567 Ma commonly held to be “time zero” of the protoplanetary disk. Refractory inclusions comprise *calcium-aluminum-rich inclusions* (CAIs) and (somewhat less refractory) *amoeboid olivine aggregates* (AOAs). They are called “refractory” because their mineralogy corresponds to the first solids to appear in a cooling gas of solar composition (at ~1500–1800 K) according to thermodynamic calculations. A condensation origin in the disk seems likely, although some CAIs show (mass-dependent) heavy isotope enrichments suggestive of evaporation residues. Many refractory inclusions in general seem to have suffered several high-temperature episodes, sometimes leading to their melting (which may or may not be comparable to mainstream chondrule-forming events). The high temperatures required for CAI formation suggest an origin close to the Sun. While solar irradiation would only heat the very inner disk edge to the desired level, the dissipation of turbulence may produce the required heating, at least intermittently, further away, perhaps up to a heliocentric distance of an AU or so, especially in the early stages of the disk evolution.

In the most pristine chondrites, the *matrix* appears as an aggregate of micron-size crystalline and amorphous silicates and opaque phases. The matrix is composite in origin. There certainly are debris of the above high-temperature components and byproducts of their formation (in particular in fine-grained rims around chondrules). No less certainly, the matrix also contains dust that escaped any high-temperature processing in the disk. Indeed, monomineralic grains of very anomalous isotopic ratios (deviating from solar values sometimes by orders of magnitude) have been found: They are interpreted as intact condensates from the atmospheres of dying stars (red giants, supernovae, etc.) predating the formation of the Sun and are thus referred to as *presolar grains*.

They offer unique insight into stellar nucleosynthesis and our interstellar heritage. Most presolar grains, which originally made the bulk of the disk dust, have been destroyed, and those identifiable today never exceed a 1000th part of the matrix but other grains, for example, such grown in the interstellar medium itself, may not be isotopically recognizable and thus the exact extent of unmodified interstellar heritage in chondritic matter is not known. Matrix is the carrier of organic matter (in diffuse form or in micron-sized particles) and water (or rather hydroxyl locked in hydrous silicates). Organic matter, which may represent a few percent of the matrix, is present in insoluble and soluble form. The insoluble organic matter (IOM), which makes the majority, is dominated by aromatic units while the soluble organic matter (SOM) may comprise such molecules considered as “prebiotic” such as sugars or amino acids. What part formed (or was modified) in the interstellar medium, the disk or after accretion remains contentious.

The modal abundances of the above chondrite components vary. *Ordinary chondrites*, which make up 80% of falls, typically contain more than 80 vol% chondrules. *Enstatite chondrites* are similarly chondrule-dominated but set apart by a more reduced opaque and silicate mineralogy. Refractory inclusions are notable (a few vol %) only in *carbonaceous chondrites* which also contain less chondrules and more matrix up to 100 vol% for CI chondrites (hence the larger bulk carbon content of many of them, though others are not more C-rich than noncarbonaceous chondrites) and as such qualify as the most primitive chondrites. Some chondrites (CH, CB) genetically associated with the carbonaceous chondrites are metal-rich and hold quite distinctive (dominantly nonporphyritic) chondrules; the latter are commonly held to be, at least in part, the results of impacts, but this does not prejudice the origin of their counterparts in “mainstream” chondrites.

While chondrites have changed little since accretion, they are not entirely pristine. Heating due to ^{26}Al decay may have caused metamorphism, with recrystallization gradually blurring the individual components and diffusion erasing

the original disequilibrium of the mineral assemblage, as in many ordinary and enstatite chondrites. If the parent body incorporated water ice, its melting may have incurred aqueous alteration causing oxidation of opaque phases, hydration of originally anhydrous minerals, and precipitation of new phases (e.g., carbonates). Such was the fate of many carbonaceous chondrites. In CI chondrites such as Orgueil, aqueous alteration has destroyed almost all high-temperature components. Metamorphism and aqueous alteration are evaluated on a single petrographic (or “petrologic”) scale from 1 to 7 devised by Van Schmus and Wood (1967). Type 3 chondrites are the most pristine, while types 4–7 correspond to increasing degrees of thermal metamorphism and types 2 and 1 to increasing degrees of aqueous alteration. Metamorphism and aqueous alteration were not entirely mutually exclusive, and evidence for both may be found in the same chondrite.

Differentiated Meteorites

While chondrites escaped melting, heating had of course no reason to stop short of solidus temperatures in all planetesimals. Thus, chondritic composition protoliths which exceeded about 950 °C suffered partial melting of metals and sulfide, and only 100 °C more sufficed to cause partial melting of silicates. Some meteorites are solid residues of such partial melting and thus represent an arrested stage of the differentiation process. They are called *primitive achondrites* for they generally retain a near-chondritic (primitive) bulk chemical composition (depending on the amount of melt extracted or gained) but have essentially lost their original chondritic texture (save perhaps for very rare relict chondrules).

At temperatures above silicate melting, significant mobility of melts was possible and so the parent body could segregate different phases according to density. This is *differentiation*. Dense metallic liquids, scavenging siderophile and chalcophile elements, would congregate to form an iron core, from which the *iron* meteorites crystallized. Irons from individual planetesimal cores show a range in composition because of fractional crystallization, where early crystallized irons concentrated compatible elements (i.e., elements partitioning preferentially into the solid, e.g.,

iridium) and later solidified irons had a greater share of incompatible elements. The metal originally crystallized as meter-size *taenite* (a face-centered cubic iron-nickel alloy) crystals but these underwent subsolidus exsolution of *kamacite* (a nickel-poorer body-centered cubic iron-nickel alloy) lamellae. Upon etching a polished slab of an iron meteorite, the less acid-resistant kamacite lamellae will appear as intercrossing sets of parallel silvery bands forming so-called *Widmannstätten patterns*. Macroscopic Widmannstätten patterns, which develop only because of the slow cooling (typically 1–100 K/Ma) in planetesimal interiors, are notoriously diagnostic of extraterrestrial metal. Strictly speaking, they are well-developed only in the (majority) structural class called *octahedrites* (because the kamacite plate orientations are parallel to the faces of a regular octahedron); too nickel-poor irons are dominated by kamacite and are called *hexahedrites* while nickel-rich ones contain only microscopic kamacite spindles and are called *ataxites*. Some irons do not seem to have fractionally crystallized (or “fracrystallized” for short), retaining near solar proportions of siderophile elements, and often contain silicate inclusions. These irons (once termed “nonmagmatic,” when their igneous nature was questioned, but more appropriately called “non-fracrystallized”) may have formed as a result of a catastrophic impact, mixing a still-molten (and unfractionated) core with mantle material. An impact may have alternatively formed a local melt pool at the surface of a chondritic body which would have partly differentiated. Some fracrystallized irons contain abundant olivine inclusions and are known as *pallasites*, which may also be the result of impact, perhaps at the core-mantle boundaries of their parent bodies.

Turning attention to the rocky outer layers, partial silicate melts, typically of basaltic composition, would tend to migrate toward the surface of the differentiating parent body, building a crust enriched in incompatible lithophile elements. The differentiating parent body might temporarily host a global magma ocean (sequestering the available ^{26}Al) there. The mantle underlying the crust may still contain partial melt residues (i.e., primitive achondrites) but the other rocks, whether formed by closed-system crystallization of a melt or the

accumulation of crystals settled from a magma body, are fully magmatic (or igneous) in nature and called *evolved achondrites*. Eucrites are example basaltic or gabbroic achondrites, while diogenites feature orthopyroxenites formed in generally deeper-seated plutons. So, an intact differentiated parent body comprises an iron core and achondritic mantle and crust. Many achondrites are brecciated (such as the howardites mixing eucritic and diogenitic clasts), and mesosiderites mix eucrite-diogenite-like material with metal presumably derived from the naked iron core of some disrupted planetesimal.

Key Research Findings

Meteorite Genetics

Meteorites do not present a continuum in compositional (isotopic, chemical, and textural) space. Rather, they form discrete clusters known as *groups* which are generally believed to represent individual primary parent bodies (or a set of similar parent bodies). Indeed, although the protoplanetary disk may have produced a continuum of planetesimals, it must be remembered that the asteroid main belt hosts but a tiny portion of the original population so sampling is necessarily sparse.

Groups among chondrites are given one- or two-letter designations. For example, ordinary chondrites are subdivided into H, L, and LL groups, which stand for “high,” “low,” and “low low” iron contents (anticorrelated with FeO contents in silicates), respectively; same for EH and EL for enstatite chondrites (at least etymologically, for they may actually only differ in redox state). Carbonaceous chondrite groups are denoted with a “C” plus the initial of the type meteorite. For instance, “CM chondrites” refers to Mighei-type carbonaceous chondrites (such as Murchison). The petrologic type is usually combined with the group acronym to display the complete classification, for example, Murchison is a CM2 chondrite while Orgueil is a CI1.

Iron chemical groups are given combinations of Roman numerals (from I to IV, in order of decreasing moderately volatile element content)

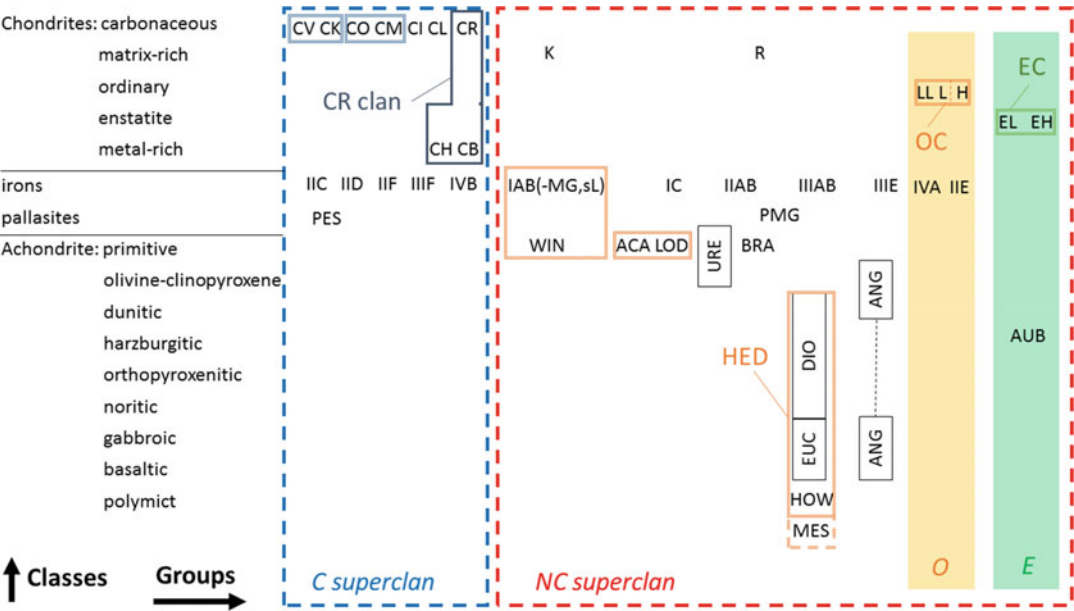
and letters (sometimes combined, depending on the vicissitudes of subdivisions and recombinations over the past half century), such as IIE or IIIAB, for example. Achondrite groups are given names ending in “-ites,” usually built on the name of a type of meteorite, for example, aubrites are enstatite achondrites named after the Aubres fall in France. Many meteorites are not affiliated to any established group (whose recognition by the Nomenclature Committee requires at least five unpaired members) and are termed “ungrouped” or “anomalous,” if allowance is made for them, more than 100 primary parent bodies may be represented in our meteorite collections (Greenwood et al. 2020).

Some sets of recognized groups actually represent different lithologies of a single primary parent body, such as the isotopically similar howardites, eucrites, and diogenites, collectively referred to as the “HED” clan, which are widely believed to originate from asteroid Vesta, based on

spectroscopic correspondence with its largely basaltic crust. Accounting for chemically anomalous irons, many more iron cores than mantle or crusts seem to be sampled; this paradox is the “dunite problem.” Possibly, most irons come from a very collisional inner solar system that essentially “battered to bits” early differentiated planetesimals, with only the more durable metallic fragments surviving to the present day.

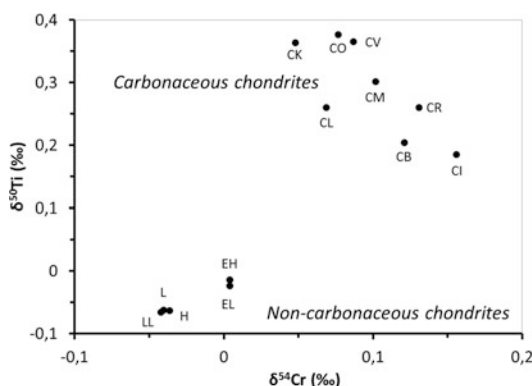
Isotopic similarity is no infallible proof of a common parent body (e.g., enstatite chondrites, aubrites, Earth, and the Moon are nearly isotopically indistinguishable) but does at least indicate provenance of a common restricted space-time section of the protoplanetary disk called a “reservoir” in cosmochemical parlance. Such affinities are depicted in Fig. 1.

On a broader scale, isotopic data show a remarkable first-order dichotomy between carbonaceous (C) and noncarbonaceous (NC) chondrites, which



Meteorites, Fig. 1 Classification of asteroidal meteorites. Petrological classes (chondrites, irons, achondrites, with indicative subdivisions) are presented in the vertical direction and groups in the horizontal direction, along with higher-order groupings (in particular the distinction between the carbonaceous (C) and non-carbonaceous (NC) superclans). *ACA* acapulcoite, *ANG* angrite, *AUB* aubrite, *BRA* brachinite, *DIO* diogenite, *EC* enstatite chondrites, *HED* howardite-eucrite-diogenite, *HOW* howardite,

K Kakangari chondrites, *LUN* Lunar, *LOD* lodranite, *MES* mesosiderite, *OC* ordinary chondrite, *PES* pallasite Eagle Station group, *PMG* pallasite main group, *R* Rumuruti chondrites, *URE* ureilite, *WIN* winonaite. Carbonaceous chondrite group-type meteorites: *CB* Bencubbin, *CH* ALH 85085, *CI* Ivuna, *CL* Loongana 001, *CM* Mighei, *CO* Ornans, *CR* Renazzo, *CV* Vigarano. See text for more detail



Meteorites, Fig. 2 The carbonaceous/non-carbonaceous chondrite dichotomy. $\delta^{50}\text{Ti}$ and $\delta^{54}\text{Cr}$ refer to relative deviations of the $^{50}\text{Ti}/^{47}\text{Ti}$ and the $^{54}\text{Cr}/^{52}\text{Cr}$ ratios relative to a terrestrial standard. (Data from Dauphas and Schauble (2016))

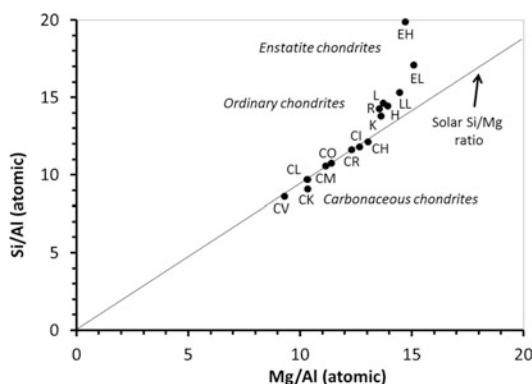
also applies to differentiated meteorites, with most of them belonging to the NC *superclan* (Fig. 2). Compared to NC meteorites (and Earth), C meteorites are enriched in neutron-rich isotopes of Ti and Cr and are ^{16}O -rich (in a mass-independent way). Since refractory inclusions (abundant only in C chondrites) display such enrichments to an even higher degree, it is tempting to ascribe the difference to mere addition of refractory inclusions, but mass balance calculations require a part of the host chondrite to carry such isotopically anomalies as well. The NC and C (super)reservoirs are widely believed to represent the inner and outer regions of the solar protoplanetary disk, respectively, consistent with the present-day segregation of S and C complex asteroids, and the divide between the two (which may have been close to the snow line) might relate to Jupiter. It is somewhat paradoxical, then, that carbonaceous chondrites should be those *most* enriched in refractory inclusions believed to have formed close to the young Sun. This has motivated various astrophysical models of outward transport of solids (e.g., Jacquet 2014).

For many isotopic systems, the differences must ultimately relate to variable populations of presolar grains in the building blocks of planetesimals. Indeed, the isotopic composition of C chondrites can be often rationalized as an overabundance of a nucleosynthetic component

produced in a neutron-rich stellar environment (e.g., a supernova). One school of thought considers that “thermal processing” preferentially evaporated some presolar grains, but it is unclear how this could have favored systematically the same nucleosynthetic component for elements of very different volatilities and presumed carriers. Another possibility is that this heterogeneity was inherited from the *protosolar cloud*, that is, the molecular cloud fragment which collapsed to form the early Solar System. Transport and mixing in the disk would have diminished the primordial heterogeneity, but would not erase it entirely. Refractory inclusions, which are isotopically more anomalous and variable than bulk chondrites, would fossilize early stages in this process. Ultimately, the heterogeneity may relate to fresh inputs of stellar ejecta. ^{26}Al itself may have been introduced by the winds of a massive star, which may have triggered the gravitational collapse of the protosolar cloud.

Other isotopic variations in meteorite whole-rocks or components were acquired within the disk. Some isotopes, such as short-lived beryllium-10 (half-life: 1.5 Ma) evinced by excesses of radiogenic boron-10 in CAIs, may have been produced during irradiation by energetic solar protons. The oxygen in solids, whose original isotopic composition seems to be recorded by refractory inclusions (which coincide with the present-day solar wind, notwithstanding mass-dependent fractionation), evolved toward ^{16}O -poorer (by 5–6%) composition prior to the formation of meteorite parent bodies, apparently by isotopic exchange with isotopically heavy water of as yet uncertain origin. In addition to mass-dependent effect, mass-dependent isotopic variations (e.g., for moderately volatile elements) may reflect kinetic gas-condensate exchanges.

While much attention is nowadays given to isotopic diversity, chemical variations in the disk were greater, sometimes at a few tens of %. While chondrites were introduced above as primitive solar material, strictly speaking, only CI carbonaceous chondrites provide a good chemical match with the solar photosphere. Other carbonaceous chondrites are typically enriched in refractory elements and show a monotonic depletion of



Meteorites, Fig. 3 Major lithophile element fractionation among chondrites. Carbonaceous and non-carbonaceous chondrites form distinct trends intersecting at solar (CI) composition. (Data from Hutchison (2004) and Metzler et al. (2021))

moderately volatile elements as a function of theoretical half-condensation temperature. This latter depletion is also apparent for non-carbonaceous chondrites, which are *depleted* in refractory elements and have subsolar Mg/Si (Fig. 3). Such chemical fractionations must reflect incomplete condensation processes and aerodynamic sorting of solids (which may also have incurred metal-silicate fractionations in individual reservoirs, for example, between H, L, and LL ordinary chondrites), but such processes are poorly understood. The average composition of differentiated parent bodies is difficult to reconstruct from individual meteorites, but great depletions in moderately volatile elements, sometimes by orders of magnitude, are apparent. While formation in very hot regions of the disk has been entertained, the parent bodies may have outgassed after accretion, because of radiogenic and/or impact heating.

Applications

Meteorites are samples of small bodies of the Solar System and, as such records of the first Ma of Solar System history and “ground truth” for protoplanetary disk astrophysics. Chondritic and iron asteroids are also entertained as mining resources for metal and water.

Future Directions

Overall, meteorites still present tantalizing first-order enigmas as to the genesis of their various components or their diversity as whole rocks. This is because, as rocks, they lack geologic context, though sample-return missions contribute to reconstruct one. The interaction with astronomical observations of protostars (and astrophysical modelling) also provides a bridge toward our past 4.57 Ga ago. Primitive Solar System geology can thus still hope to find its Wegener!

Cross-References

- ▶ [ALH 84001](#)
- ▶ [CAIs](#)
- ▶ [Chondrite](#)
- ▶ [Comet](#)
- ▶ [Interplanetary Dust Particle](#)
- ▶ [Meteorite, Allende](#)
- ▶ [Meteorite, Murchison](#)
- ▶ [Meteorite, Orgueil](#)
- ▶ [Microfossils](#)
- ▶ [Micrometeorites](#)
- ▶ [Molecules in Space](#)
- ▶ [Planet Formation](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Sun \(and Young Sun\)](#)
- ▶ [System Solar Formation, Chronology of](#)

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Meteorites, History of

Stéphane Le Gars

Centre François Viète, Université de Nantes,
Nantes, France

History

Meteorites have been objects of reverence in many premodern cultures, for example, in North America and in Europe, when the local population believed that they had fallen from the sky (e.g., Nininger 1972). Meteoritic iron was the only source of that metal before the invention of iron smelting and the beginning of the Iron Age; early iron weapons were thus exceptionally valuable. It is at the end of the eighteenth century that meteorites obtained the status of scientific objects. In

1794, the German scientist Ernst Florens Friedrich Chladni (1756–1827) explained the result of the observational comparisons he had made among lots of “fallen stones” and made a link between these stones and the fireballs observed for a long time in the atmosphere. This first systematic work on objects that were at that time despised induced him to ascribe an extraterrestrial origin to what were soon to be called “meteorites.” His results were confirmed at the beginning of the nineteenth century by chemical analysis and the discovery of the asteroid belt between Mars and Jupiter.

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Meteoritics

► [Cosmochemistry](#)

Meteoroid

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A meteoroid is a solid object orbiting the Sun (i.e., in interplanetary space) that is smaller than an ► [asteroid](#) but considerably larger than a single atom. The size demarcation between asteroids and meteoroids is somewhat arbitrary but is sometimes set at about 10 m (see ► [asteroid](#)). When a meteoroid strikes the atmosphere of the Earth, it produces the phenomenon called a meteor (popularly known as a “shooting star”) as it is heated by friction and completely or partially incinerated. If part of the meteoroid reaches the surface of the Earth, the surviving object or objects are called ► [meteorite\(s\)](#).

Cross-References

- ▶ [Asteroid](#)
- ▶ [Meteor](#)
- ▶ [Meteorites](#)

Meter-Size Catastrophe

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In a ▶ [protoplanetary disk](#), dust and gas orbit the star at different rates: gas pressure slows the revolution of the gas molecules, but not the much more massive dust particles. Therefore, the faster moving dust particles experience a headwind and a corresponding drag force due to the gas, which can lead to orbital decay for the particles. Small particles ($\sim 1\text{ }\mu\text{m}$) behave essentially like the gas and do not feel a strong headwind. Large particles ($>10\text{--}100\text{ m}$) have sufficient inertia to minimize orbital changes due to gas drag. However, at roughly 1 cm to 1 m in size, the effect of gas drag on particle orbits is the strongest. Calculations show that particles about 1 m in size feel the most gas drag, and they may spiral into their star from a distance of 1 AU so quickly that they probably cannot merge and grow fast enough to form 1 km-sized ▶ [planetesimals](#). Consequently, unless particles grow quickly through this phase, or unless particles of much bigger size are formed by collective mechanisms from smaller mass particles, the formation of planet would be difficult to explain – a potential “catastrophe” for theories of planetary formation.

Cross-References

- ▶ [Gas Drag](#)
- ▶ [Orbit](#)
- ▶ [Planet Formation](#)

Methanal

- ▶ [Formaldehyde](#)

Methanamide

- ▶ [Formamide \(\$\text{NH}_2\text{CHO}\$ \)](#)

Methanamine

- ▶ [Methylamine \(\$\text{CH}_3\text{NH}_2\$ \)](#)

Methane

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[CH₄](#)

Definition

Methane, CH_4 , is the simplest hydrocarbon molecule. Methane is a major component of natural gas, and is known as one of the major greenhouse gases. Both gaseous and solid methane have been detected in molecular clouds, and it has also been found in cometary comae. Methane is a major carbon species in the atmospheres of the outer planets such as ▶ [Jupiter](#) and Saturn. ▶ [Titan](#), the largest satellite of Saturn, has a dense atmosphere containing methane, and methane can form lakes on the surface of Titan.

Overview

Methane is a tetrahedral molecule, where four hydrogen atoms are covalently bound to the

central carbon atom with a bond length of 0.1087 nm and a bond angle (H–C–H) of 109.5°. Its melting point is 91 K, and its boiling point is 112 K. It is combustible and has been used as fuel. Methane hydrate, methane surrounded by water molecules forming a clathrate, has been found on the ocean floor and in permafrost since 1971, and is considered important fuel for the future.

Methane is a minor component of the Earth atmosphere, and its global average concentration was 1803 ppm in 2009, but is increasing by 5 ppm per year mainly due to human activities. Methane is known as a greenhouse effect gas together with carbon dioxide, water vapor, and nitrous oxide.

The concentration of methane in primitive Earth's atmosphere has been the subject of controversy since the mid-twentieth century. Some scientists, including Harold Urey, postulated that methane was its major component together with hydrogen and ammonia. Others, such as William Rubey, suggested that the atmosphere was less reducing and that carbon dioxide and nitrogen were its major constituents. Stanley Miller, following Urey's idea, performed in 1953 a historic spark discharge experiment in a gas mixture of methane, ammonia, hydrogen, and water. It was observed that a wide variety of organic compounds including amino acids could be easily formed from the gas mixture. A great number of experiments were further conducted using a methane-ammonia type gas mixture and a variety of energies (UV, heat, radiation, etc.) and formation of amino acids were also confirmed in them.

The scenario for the formation of Earth's atmosphere by impact degassing during heavy bombardment, suggests that methane and ammonia were not major components of the primitive atmosphere, and the formation of bioorganic compounds from the atmosphere becomes more difficult. Amino acid formation could however still have been possible if methane was present in the primitive Earth's atmosphere as a minor constituent, as seen in Titan atmosphere. Titan has a dense atmosphere (ca. 150 kPa) with a predominant portion of dinitrogen and a few percent of methane. By the action of plasma

discharge, UV and/or proton irradiation of simulated Titan atmosphere, complex organic compounds, sometimes referred to as tholins, are formed together with a wide variety of higher hydrocarbons and nitriles. The Cassini spacecraft discovered lakes on Titan surface, and the lakes should contain liquid methane and ethane. Cassini also found methane rain. Thus, Titan could have a methane cycle, in place of a water cycle as found on Earth.

Another possible environment for abiotic synthesis is submarine hydrothermal systems. In 1977, scientists diving off the coast of the Galapagos Islands, found superheated seawater erupting from the sea bottom. The fluid temperature was over 300 °C and contained reducing gases including methane, hydrogen, and hydrogen sulfide. It was postulated that abiotic reactions could have taken place using methane and other compounds in submarine hydrothermal systems. It is known that chemosynthetic microorganisms make biospheres near such environments. Chemosynthetic microorganisms include methanogens that reduces carbon dioxide to form methane and methanotrophs that oxidize methane. Thus, methane is considered an important biosignature.

Several groups have detected methane on Mars. Since methane is easily decomposed in Mars' atmosphere, discovery of methane suggested that continuous production of methane might be an evidence of life on Mars.

Cross-References

- [Chemical Evolution](#)
- [Comet](#)
- [Hydrocarbons](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Jupiter](#)
- [Mars](#)
- [Methanogens](#)
- [Methanotroph](#)
- [Miller, Stanley](#)
- [Titan](#)

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Methane Oxidation

Lisa Y. Stein

Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada

Keywords

Methanotroph · Methane monooxygenase · Methyl-coenzyme M reductase · Anaerobic oxidation of methane (AOM) · Anaerobic methane-oxidizing archaea (ANME) · Nitrite-driven anaerobic methane oxidation (n-DAMO) · Trace methane oxidation (TMO)

Definition

Methane oxidation is the major methane sink in the biosphere, accomplished by diverse and ubiquitous microorganisms in the bacterial and archaeal domains of life. Methane oxidation occurs from fully oxic, to hypoxic, to anoxic environments. Aerobic and intra-aerobic methane oxidation requires the methane monooxygenase enzyme (MMO) to activate methane (Ettwig et al. 2010), whereas anaerobic methane oxidation by archaea involves the reverse methanogenesis pathway powered by methyl-coenzyme M reductase (MCR) (Evans et al. 2019). Anaerobic methane oxidation can be coupled to the reduction of sulfate (Milucka et al. 2012), nitrate (Haroon et al. 2013), nitrite (Ettwig et al. 2010), and iron/manganese (Ettwig et al. 2016), uniting a multitude of biogeochemical cycles. The diversity of metabolic strategies for methane oxidizers suggests that they could thrive in extraterrestrial ecosystems where methane is sustainably produced.

Overview

Organisms

Methane is produced in any ecosystem where there is plentiful organic matter available for fermentation, followed by methanogenesis. In turn, methane oxidation is favored by microbes that can acquire methane and metabolize it as a source of both carbon and reductant to drive cellular processes. These microbes are called “methanotrophs,” literally methane eaters, and have evolved specialized pathways to generate proton motive force from methane oxidation and can assimilate single-carbon molecules into biomass.

Aerobic methanotrophs are found in the *Proteobacteria* phylum in the classes *Alphaproteobacteria* and *Gammaproteobacteria* (Bowman 2006; Webb et al. 2014) and in the *Verrucomicrobia* phylum. A primary difference between *Alpha*- and *Gammaproteobacteria* methanotrophs is that the former uses the serine pathway and the latter uses the ribulose monophosphate pathway to assimilate formaldehyde. Alternatively, methanotrophs in the *Verrucomicrobia* phylum fix carbon dioxide using the Calvin-Benson-Bassham (CBB) cycle (Khadem et al. 2012) and can grow chemolithotrophically from hydrogen oxidation in addition to growing on methane (Carere et al. 2017). Some *Alphaproteobacteria* methanotrophs have metabolic flexibility beyond methane and can grow on multicarbon compounds (Tamas et al. 2014).

The anaerobic methanotrophs include both bacteria in the NC10 phylum (Ettwig et al. 2010) and archaea in the Euryarchaeota phylum (Evans et al. 2019). The NC10 bacteria, typified by the species *Ca. ‘Methylomirabilis oxyfera,’* perform “intra-aerobic methane oxidation” wherein methane is oxidized at the expense of nitrite reduction, a process that produces O₂ from the dissimilation of the metabolic intermediate, nitric oxide. The archaeal anaerobic methane oxidizers (ANME) perform reverse methanogenesis and consume methane as a carbon/energy source. Some can also oxidize multicarbon compounds in addition to methane (Evans et al. 2019).

Certain genera of *Gammaproteobacteria* methanotrophs can grow under extremely

hypoxic conditions by oxidizing methane at the expense of nitrate (Kits et al. 2015) or by fermenting formaldehyde using central carbon pathways (Kalyuzhnaya et al. 2013). These particular methanotrophs have systems to scavenge oxygen at extremely low concentrations and are not considered true anaerobes, but can be plentiful in environments marked by extreme hypoxia to anoxia (Chistoserdova and Kalyuzhnaya 2018).

Enzymology

Aerobic methane oxidation in *Proteobacteria* and *Verrucomicrobia* relies on a series of enzymes that transform methane sequentially into methanol, formaldehyde, formate, and carbon dioxide. The key enzyme in this process is methane monooxygenase (MMO), which has both a soluble cytoplasmic and a particulate membrane-bound form that share an evolutionary history (Osborne and Haritos 2018). There are also two forms of methanol dehydrogenase (MDH), a calcium-dependent (MxaF) and a lanthanum-dependent (XoxF) form (Chistoserdova and Kalyuzhnaya 2018). XoxF is one of very few enzymes known to require rare Earth elements for its active site. The tetrahydromethanopterin-/methanofuran (H₄MPT/MF)-linked pathway that facilitates conversion of formaldehyde to formate is ancient and links all domains of life (Chistoserdova and Kalyuzhnaya 2018). The evolutionary history of this formaldehyde-activating pathway suggests that metabolism of C1 molecules originated very early in life history. Formate dehydrogenase is the final enzyme in the methane oxidation pathway that produces CO₂ and intracellular reductant (NADH). Carbon assimilation by proteobacterial methanotrophs proceeds at the level of formaldehyde via the serine or ribulose monophosphate pathways (Bowman 2006; Webb et al. 2014).

The enzymology of anaerobic methane oxidation by NC10 bacteria is the same as that for the aerobic methanotrophs with the exception of nitrite reductase and nitric oxide dismutase (NOD) enzymes that terminate the electron transport chain or produce O₂ for methane oxidation, respectively (Ettwig et al. 2010). NC10 bacteria,

like the *Verrucomicrobia*, fix CO₂ via the CBB pathway (Rasigraf et al. 2014). Anaerobic methane oxidation by ANME archaea relies on the reversibility of the key methanogenesis enzyme, methyl-coenzyme M reductase (Mcr), and can be coupled to the reduction of many molecules including nitrate, iron, manganese, and sulfate (Timmers et al. 2017). Some pure cultures of methanogenic archaea can oxidize small amounts of methane, but only during net methane production in a process called “trace methane oxidation (TMO)” (Timmers et al. 2017). TMO does not allow for energy conservation and is likely caused by a reverse flux of substrate by individual enzymes within the methanogenic pathway.

Environments and Astrobiology

While aerobic methanotrophs are pervasive in nearly every ecosystem with ready access to oxygen and methane, anaerobic methanotrophs and those that grow under extreme hypoxia are most relevant for understanding the origins of methanotrophy on Earth and the possibility for similar metabolism to exist on extraterrestrial bodies. Due to common nomenclature, ANME archaea have been designated as “reverse methanogens,” while in reality there is evidence that these microbes initially arose as anaerobic methanotrophs and not as methanogens (Russell and Nitschke 2017). The speculative model involves a “denitrifying methanotrophic acetogenic pathway” whereby methane combines with formate or CO to generate acetate, a common product of ancient carbon fixation pathways. In the model, reduction of nitrate/nitrite to NO would activate methane oxidation and also provide assimilable nitrogen. This series of reactions can be coupled to serpentinization reactions that generate formate, H₂, and reductant at hydrothermal vents, a favored environment for modeling the origins of life.

Aside from ANME archaea, methanotrophs with MMO enzymes in the *Proteobacteria*, *Verrucomicrobia*, and NC10 phyla also thrive under hypoxic to anoxic environments by tightly coupling oxygen production and consumption (Chistoserdova and Kalyuzhnaya 2018). In an astrobiology context, both perchlorate and

methane have been detected on Mars as early as the Viking Lander experiments, although the source and sustainability of these molecules are still questioned (Levin and Straat 2016). If perchlorate and methane were continuously generated and available in the Martian subsurface, microorganisms could conceivably reduce perchlorate to generate O₂, which in turn could be scavenged by methanotrophs to activate methane. Indeed, the finding of methanotrophs with oxygen-dependent enzymology thriving in anoxic environments on Earth suggests that cryptic oxygen cycling is a normal part of ecosystem function (Chistoserdova and Kalyuzhnaya 2018). Certainly, sustainable sources of other essential elements including nitrogen, sulfur, phosphorous, transition metals, etc. were necessary for establishing viable cellular life on Earth and are likely also necessary for diversifying enzymology and stabilizing cellular life in other planetary contexts. However, biological methane oxidation as a key catabolic pathway remains a strong candidate for life on other planets as well as for origins of life on Earth.

Summary

Biological methane oxidation is an ancient metabolism that is performed by both *Bacteria* and *Archaea* from fully oxic to anoxic ecosystems. Methanotrophic microorganisms evolved specialized pathways to activate methane and use it as both a carbon and energy source. Two enzymatic mechanisms for methane activation have been identified: methane monooxygenase and methyl-coenzyme M reductase. The ability of aerobic methanotrophs to tightly couple oxygen consumption with oxygen generation, as well as the diversity of electron acceptors that connect to methane oxidation, suggests that this metabolism is adaptive to a wide range of ecosystems, possibly including extraterrestrial bodies.

Cross-References

- [Habitability on Mars](#)
- [Methane](#)

- [Methanogenesis](#)
- [Nitrates on Mars](#)
- [Perchlorates on Mars](#)
- [Serpentinization \(Mars\)](#)

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Methanethioaldehyde

- [Thioformaldehyde \(H₂CS\)](#)

Methanethiol

- [Thioformaldehyde \(H₂CS\)](#)

Methanethiol (CH₃SH)

Didier Despois¹ and Audrey Coutens²

¹Laboratoire d’Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

²Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Toulouse, France

Synonyms

CH₃SH; Mercaptomethane; Methyl mercaptan; Thiomethanol

Chemical Formula

CH₃SH

Definition

Methanethiol (its IUPAC official name) is a colorless gas under standard temperature and pressure, becoming liquid at 6 °C. It is the simplest thiol (thiols are analogs to alcohols, with an SH group replacing OH). Methanethiol has a strong rotten cabbage smell, so that some is added to natural gas to ease leak detection. It is produced by decaying organic matter in marshes and by decomposition of an algal metabolite (DMSP, dimethyl sulfonio propionate). It is the main sulfur source of some marine bacteria and a possible substrate for methanogenesis. In prebiotic chemistry, its presence allows for the synthesis of the S-bearing amino acid methionine in Urey-Miller experiments (Miller 1974). Methanethiol has been found in interstellar space.

History

Methanethiol was first detected in the interstellar medium towards the high-mass star-forming region Sgr B2 close to the Galactic center by Linke et al. (1979). Since then, it was found towards other astrophysical objects including the high-mass star-forming regions G327.3–0.6 (Gibb et al. 2000), Orion KL (Kolesníková et al. 2014), IRAS 16547–4247 (Zapata et al. 2015), and G31.41+0.31 (Gorai et al. 2021), the low-mass protostar IRAS16293–2422 (Majumdar et al. 2016) and the dense cores B1-b (Cernicharo et al. 2012) and L483 (Agúndez et al. 2019). Methanethiol was also detected in the coma of comet 67P/Churyumov–Gerasimenko in the framework of the Rosetta mission (Calmonte et al. 2016).

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [IRAS16293-2422](#)
- [Methionine](#)

- [Molecules in Space](#)
- [Rosetta Spacecraft](#)
- [SgrB2](#)
- [Thioformaldehyde \(H₂CS\)](#)

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Methanimine (CH₂NH)

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Lederle Graduate
Research Tower B 619E, Amherst, MA, USA

Keywords

Glycine · Interstellar · Molecules

Synonyms

[Methylenimine](#)

Chemical Formula

CH₂NH

Definition

The organic molecule methanimine is not terribly stable under terrestrial conditions, being a minor equilibrium product of the reaction of ammonia and formaldehyde. It has been suggested as a possible precursor to the amino acid glycine in some astrophysical settings (e.g., Godfrey et al. 1973).

Overview

Methanimine was one of the first relatively complex organic molecules detected in the interstellar medium (Godfrey et al. 1973), towards the Galactic Center molecular cloud SgrB2. It has subsequently been found in several “hot core” sources, interstellar molecular clouds where massive stars are forming (Dickens et al. 1997). Methanimine may also be present in the atmosphere of Saturn’s satellite Titan (Vuitton et al. 2006).

Cross-References

- [Glycine](#)
- [Hot Core](#)
- [Interstellar Medium](#)
- [Methylamine \(CH₃NH₂\)](#)
- [SgrB2](#)
- [Titan](#)

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Methanobacteria

► Methanogens

Methanogenesis

Jennifer Glass¹ and William B. Whitman²

¹Georgia Institute of Technology, Atlanta, GA, USA

²University of Georgia, Athens, GA, USA

Keywords

Archaea · Extremophiles · Anaerobic · Methane · Nickel · Respiration

Acronyms

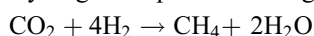
MCR Methyl coenzyme M reductase

Definition

Methanogenesis is an anaerobic respiration leading to the biological production of methane.

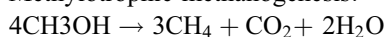
Chemical Formulas

Hydrogenotrophic methanogenesis:



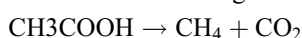
$$\Delta G^\infty = -135.6 \text{ KJ mol}^{-1} \text{ methane}$$

Methylotrophic methanogenesis:



$$\Delta G^\infty = -112.5 \text{ KJ mol}^{-1} \text{ methane}$$

Aceticlastic methanogenesis:



$$\Delta G^\infty = -31.0 \text{ KJ mol}^{-1} \text{ methane}$$

(1)

History

The discovery of biological methane production as flammable marsh gas dates back to the Italian physicist Alessandro Volta in the mid-1700s. Methanogenic archaea were first isolated in the 1930–1940s, but not recognized as Archaea until the late 1970s (Balch et al. 1979). Elucidation of the pathway of methanogenesis was achieved during the 1980–1990s. In the twenty-first century, gene sequencing from environmental DNA revealed a much wider diversity of methanogens than previously recognized, much of which remains uncultivated.

Overview

Methanogenesis, or biological production of methane via anaerobic respiration, accounts for 70% of the 500–600 tera-grams of methane emitted to Earth's atmosphere each year (Lyu et al. 2018). To date, all the methanogens discovered so far are: (1) strict anaerobes with metal-rich enzymes that are highly sensitive to molecular oxygen; (2) obligate methanogens that only grow while making methane, and (3) *Archaea* that are evolutionarily very distinct from the more familiar *Bacteria* (Whitman et al. 2014). Methanogens are commonly considered the bottom of the proverbial anaerobic “food chain” and use the poor electron acceptor carbon dioxide. They harvest the scarce energy left once complex carbon molecules have been broken down to simpler organics like acetate and methylated compounds, or they use hydrogen gas, formate, simple alcohols, or carbon monoxide to reduce carbon dioxide to methane (see [Chemical Formulas](#)). Therefore, methanogenesis only dominates in anoxic ecosystems when better electron acceptors (e.g., oxygen, nitrate, sulfate, and oxidized metals) become depleted. Methanogenic habitats can be natural (e.g., wetlands, sediments, soils, gastrointestinal tracts of animals) or created by humans (e.g., wastewaters, rice paddies, livestock ruminants, and the lower intestinal track in humans).

Energetics of Methanogenic Metabolisms

Methanogens are named according to their

substrate. Aceticlastic methanogens use acetate, splitting it into carbon dioxide and methane. Methylothermophilic methanogens use methanol or other methyl-containing compounds as the carbon donor. Often the methyl group is reduced to methane with hydrogen, but some methylothermophiles can also oxidize the methyl groups to reduce the remaining methyl groups in a process called disproportionation. Hydrogenotrophic methanogens often use hydrogen gas to reduce carbon dioxide to methane, but some can use other electron donors such as formate and simple alcohols such as isopropanol and ethanol. However, they have a very limited capacity to oxidize complex organic molecules, and isopropanol is only oxidized to acetone and ethanol is only oxidized to acetate.

The energy yield of cellular respiratory processes can be predicted from the magnitude of the free energy change; the more negative the ΔG° value, the higher the energy and growth yield. At standard state conditions, hydrogenotrophic methanogenesis is predicted to yield the highest change in free energy (see [Chemical Formulas](#)). However, the actual $\Delta G'$ for hydrogenotrophic methanogenesis is typically much lower than the standard state value because $\Delta G'$ varies with the fourth power of hydrogen concentration, and hydrogen concentrations are often extremely low in natural environments. Thus, methylothermophilic methanogenesis is often more energetically favorable than hydrogenotrophic methanogenesis under conditions found in the environment. Aceticlastic methanogenesis is typically the least energetically favorable of the three types (Lyu et al. 2018). Unlike many other microbes, methanogens cannot grow via fermentation or using alternative electron acceptors.

Ecology of Methanogens Hydrogenotrophic methanogens are responsible for approximately a third of methane emissions, and aceticlastic methanogens are responsible for the other two-thirds (Angle et al. 2017; Lyu et al. 2018). Importantly, hydrogenotrophic methanogenesis also maintains the low concentrations of hydrogen necessary to allow the complete degradation of complex organic compounds to acetate and

carbon dioxide in a process called interspecies hydrogen transfer. Hydrogenotrophic methanogenesis dominates in ecosystems where hydrogen can accumulate due to geothermal gaseous sources (e.g., hydrothermal vents; 3% of global methane emissions) and in the digestive tracts of animals such as livestock (25% global emissions) and termites (4% global emissions) where fermentation by other microorganisms provides a hydrogen source and organic acids are assimilated by the animal. Aceticlastic methanogens dominate in anaerobic digestors (sewage treatment, 6% global emissions), rice fields (15% global emissions), and wetlands (33% global emissions). Methylothermophilic methanogenesis is a minor source of global methane emissions and occurs primarily in marine (4% global emissions) and hypersaline environments where the osmolytes betaine and dimethylsulfoniopropionate are abundant sources of methyl-containing compounds (Lyu et al. 2018). Coal bed methane is also produced by methylothermophilic methanogens from methoxylated aromatic compounds (Mayumi et al. 2016).

Biochemistry of Methanogenesis In contrast to the simplicity of the chemical reactions (see [Chemical Formulas](#)), the biochemical complexity of methanogenesis is comparable to that of photosynthesis (DiMarco et al. 1990; Thauer et al. 2008). Depending on the substrate, up to seven unusual coenzymes participate in the pathway, and about 200 genes are required to synthesize the enzymes and coenzymes for methanogenesis. Abundant metals, particularly iron, nickel, cobalt, and molybdenum or tungsten, are required for methanogenesis (Glass and Orphan 2012). Some methanogens also use selenium to make selenocysteine, the 21st amino acid (Rother and Krzycki 2010). All methanogenic pathways have in common the last enzyme, methyl coenzyme M reductase (MCR), and the *mcrA* gene is widely used as a molecular marker for methanogens in the environment. MCR uses the thiol on coenzyme B to reduce methylcoenzyme M, forming the heterodisulfide of coenzyme M and coenzyme B and methane. Heterodisulfide is converted back to coenzymes M and B by the iron-sulfur protein

heterodisulfide reductase. MCR contains the unique nickel-porphyrin coenzyme F₄₃₀, which has an extremely low mid-point potential (−650 mV) and is therefore extremely oxygen-sensitive. Methanogens with the acetoclastic pathway use cytochromes for electron transfer and proton pumps for ATP synthesis, while hydrogenotrophic methanogens use flavin-based electron bifurcation and sodium pumps for ATP synthesis (Lyu et al. 2018; Thauer et al. 2008). Acetoclastic methanogens require activation of acetate to acetyl-CoA by ATP prior to splitting it into carbonyl and methyl groups. Methylophilic methanogens use cobamide-containing methyltransferases to transfer the methyl group to methylcoenzyme M. Some of these methyltransferases use the 22nd amino acid, pyrrolysine (Rother and Krzycki 2010).

Taxonomy of Methanogenesis Historically, methanogens were classified in the *Euryarchaeota* phylum of the *Archaea*. However, recent analyses of the genomes of pure cultures and metagenome assembled genomes, or MAGs, from environmental DNA indicate that methanogenesis is widely distributed among many phyla of *Archaea*. These results are consistent with the ancient origin of methanogenesis (see below) and the variety of biochemical pathways of methanogenesis. All methanogenic archaea isolated in pure culture appear to belong to one of three phyla. The first phylum *Methanobacteriota* contains three out of eight of the currently known orders of cultured methanogens: *Methanobacteriales*, *Methanopyrales*, and *Methanococcales*. All are hydrogenotrophs and related to the nonmethanogenic thermophilic heterotrophs *Thermococcales*. The cell walls of *Methanobacteriales* and *Methanopyrales* contain pseudomurien, a peptidoglycan similar to that in bacteria. These diverse taxa include *Methanobrevibacter*, the methanogen common in the gastrointestinal tract of humans and many animals, as well as the hyperthermophiles *Methanothermus* and *Methanopyrus* from hydrothermal vents. The *Methanococcales* contains mesophiles, thermophiles, and hyperthermophiles isolated from marine environments, and includes *Methanococcus*, one of the two methanogenic genera with a well-developed genetic system.

Four of the remaining orders of cultured methanogens (*Methanosarcinales*, *Methanocellales*, *Methanonatronarchaeales*, *Methanomicrobiales*) all belong to the phylum *Halobacteriota* of more metabolically diverse methanogens as well as non-methanogens including extremely halophilic *Halobacteria* and sulfate-reducing *Archaeoglobales* (Lyu et al. 2018). Hydrogenotrophic methanogenesis is present in all methanogenic orders in the second phylum except *Methanonatronarchaeales*, which are methylotrophic. Acetoclastic methanogenesis is only found in *Methanosarcinales*, which includes *Methanosarcina*, the other methanogen with a well-developed genetic system. *Methanosarcina* spp. are unusual in that they can utilize all three classes of methanogenic substrates: hydrogen, acetate, and methyl-compounds. *Methanohalobium*, an extremely halophilic methylotroph, is also a member of the *Methanosarcinales* order. The *Methanosarcinales* are also closely related to taxa that can anaerobically oxidize methane (ANME-2 clade) but have never been grown in pure culture. The *Methanonatronarchaeales* order contains extremely halophilic methylotrophs, but it is specifically related to the non-methanogenic *Halobacteria*. The *Methanocellales* order includes hydrogenotrophic methanogens common in rice paddy soil that are oxygen tolerant as well as psychrophilic permafrost methanogens. The *Methanomicrobiales* includes a wide variety of hydrogenotrophic methanogens common in bioreactors, fresh water, and brackish water. Lastly, the *Methanomassiliicoccales* are the only order of methanogens in the phylum *Thermoplasmata*. These obligate methylotrophs are common in the gastrointestinal tracts of ruminants and other mammals as well as anaerobic sediments.

Genes encoding *mcrA* have also been discovered in genomes of the uncultivated archaeal of the phylum *Bathyarchaeota* (Evans et al. 2015), *Verstraetearchaeota* (Vanwonterghem et al. 2016), as well as other archaea genomes. In some cases, there is little evidence for the metabolic function of these genes (see Evans et al 2019 for a review), suggesting that the biochemistry of methanogenesis may be more complex than currently understood.

year freeze and thaw cycles like those on Mars (Mickol et al. 2018). *Methanothermococcus okinawensis* (*Methanococcales*) endures high pressures up to 50 bar, similar to those of Enceladus, and also persists in the presence of acetylene, a methanogen inhibitor (Taubner et al. 2018). *Methanosarcina barkeri* (*Methanosarcinales*) can survive ultra-low pressures (6 mbar), desiccation, and regolith similar to the Martian subsurface (Kral and Altheide 2013). Salt tolerance is dependent on the type of methanogenesis, due to the energy requirements for salt tolerance via biosynthesis of organic osmolytes or pumping salt for osmotic balance (see refs in Enzmann et al. 2018). Therefore, methylotrophic methanogens tend to be capable of surviving at much higher salinities than hydrogenotrophic and acetoclastic methanogens; *Methanonatronarchaeum thermophilum* (*Methanonatronarchaeales*) grows optimally at 4 M sodium using a salt-in strategy (Sorokin et al. 2017).

Other Biological Methane Sources In addition to methanogenic archaea, there are several other minor sources of biogenic methanogenesis that are uncoupled to energy conservation and occur in both oxygenated and anoxic environments. The finding of methanogenesis in the presence of oxygen has been referred to as the “methane paradox” because methanogenesis is otherwise limited to strict anaerobes. The best studied pathway of aerobic methane production is demethylation of methylphosphonates during phosphorus acquisition by heterotrophic bacteria. Filamentous and unicellular cyanobacteria cultures have been reported to produce methane in the presence of oxygen, although the pathway and biochemical mechanism for this process remains unknown (Bizic-Ionescu et al. 2018). Likewise, the bacterium *Acidovorax* uses a pyridoxal phosphate-dependent enzyme to generate ammonia and methane from methylamine (Wang et al. 2021). “Mini-methane producers” are fermentative bacteria that form methylcobamides as intermediates in their metabolism. Exposure of methylcobamides to light releases small amounts of methane. Lastly, most living organisms produce small amounts of methane upon exposure to oxidative stress (Ernst et al. 2022).

More Information For more complete coverage of the ecology, physiology, biochemistry and genetics of methanogenesis, readers are referred to Ferry (2012). For a database of methanogen growth conditions, readers are referred to Michał et al. (2018). For more information on methanogens in the context of astrobiology and geochemistry, readers are referred to Taubner et al. (2015) and Strapoć (2017), respectively.

Cross-References

- Archaea
- Enceladus
- Extremophiles
- Faint Young Sun Paradox
- Mars
- Stable Isotopes
- Titan

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Methanogenic Archaea

► Methanogens

Methanogens

José Luis Sanz
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Anaerobic respiration · Archaea ·
Euryarchaea · Hydrogen · Methane

Synonyms

Methanobacteria; Methanogenic archaea

Definition

Methanogens are ► [microorganisms](#) whose metabolism generates ► [methane](#). All methanogenic organisms belong to the Domain ► [Archaea](#), phylum ► [Euryarchaeota](#). They are very diverse, morphologically (rods, filaments, cocci, sarcina among others) as well as phylogenetically: they are distributed in four Classes and five Orders: *Methanobacteriales*, *Methanococcales*, *Methanomicrobiales*, *Methanosarcinales*, and *Methanopyrales*. Methanogenic archaea, also referred to as methanobacteria, are the living beings most sensitive to oxygen (see ► [Anaerobe](#)), which is why they only develop in anaerobic and reducing environments (with redox potentials below -200 mV). Despite this limitation, their ecological niches are widely distributed: aquatic sediments (marshes, swamps), stagnant soil (peat bogs, ricefields), marine geothermal vents, the digestive tract of certain animals (ruminants or termites), sludge or wastewater digestors, etc.

Overview

Methanogens derive energy exclusively through the production of ► [methane](#) (a process known as methanogenesis). Methanogenesis constitutes the last step in the degradation/mineralization of organic matter in the absence of oxygen, an essential link in the carbon cycle. There are a few substrates for methanogenesis. All methanogenic Archaea (with only one exception) are able to reduce CO_2 with H_2 forming CH_4 (hydrogenotrophic methanogenesis), fixing CO_2 by the carbon monoxide pathway to synthesize their biomass. They are, therefore, chemolithoautotrophs. Many, but not all, hydrogenotrophic species can alternatively use formic acid. Another substrate that can be converted into methane is acetate (acetoclastic methanogenesis). Even

though only two genera, *Methanosarcina* and *Methanosaeta*, are acetoclastic methanogens, they are of great importance, which is reflected in the fact that two-thirds of the methane produced from complex organic matter comes from acetate. Certain members of *Methanomicrobia* can use C1-compounds (methanol or methylamines), but their relevance in the environment anaerobic full-scale digestors is limited.

Many of the ► [coenzymes](#) involved in methanogenesis are present exclusively in methanogens. Some, like the electron transporter F420, emit blue-green fluorescent light, which is useful for identifying methanogens by fluorescence microscopy. Others are involved in the final step of all methanogenesis reactions (conversion of methyl groups into methane). Coenzyme M ($\text{HS} - \text{CH}_2 - \text{CH}_2 - \text{SO}_3^-$) is among these and it is present exclusively in these organisms, which is why an analog of this coenzyme (BESA: bromo-ethanesulfonic acid) is used to specifically inhibit methanogenesis. From an energetic point of view, methanogenesis is a very inefficient process, generating only one ATP per mole of methane produced. The yield is therefore very small (only 2% of fixed CO_2 becomes biomass), and the generation times of methanogens are long (1–7 days in optimum conditions). Both of these characteristics make methanogenesis a key step in anaerobic digestion. This is of particular relevance in anaerobic treatment of wastewaters and in biomethanization processes. Although methane can be produced abiotically, 80% of the Earth methane is biologically produced by methanogens. Methanogenesis is of astrobiological interest as a unique and very ancient mode of energy conservation and especially after the recent detection of methane in the Mars atmosphere.

Cross-References

- [Archaea](#)
- [Euryarchaeota](#)

- [Methane](#)
- [Methanotroph](#)

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Methanoic Acid

- [Formic Acid](#)

Methanol

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Synonyms

[Methyl alcohol](#)

Definition

Methanol is the simplest ► [alcohol](#), with the structural formula CH_3OH . The International Union of Pure and Applied Chemistry (IUPAC) recommends using the term methanol rather than methyl alcohol. Methanol is a colorless, volatile, and flammable liquid under standard conditions. Its melting and boiling point are $-97.8\text{ }^\circ\text{C}$ and $64.7\text{ }^\circ\text{C}$, respectively. It is a product of anaerobic metabolism of certain groups of bacteria and of the abiotic reduction of carbon monoxide with hydrogen. It is toxic to humans and other organisms since it is converted in vivo to formic acid, which many organisms have trouble metabolizing. Methanol is widely distributed in interstellar space, where it was identified in 1970. It is particularly abundant in star-forming regions such as ► [hot cores](#) and ► [hot corinos](#). Methanol has also been identified in comets. Methanol has been used as one of the carbon sources in simulated ► [interstellar ices](#), and amino acids are formed by irradiation with charged particles or ultraviolet light in the presence of a nitrogen source such as ammonia.

Cross-References

- [Alcohol](#)
- [Comet \(Nucleus\)](#)
- [Ethanol](#)
- [Hot Core](#)
- [Hot Corino](#)
- [Interstellar Ices](#)
- [Molecules in Space](#)

Methanophiles

- [Methanotroph](#)

Methanotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Methanophiles](#)

Definition

Methanotrophs are organisms which are able to obtain energy by oxidizing ► [methane](#) (CH₄). Methane, found widely in nature, is produced in strict anaerobic conditions by methanogenic Archaea (see ► [Methanogens](#)). It is the main gas in anoxic muds, marshes, lakes, rice paddies, and landfill. Methane is the major constituent of natural gas and is also present in many coal formations. It can be used as an electron donor by methanotrophic bacteria. Methanotrophs can also use other one carbon compounds as a source of energy and carbon. Most of the known methanotrophs are aerobic, although, recently, methanotrophic activities in anoxic environments have been detected. All methanotrophs possess a specific enzyme, methane monooxygenase, which can insert an oxygen atom into the methane molecule generating methanol. The oxygen requirement for the oxygenation of methane explains their obligate aerobic character. The anoxic oxidation of methane requires a consortium of methanotrophic and sulfate reducing bacteria. Methanotrophs are widespread in both aquatic and terrestrial environments and are found wherever stable sources of methane are present. They play an important role in the carbon cycle.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)

- [Carbon Cycle, Biological](#)
- [Methanogens](#)
- [Sulfate Reducers](#)

Methenamine

- [Hexamethylenetetramine](#)

Methinophosphide

- [Phosphaethyne \(HCP\)](#)

Methionine

Kensei Kobayashi
Yokohama National University, Tokiwadai,
Hodogayaku, Yokohama, Japan

Definition

Methionine is a sulfur-containing ► [amino acid](#) with the side chain –CH₂CH₂SCH₃. Among the 20 protein amino acids, only methionine and ► [cysteine](#) have ► [sulfur](#). Its three-letter symbol is Met, and its one-letter symbol is M. The molecular weight of methionine is 149.21, and its isoelectric point (pI) is 5.74. In the standard genetic code table, only one codon AUG corresponds to methionine, and this codon is also an initiation codon. Eukaryotes and archaea, therefore, synthesize all their ► [proteins](#) with methionine at N-terminal (the amino acid with free –NH₂ group at the end of proteins). Most of N terminal methionine are removed after the translation processes. Methionine is an essential amino acid for humans.

Cross-References

- [Amino Acid](#)
- [Cysteine](#)

- [Protein](#)
- [Sulfur](#)

Methoxy Radical (CH₃O)

William M. Irvine

Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

CH₃O

Definition

The methoxy radical CH₃O has been detected in the ► [interstellar medium](#) in a cold ► [dense core](#) (Cernicharo et al. [2012](#)). Its chemistry is presumably related to that of other known interstellar molecules such as formaldehyde (H₂CO) and methanol (CH₃OH).

Cross-References

- [Interstellar Chemical Processes](#)
- [Molecules in Space](#)

References and Further Reading

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- Jimenez-Serra I et al (2017) The spatial distribution of complex organic molecules in the L1544 pre-stellar core. *Astrophys J Lett* 830:L6

Methoxyethane

- [Ethyl Methyl Ether \(C₂H₅OCH₃\)](#)

Methoxymethane (IUPAC Name)

- [Dimethyl Ether \(CH₃OCH₃\)](#)

Methoxymethanol (CH₃OCH₂OH)

Brett A. McGuire^{1,2}, Andrew M. Burkhardt³ and Ci Xue⁴

¹Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA, USA

²National Radio Astronomy Observatory, Charlottesville, VA, USA

³Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA

⁴University of Virginia, Charlottesville, VA, USA

Chemical Formula

CH₃OCH₂OH

Definition

Methoxymethanol (CH₃OCH₂OH) is an interstellar complex organic molecule and alcohol first detected in Atacama Large Millimeter/submillimeter Array (ALMA) observations of the high-mass star-forming region NGC 6334I. On Earth, this organic compound is mostly used as a solvent.

History

The only reported detection of methoxymethanol was by McGuire et al. ([2017](#)) in ALMA observations of the high-mass star-forming region NGC 6334I using ALMA observations at 1 mm. The primary formation mechanism was hypothesized to be through the reaction of methanol (CH₃OH), photodissociation product radicals methoxy

(CH₃O), and hydroxymethyl (CH₂OH). Chemical models using the magickal code (Garrod 2013) underproduced methoxymethanol, however, by more than five orders of magnitude. Several additional formation pathways were suggested, including O(¹D) insertion reactions (Bergner et al. 2017), cosmic-ray driven chemistry (Shingledecker and Herbst 2018; Zhu et al. 2019), and photochemistry product of condensed methanol (Schneider et al. 2019).

Cross-References

- [Alcohol](#)
- [ALMA](#)
- [Cosmic Rays in the Heliosphere](#)
- [Interstellar Medium](#)
- [Methanol](#)
- [Molecules in Space](#)

References and Further Reading

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Methyl Acetate (CH₃COOCH₃)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

CH₃COOCH₃; [Methyl ethanoate](#)

Definition

Under standard laboratory conditions methyl acetate is a flammable liquid that is weakly polar; it is used as a solvent in some glues and related products.

History

Methyl acetate is one of the larger organic molecules detected by radio astronomers in hot cores, regions of the interstellar medium where massive stars are forming. Its isomer ► [ethyl formate](#) has also been found in ► [hot cores](#) (Tercero et al. 2013). Formation of such molecular species is thought to involve both reactions on or in the icy mantles of ► [interstellar dust](#) grains and gas phase bimolecular reactions.

Cross-References

- [Ethyl Formate](#)
- [Hot Core](#)
- [Interstellar Ices](#)
- [Molecules in Space](#)

References and Further Reading

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Methyl Alcohol

- [Methanol](#)
-

Methyl Aldehyde

- [Formaldehyde](#)
-

Methyl Amine

- [Methylamine \(CH₃NH₂\)](#)
-

Methyl Carbylamine

- [Methyl Isocyanate \(CH₃NCO\)](#)
-

Methyl Chloride

- [Chloromethane \(CH₃Cl\)](#)
-

Methyl Cyanide

- [Acetonitrile](#)
-

Methyl Ethanoate

- [Methyl Acetate \(CH₃COOCH₃\)](#)
-

Methyl Ethyl Ether

- [Ethyl Methyl Ether \(C₂H₅OCH₃\)](#)

Methyl Formate (HCOOCH₃)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[Formic acid methyl ester](#); [HCOOCH₃](#); [Methyl methanoate](#)

Definition

Methyl formate is the simplest ester and the condensation product of methanol and formic acid. It is liquid under standard pressure between $-100\text{ }^{\circ}\text{C}$ and $32\text{ }^{\circ}\text{C}$. It is a very volatile, highly flammable, and harmful compound. It is used as an insecticide and has been used formerly in refrigeration. It has been detected in the interstellar medium, where it is more abundant than its two ► [isomers](#), ► [acetic acid](#) CH₃COOH and ► [glycolaldehyde](#) CH₂OHCHO. It is one of the largest organic molecules detected in comet Hale-Bopp.

History

Brown et al. (1975) detected methyl formate in emission in the spectrum of the Galactic Center source Sagittarius B2. Several emission lines previously assigned to rotationally distorted methane in the Orion molecular cloud were correctly assigned to methyl formate by Ellder et al. (1980), from which it became apparent that the millimeter-wavelength spectrum of molecular clouds typically contain a multitude of methyl formate rotational transitions. The detection of methyl formate in comet C/1995 O1 (Hale-Bopp) was reported by Bockelée-Morvan et al. (2000).

Cross-References

- [Acetic Acid](#)
- [Comet](#)

- [Glycolaldehyde \(HOCH₂CHO\)](#)
- [Molecules in Space](#)

Gerasimenko by the Philae lander of the ESA Rosetta mission.

References and Further Reading

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Methyl Isocyanate (CH₃NCO)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Isocyanatomethane](#); [Methyl carbylamine](#)

Chemical Formula

CH₃NCO

Definition

The organic molecule methyl isocyanate is a colorless, flammable liquid at standard temperature and pressure, which is used in the production of some pesticides and adhesives. It is extremely toxic to humans. It has recently been detected in the interstellar medium (in the Galactic Center cloud SgrB2(N)), the low mass protostar IRAS16293-2422, and comet 67P/Churyumov-

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Comet](#)
- [ESA](#)
- [Interstellar Medium](#)
- [IRAS16293-2422](#)
- [Philae Lander](#)
- [Rosetta Spacecraft](#)
- [SgrB2](#)

References and Further Reading

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M

Methyl Mercaptan

- [Methanethiol \(CH₃SH\)](#)

Methyl Methanoate

- [Methyl Formate \(HCOOCH₃\)](#)

Methyl Oxirane

- [Propylene Oxide \(CH₃CHCH₂O\)](#)

Methyl Radical (CH₃)

William M. Irvine
Department of Astronomy,
University of Massachusetts,
Amherst, MA, USA

Synonyms

CH₃

Definition

The methyl radical CH₃ is stable enough to be observable under laboratory conditions in a dilute gas, although it readily dimerizes to ethane. It is an important intermediary in gas-phase interstellar chemistry. The incorporation of a methyl group, –CH₃, into organic compounds can have fundamental biological effects.

History

The CH₃ radical was detected in interstellar molecular clouds at wavelengths of about 16 microns using the Infrared Space Observatory (Feuchtgruber et al. 2000). It is also present in planetary/satellite atmospheres such as that of Titan (Luspay-Kuti et al. 2016).

Cross-References

- [Infrared Space Observatory](#)
- [Molecules in Space](#)
- [Radical](#)

References and Further Reading

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- Luspay-Kuti A, Mandt KE, Westlake JH, Plessis S, Greathouse TK (2016) The role of nitrogen in Titan's upper atmospheric hydrocarbon chemistry over the solar cycle. *Astrophys J* 823:763

Methyl Triacetylene (CH₃C₆H)

William M. Irvine
Department of Astronomy,
University of Massachusetts,
Amherst, MA, USA

Chemical Formula

CH₃C₆H

Definition

Methyl triacetylene is the heaviest methyl polyne (organic molecule with two or more sets of alternating single and triple bonds) thus far detected by radio astronomers in interstellar molecular clouds.

History

Methyl triacetylene joins a number of other carbon chain molecules identified in interstellar molecular clouds or the envelopes of carbon stars. These include nitriles up to HC₈CN, methyl polyynes, bare carbon chains up to C₅, radicals up to C₈H and the corresponding anions, and related species such as C₄Si, C₃O, and C₃S (see ► [“Molecules in Space,”](#) where references to many initial detections are given). Polyacetylenes such as HC₆H are also present, but, since their symmetry precludes a permanent electric dipole moment and hence pure rotational transitions accessible to radio astronomers, they have been observed through their vibrational transitions in the infrared.

Cross-References

- [Carbon](#)
- [Circumstellar Chemistry](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

Methylamine (CH₃NH₂)

William M. Irvine

Department of Astronomy, University of
Massachusetts Amherst, Lederle Graduate
Research Tower B 619E, Amherst, MA, USA

Keywords

Amino acid · Interstellar · Molecules

Synonyms

[Aminomethane](#); [Methanamine](#); [Methyl Amine](#)

Chemical Formula

CH₃NH₂

Definition

Methylamine (IUPAC names aminomethane or methanamine) is the simplest primary amine. At standard temperature and pressure, it is a colorless gas, with the liquid boiling at $-6.5\text{ }^{\circ}\text{C}$ at 1 atm. It has a fishy odor resembling that of ammonia, not surprisingly since it is derived from ammonia by replacing one hydrogen atom by a methyl group (CH₃).

Overview

Methylamine is a possible precursor to the amino acid glycine (e.g., Halfen et al. 2013) as well as various N-methyl amino acids which are sometimes detected in meteorites or laboratory simulations of prebiotic chemistry. The rotational spectrum of methylamine is complex, since it is an asymmetric top with two large amplitude internal motions: methyl group torsion and inversion of the amine hydrogens (see Spectroscopy, Rotational (Radioastronomy)). Nonetheless, it was one of the first relatively complex organic molecules

detected in the interstellar medium (Kaifu et al. 1974), towards the Galactic Center molecular cloud SgrB2.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Ammonia](#)
- ▶ [Carbonaceous Chondrite](#)
- ▶ [Glycine](#)
- ▶ [Interstellar Medium](#)
- ▶ [Molecular Cloud](#)
- ▶ [SgrB2](#)
- ▶ [Spectroscopy, Rotational](#)

References and Further Reading

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Methylene (CH₂)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

[CH₂](#)

Definition

Methylene (CH₂) is the simplest ▶ [carbene](#). The carbon is covalently bonded to two hydrogen atoms and bears two nonbonded electrons whose spins may be antiparallel (singlet state) or parallel (triplet state). It is an intermediary in the production and destruction of interstellar organic molecules.

History

Interstellar methylene was detected at a wavelength of about 4 mm by Hollis et al. (1995).

Cross-References

- [Carbene](#)
- [Interstellar Chemical Processes](#)
- [Molecules in Space](#)

References and Further Reading

Hollis JM, Jewell PR, Lovas FJ (1995) Confirmation of interstellar methylene. *Astrophys J* 438:259–264

Methylene Oxide

- [Formaldehyde](#)

Methylenimine

- [Methanimine \(CH₂NH\)](#)

Methylethylene

- [Propylene \(CH₃CHCH₂\)](#)

Methyldidyne (CH)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[CH](#)

Definition

The diatomic radical CH (methyldidyne), containing carbon and hydrogen, was one of the first interstellar molecules to be identified, in 1937 by T. Dunham and also by P. Swings and L. Rosenfeld. It is widespread in the diffuse ► [interstellar medium](#), where it produces absorption lines in the visible spectrum of background stars. It is an important intermediary in the production and destruction of interstellar organic molecules. Methyldidyne is also present in the coma (atmosphere) of ► [comets](#), where it is presumably a photodissociation product of organic molecules sublimating from the cometary nucleus.

History

After the first detection of the interstellar OH radical by radio astronomers in 1963, several groups looked for radio emission from interstellar CH. The search was difficult, however, because no laboratory measurements of the lowest frequency transitions was available, and theoretical predictions of the relevant frequencies were not very accurate. Radio astronomers at the Onsala Space Observatory in Sweden, led by Director Olof Rydbeck, succeeded in 1973 after a special maser receiver designed specifically for the search was built at the Chalmers Institute of Technology for use at the Observatory. Subsequently, CH emission has been detected in many interstellar molecular clouds.

More recently, submillimeter observations of CH with the - > Herschel Space Observatory and the Stratospheric Observatory for Infrared Astronomy (SOFIA) have allowed the CH abundance to be probed in different types of regions, suggesting that CH can be widely used as a proxy to estimate the molecular hydrogen (H₂) abundance (e.g., Sheffer et al. 2008; Morris et al. 2016; Wiesemeyer et al. 2018).

Cross-References

- [Comet](#)
- [Herschel Mission](#)

- [Hydroxyl Radical \(OH\)](#)
- [Interstellar Medium](#)
- [Maser](#)
- [Molecules in Space](#)

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Methylidyne Cation (CH⁺)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[CH⁺](#)

Definition

The ► [methylidyne](#) ion CH⁺ was one of the first molecules detected in the ► [interstellar medium](#), being identified in absorption at visible/near ultraviolet wavelengths in the spectra of background stars in 1941 by Douglas and Herzberg. CH⁺ emission at visible wavelengths is seen from the tails of ► [comets](#). Pure rotational transitions have been observed at far infrared wavelengths from

- [planetary nebula](#), ► [molecular clouds](#), and
- [Photodissociation regions](#) using the ISO and Herschel satellites.

Cross-References

- [Comet](#)
- [Interstellar Medium](#)
- [Methylidyne \(CH\)](#)
- [Molecules in Space](#)
- [Planetary Nebula](#)

References and Further Reading

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MGS

- [Mars Global Surveyor](#)

Micas

- [Phyllosilicates, Extraterrestrial](#)

Micelle

David Deamer
Department of Chemistry, University of California, Santa Cruz, Santa Cruz, CA, USA

Definition

Micelles are self-assembled aggregates of amphiphilic molecules such as soaps, surfactants, and detergents. These compounds are called amphiphiles because each molecule consists of a

hydrophobic hydrocarbon chain with a hydrophilic polar or ionic head group such as hydroxyl, carboxylate, phosphate, or sulfate at one end. Amphiphiles exist in solution as individual molecules, but at a certain concentration (the critical micelle concentration, or cmc), they assemble into micelles that typically contain a few hundred molecules. Micelles in aqueous phases have hydrocarbon chains directed inward while hydrophilic head groups line the surface. The formation of micelles is one of the simplest examples of a ► [self-assembly](#) process in an aqueous medium.

Cross-References

- [Amphiphile](#)
- [Lipid Bilayer](#)
- [Self-Assembly](#)

Micro-Monte-Carlo Models

Eric Herbst

University of Virginia, Charlottesville, VA, USA

Definition

In a microscopic Monte Carlo model, when used for grain chemistry, the positions of each atom or molecule on the grain mantle can be followed. Thus, for an ice mantle consisting of 50 monolayers, the approach will follow all of the atoms and molecules as well as unoccupied sites for each of the 50 monolayers. In the simplest approach, each monolayer is modeled as a rectangular grid of potential wells in lattice sites with or without occupation. The atoms or molecules move from lattice well to well and possibly react when they land in the same site, while the species in the outermost layer also desorb into the gas, as gas-phase species accrete onto the outermost monolayer. The choice of which process happens in which time period depends upon the approach utilized. In the continuous time random-walk approach, a kinetic Monte Carlo approach used most commonly in the astrochemical literature, a Poisson (or waiting time) distribution

($\psi_a(t) = k_a \exp(-k_a t)$) is used, where k_a is the rate coefficient for process a , and its inverse is the average time between events for process a . Distributions are used for four discrete and competitive types of events: hopping between adjacent sites, desorption, deposition (accretion), and reactions, which can occur diffusively by the Langmuir-Hinshelwood mechanism, or via a direct hit during deposition according to the Eley-Rideal mechanism. Diffusive reactions occur when two species hop or tunnel into the same lattice well, and the possible reaction does not have a very high activation energy barrier. For a significant barrier, the possibility of tunneling must be included. The waiting time WT for each event a is defined by the equation $WT_a = -\ln X/k_a$, where X is a random number in the range 0 to 1. Note that $X = 0.5$ corresponds to a waiting time of $0.693/k_a$. As each process gets a waiting time and the clock moves forward, the process with the nearest waiting time undergoes the next process and afterwards receives another waiting time. Meanwhile, the clock moves once again to the process with the shortest time before execution. As in the macroscopic case, the microscopic Monte Carlo approach must be run more than once.

At their current stage of development, microscopic Monte Carlo models of grain chemistry can now include hopping and reactions in the bulk of the ice mantle and can be coupled to macroscopic Monte Carlo models of the gas-phase chemistry. The combined gas-phase grain chemistry simulations are still limited to times shorter than the lifetimes of interstellar clouds and to temperatures not much higher than 20 K because of the greater expense of running them to longer times and at higher temperatures (Chang and Herbst 2016). There are intermediate models, which contain a degree of complexity in between the microscopic and macroscopic approaches. One such model has been used to model the chemistry that occurs as material near a protostar heats up (Vasyunin and Herbst 2013). Moreover, fixed grid models are being replaced by models in which the surface species move according to potentials such as the pairwise Lennard-Jones (6–12) function as well as more complex potentials. These models have also been used to simulate how ice mantles form on individual grains (Clement et al. 2018).

Cross-References

- ▶ [Cosmic-Ray-Induced Desorption](#)
- ▶ [Dense Core](#)
- ▶ [Desorption](#)
- ▶ [Eley-Rideal Mechanism](#)
- ▶ [Gas-Grain Chemistry](#)
- ▶ [Interstellar Chemical Processes](#)
- ▶ [Interstellar Ices](#)
- ▶ [Langmuir-Hinshelwood Mechanism](#)
- ▶ [Macro Monte Carlo Models](#)
- ▶ [Master Equation Models](#)
- ▶ [Physisorption](#)
- ▶ [Rate Equation Models](#)
- ▶ [Reaction Rate Coefficient](#)

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Microalgae

- ▶ [Phytoplankton](#)

Microbe

- ▶ [Microorganism](#)

Microbial Community Gene Expression Profile

- ▶ [Metatranscriptome](#)

Microbial Community RNAs

- ▶ [Metatranscriptome](#)

Microbial Ecology Evaluation Device

- ▶ [MEED](#)

Microbial Mats

Lucas J. Stal
Department of Marine Microbiology, Royal
Netherlands Institute of Sea Research (NIOZ),
Yerseke, The Netherlands

Keywords

Biogeochemistry · Carbon cycle ·
Cyanobacteria · Microbial ecosystem ·
Nitrogen cycle (biological) · Purple sulfur
bacteria · Sulfate reducing bacteria · Sulfur
cycle

Synonyms

[Benthic mats](#); [Biofilms](#); [Cyanobacterial mats](#);
[Farbstreifen Sandwatt](#); [Laminated microbial
ecosystems](#); [Living stromatolites](#); [Microbially
Induced Sediment Structures \(MISS\)](#); [Modern
stromatolites](#)

Definition

Microbial mats are benthic small-scale ecosystems that generally develop under environmental conditions that exclude fauna, often referred to as “extreme environments.” The biogeochemical cycles in microbial mats are usually largely closed, although small fluxes of elements are exchanged with the geo-, bio-, and atmosphere. An important feature of microbial mats is their

carbon and nitrogen autotrophy, i.e., the fixation of inorganic carbon and atmospheric nitrogen are key processes. In illuminated environments, therefore, the photoautotrophic cyanobacteria are the mat-building organisms while in the deep sea or in some caves, chemosynthetic bacteria and archaea are the primary producers.

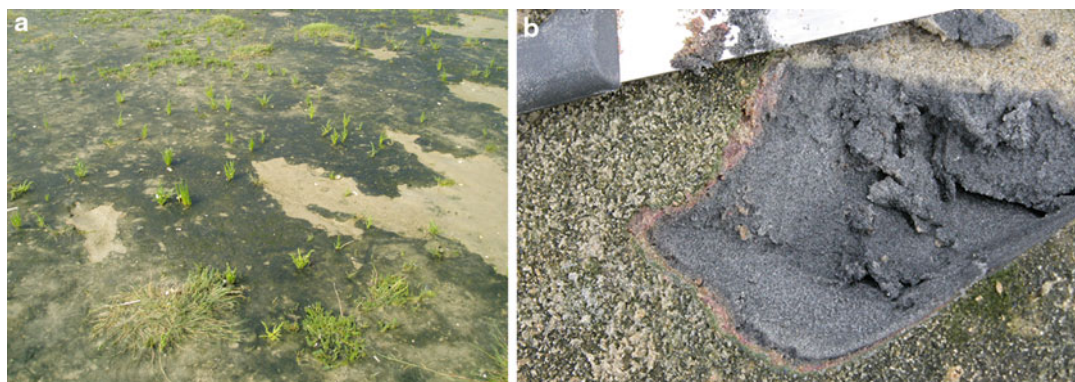
Overview

The term *microbial mat* originates from the macroscopic structure that these small-scale microbial ecosystems often adopt. Large filamentous microorganisms grow and form an entangled mass with the sediment particles on which they grow, stabilizing the sediment surface and themselves from eroding forces. Mature microbial mats can sometimes be lifted in large pieces from the sediment, just like a doormat. However, in the course of the research on microbial mats, the term has been used for any benthic microbial community that forms a macroscopic structured entity. An important driver for the study of microbial mats is that these systems are considered to be analogues of the Precambrian stromatolites, which have been recognized as the oldest known ecosystems on Earth, and their study could lift the veil of the evolution of early life.

Microbial mats often develop in environments and habitats that are characterized by extreme conditions that exclude metazoans that would otherwise graze on the microbes, preventing

them from forming a microbial mat. Microbial mats are largely closed ecosystems. This means that the biogeochemical cycles are basically closed. Therefore, a basic characteristic of microbial mats is that they are carbon autotrophic, meaning that they grow by fixing inorganic carbon. This can be done in two principally different ways, namely, by photosynthesis and by chemosynthesis. In the former, light is the source of energy and phototrophic organisms are the organisms that build the microbial mats. In chemosynthetic microbial mats, the source of energy is the oxidation of a reduced compound, often sulfide or methane. In most illuminated environments, the phototrophic cyanobacteria are the mat-building organisms. In dark environments such as in the abyssal of the oceans or in caves, hyperthermal springs, mud volcanoes, and cold seeps provide reduced compounds produced by the Earth's internal heat that drive chemosynthesis. Chemosynthetic mats may also develop in illuminated environments when, for instance, the decomposition of large amounts of organic matter in seawater produces high amounts of sulfide which is in direct contact with oxygen.

Since Precambrian stromatolites are known to have developed in shallow, illuminated coastal environments, the study of coastal microbial mats deserves special attention. Microbial mats develop in coastal intertidal sandy sediments (Fig. 1). These environments can be considered as extreme because they are periodically inundated,



Microbial Mats, Fig. 1 (a) Microbial mats growing on a sandy intertidal beach. (b) Cross-section of this mat shows the typical varicolored layers with a *purple layer* of

anoxygenic phototrophic bacteria right underneath the layer of cyanobacteria

desiccated, hyper- or hyposaline, experiencing high and low temperatures, and as a rule nutrient poor. Cyanobacteria thrive well under such conditions. As photoautotrophs, they use light, water, and CO₂ as source of energy, electrons, and carbon, respectively, which are abundantly available. Many cyanobacteria are also nitrogen autotrophs, i.e., they can utilize atmospheric N₂, the most abundant form of nitrogen on Earth and after carbon the second most important element for life. Cyanobacteria have low nutrient requirements, possess high-affinity phosphate uptake systems, and contain a variety of storage compounds.

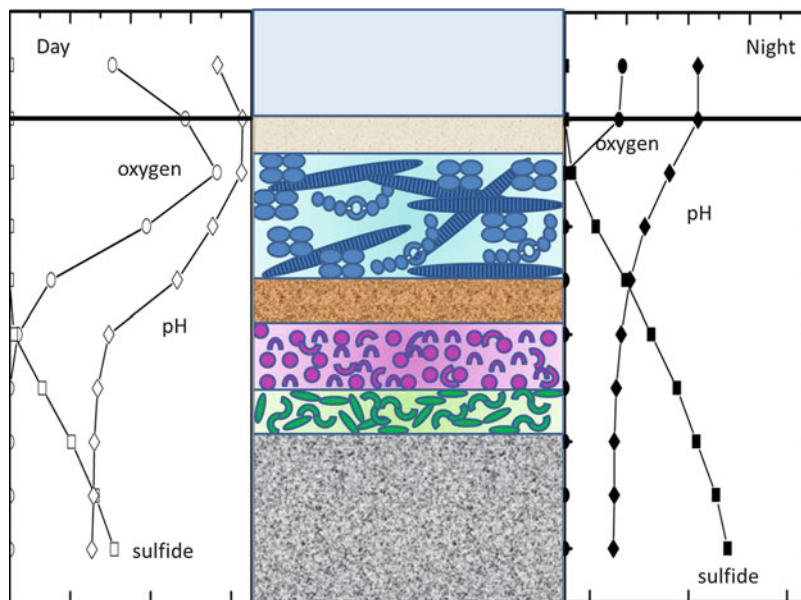
The carbon fixed by the cyanobacteria is made available to the microbial community by a variety of different ways. In the light, photorespiration may result in the excretion of glycolate while in the dark, the storage compound glycogen may be fermented to low-molecular compounds such as acetate, lactate, and ethanol. Cyanobacteria exude also exopolymeric substances and upon salinity down shock may release compatible solutes such as the carbohydrates trehalose and sucrose and the polyol glucosylglycerol. Finally, cyanobacteria may die and lyse, providing another source of organic matter and nutrients. A plethora of microorganisms will degrade these compounds, but the sulfate-reducing bacteria deserve a particular notice in marine microbial mats. At night, when oxygenic photosynthesis ceases or in the deeper aphotic layers of the mat, oxygen is quickly consumed by the microbial community, including the cyanobacteria. This happens often within minutes. Sulfate-reducing bacteria are therefore responsible for the bulk of the degradation of organic matter using the abundant sulfate (28 mM) in seawater as electron acceptor, reducing it to sulfide. The sulfide is subsequently oxidized in two ways. In the light, anoxygenic phototrophic purple sulfur bacteria use sulfide as the electron donor for photosynthesis. They oxidize it to elemental sulfur and eventually back to sulfate. These bacteria are basically anaerobic and form a pink layer below the cyanobacteria where they experience anaerobic conditions while sufficient light (particularly of the far red wavelengths) reaches them. The other group of microorganisms that oxidizes the sulfide is the colorless sulfur bacteria. They use oxygen or nitrate as electron acceptor.

As a result of the microbial activities, microbial mats are characterized by steep and fluctuating physicochemical gradients. Only during the day, oxygenic photosynthesis by the cyanobacteria enriches and supersaturates the sediment with oxygen. During the night, this oxygen is quickly respired. Sulfide accumulates during the night because light and oxygen (and usually nitrate as well) are lacking for its oxidation while the sulfate-reducing bacteria are continuing to produce it. During the day, sulfide is oxidized. The day-night rhythm and the activities of the mat microorganisms result in the continuously shifting gradients of oxygen and sulfide. Together with that, the pH shows dramatic shifts. During the day, the fixation and the consequent depletion of CO₂ causes the pH to rise to high levels (>9), while during the night, the decomposition of organic matter causes the level of CO₂ to increase and the pH to decrease (Fig. 2).

The mat-forming organisms take their positions in these physicochemical gradients. The aerobic cyanobacteria form a green layer at the surface while the anaerobic purple sulfur bacteria form a pink layer right below them. Often, a rusty layer separates them. This layer is supposedly composed of iron which forms a barrier for both oxygen and sulfide, which are toxic to the purple sulfur bacteria and cyanobacteria, respectively. Sulfide diffusing to the surface reacts with iron and oxidizes to elemental sulfur and forms insoluble iron sulfide and pyrite. Oxygen diffusing downward reacts with the iron and oxidizes it, forming iron hydroxides. It is also possible that anoxygenic photosynthetic iron-oxidizing bacteria thrive in this layer, but hitherto, this has not been demonstrated. Sulfate-reducing bacteria are obligate anaerobic microorganisms, although some can tolerate low levels of oxygen or are even capable of respiring it, although they are unable to live by aerobic respiration. For these reasons, it has been assumed that sulfate-reducing bacteria are mostly present in the permanent anoxic layers of the microbial mat. This is not the case. Sulfate-reducing bacteria occur throughout the microbial mat although the different groups show a distinct depth distribution, particularly with respect to their oxygen sensitivity. Microbial mats have also been termed laminated microbial ecosystems. The lamination is

Microbial Mats,

Fig. 2 Cartoon of a microbial mat indicating the vertically stratified and varicolored layers of functional groups of microorganisms and the chemical gradients they produce during the day (left) and during the night (right)



the result of the vertically stratified communities of different functional groups of phototrophic microorganisms, notably the cyanobacteria and the purple sulfur bacteria (and in some cases also green sulfur bacteria), giving the mat a varicolored appearance. This lamination is also called an instantaneous biological lamination to distinguish it from a historical lamination which is produced by successive microbial mats, while the older mats are only partly degraded (compare with the rings of a tree). This is often seen under extreme conditions such as hypersaline or hyperthermal environments. This historical lamination is also preserved when the mat turns to stone, i.e., when calcification takes place.

Stromatolites are by definition laminated rock and are known from the fossil record up to almost 3.5 billion years before present. The majority of modern microbial mats do not turn to stone, although it is uncertain whether this has always been like this. The fossil record also indicates the presence of noncalcified microbial mats through features known as *Microbial Induced Sediment Structures* (MISS). It is not fully clear why some mats calcify and others apparently do not. It is hypothesized that extracellular polymeric substances (EPS) produced by the *Cyanobacteria* bind calcium, thereby lowering the solubility product of calcium carbonate. When the EPS is degraded, calcium is locally released causing

saturation of calcite. Modern marine stromatolites are rare and found only in the Exuma Cays (Bahamas) and in Shark Bay (Western Australia). Stromatolites with remarkable similarity to those of the Precambrian are found in alkaline environments which may hint to an alkaline Archean ocean. It has been shown that calcification occurs in microbial mats that do not lithify, but the calcite in these mats dissolves as a result of microbial metabolism.

Cross-References

► [Biofilm](#)

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Microbial Sediment Fixation

► Biostabilization

Microbialites

► Stromatolites

Microbially Induced Sediment Structures (MISS)

► Microbial Mats

Microbially Induced Sedimentary Structures

Nora Noffke
Old Dominion University, Norfolk, VA, USA

Keywords

MISS · Siliciclastic · Microbialite · Archean · Biostabilization · Baffling and trapping · Binding · Microbial mat · Biofilm · Early life · Mars · Biosignature · Dresser Formation · Pilbara · Warrawoona Group · Pongola Supergroup · Barberton Greenstone Belt · Moodies Group · Ediacara · Neoproterozoic

Definition

Microbially induced sedimentary structures (MISS) are structures caused by biofilms and

microbial mats in siliciclastic deposits. The microbenthos responds with biostabilization to erosion, gas pressure, or evaporite mineral crystallization. Biostabilization is the fixation of grains by biofabrics and mucilages. Deposition triggers baffling and trapping: microbial filaments orientate vertically and move upward with the sedimentation rate. During dynamic quiescence, called latency, binding and growth establishes a new biofilm or mat. MISS occur in modern aquatic settings, but are abundant since the early Archean. In microscopic close-up, MISS include biofilm or mat textures, in fossil examples *in situ* preserved.

Overview

Siliciclastic sediments in coastal zones as well as in lacustrine and fluvial settings are widely colonized by microbial mats. Microbial mats are coherent organic layers covering sometimes several km² wide areas. In a microbial mat, many microorganisms occur, although in the modern time, photoautotrophic cyanobacteria are the main mat constructors. The pigments of cyanobacteria give rise to a typical bluegreen or pink color of the mats. Benthic microorganisms including cyanobacteria secrete adhesive mucilages, called extracellular polymeric substances (EPS) (Decho and Gutierrez 2017). The slimy secretions serve a number of purposes such as attachment of the microbes to a hard substrate. Freshly deposited sediment is quickly populated by cyanobacteria. Initially, single grains are overgrown by thin biofilms that over time may develop to macroscopic microbial mats. Microbial mats tend to accumulate at sites of moderate hydraulic reworking, not strong enough to destroy the mat fabrics but still prohibiting fall-out of fines. Within a biofilm or microbial mat, the constituent microbial groups are spatially arranged in a fashion that allows interlocking of their metabolic activities and optimizing the harvest of light and nutrients (Visscher and Stolz 2005).

Because microbial mats colonize the sedimentary surface, they must respond to sediment-dynamics affecting their substrate. In carbonate settings commonly of the tropical climate zone, microbial mats may form stromatolites, whereas

in clastic settings, a mechanistically complex interaction of microbenthos with sediment dynamics causes MISS (Grey and Awramik 2020). The morphologies of MISS do not resemble stromatolites, and they differ also from that of abiotic sedimentary structures, for example, ripple marks.

While MISS are known from modern environments (Gerdes et al. 1985; Carmona et al. 2012; Taher 2014; Maisano et al. 2019; and many more), fossil MISS are abundant as well (Schieber 1989; contributions in volumes by Hagadorn et al. 1999; Schieber et al. 2007; Noffke and Chafetz 2012; and many more). MISS allow detailed conclusions on climatological conditions, modern and past (overview in Noffke 2010). Ecologically and taphonomically significant are fossil microbial mats in the Neoproterozoic Ediacaran world (Gehling and Droser 2009, and many more). MISS in early Archean rocks (Noffke et al. 2008, 2013; Heubeck 2009; Noffke 2010; Homann et al. 2015, and many more) serve as models for biosignatures for life detection on Mars. The 3.48 Ga Dresser Formation exposed in the North Pole Dome, Pilbara, West Australia, includes MISS and stromatolites witnessing a complex and very early microbial ecosystem in a coastal sabkha setting (Noffke et al. 2013).

Basic Methodology

Formation of MISS is studied in modern aquatic environments, commonly in long-term observation (Noffke 2010). Laboratory experiments allow a better understanding of specific microbial behavior (Bebout and Garcia-Pichel 1995; Shephard and Sumner 2010; Mariotti et al. 2014, and many more). The prospection for fossil MISS is guided by the paleoenvironment that must have provided suitable life conditions for microbenthos. Sandstone beds of less than 20 cm thicknesses with well-preserved surfaces chronicling an ancient environmental surface seem to be most promising for MISS detection, especially if composed of more than 90% quartz grains. Geological field work documented concentration of MISS at transgression-regression branches

(Noffke et al. 2002). The morphologies of MISS seem not to have changed over Earth history (Noffke et al. 2013), so the comparison of morphologies of fossil structures with modern ones assists in confirmation of biogenicity. More so, MISS rarely occur as single phenomena but form associations with respect to the geomorphology of the ancient environment (biofilm-catenae). In thin-section view, modern and fossil MISS-samples include a wealth of microbially induced sedimentary textures (MIST) that in concert with their biological isotope signatures confirm biogenicity of a structure under consideration (Noffke et al. 2021).

Key Research Findings

MISS form and preserve in all clastic depositional settings as long as water is accessible. Microbial mats and biofilms causing MISS develop during periods of time during which the sedimentary surface is undisturbed. The assembling of a biofilm by actively moving microbes is referred to as “binding.” Growth, in contrast, is the enrichment of biomass through cell replication and EPS production. With respect to thickness of the microbial mat and its location in relation to the sediment, epibenthic (=on the seafloor living) mats and endobenthic (=within the sedimentary surface living) mats are being distinguished. Thick microbial mats, commonly of epibenthic type, show oriented grains in thin sections (Fig. 1a). The grains appear to be floating without grain-grain contact in the mat fabrics. During growth of the mat, individual sand grains of the substrate were dragged upward by the adherent EPS-rich biomass. Often the long axes of the grains are oriented parallel to the overburden pressure. Epibenthic microbial mats, especially those in semi-arid climate zones, may display seasonal varves in vertical section. Such a mat is called biovarvite (Gerdes et al. 1985).

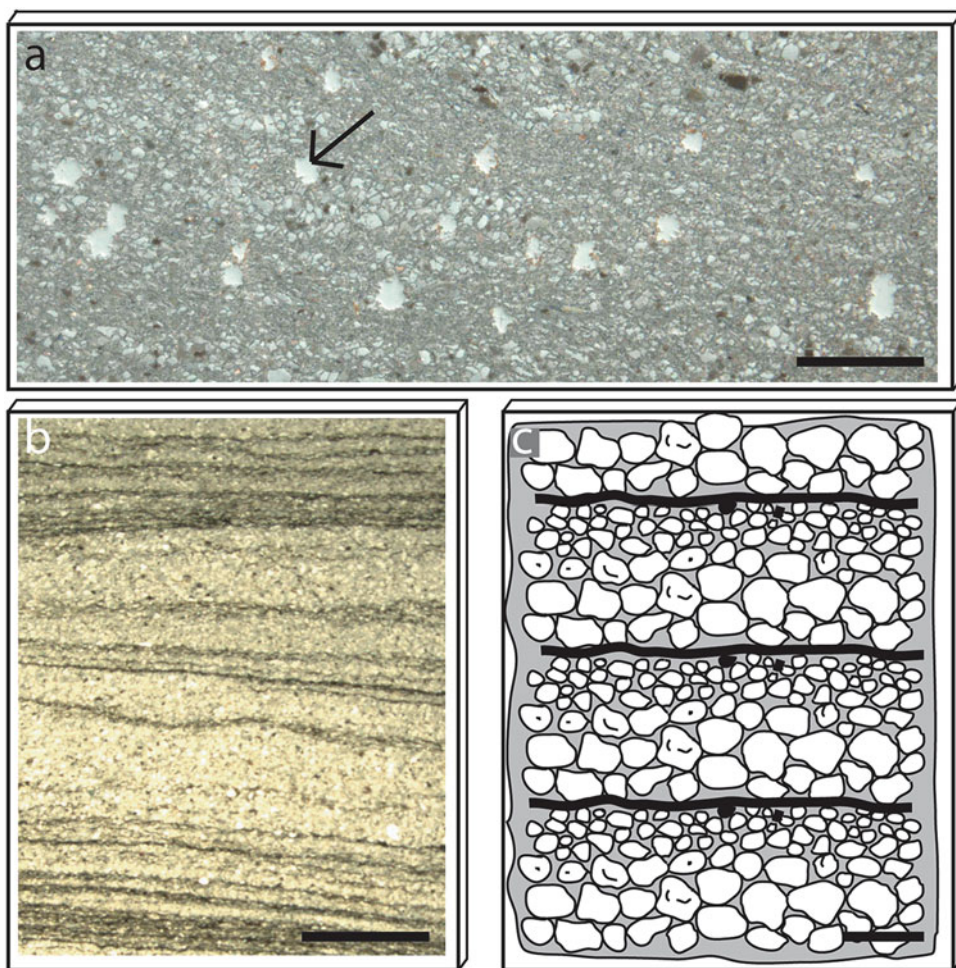
Sedimentary particles that fall out of slow-moving water currents may trigger a vertical orientation of cyanobacterial filaments on the mat surface. The filaments protrude into the supernatant water, where they foster deposition of silt-

sized sedimentary grains and heavy minerals. The behavior is known as baffling and trapping. Once buried, thin biofilm or endobenthic mats may line (imprint) the proceeding sedimentary surface. Was this surface rippled, their biofilm-drape now forms sinoidal structures visible in vertical section through the sediment.

What happens, if a microbial mat is affected by erosion? In microscopic close-up, the mat fabrics interweave the sand grains of the substrates and embeds them in ubiquitous EPS. This construction of a “network plus glue” (Fig. 1b) stabilizes the grains in their position, so they cannot be eroded anymore. By this biostabilization

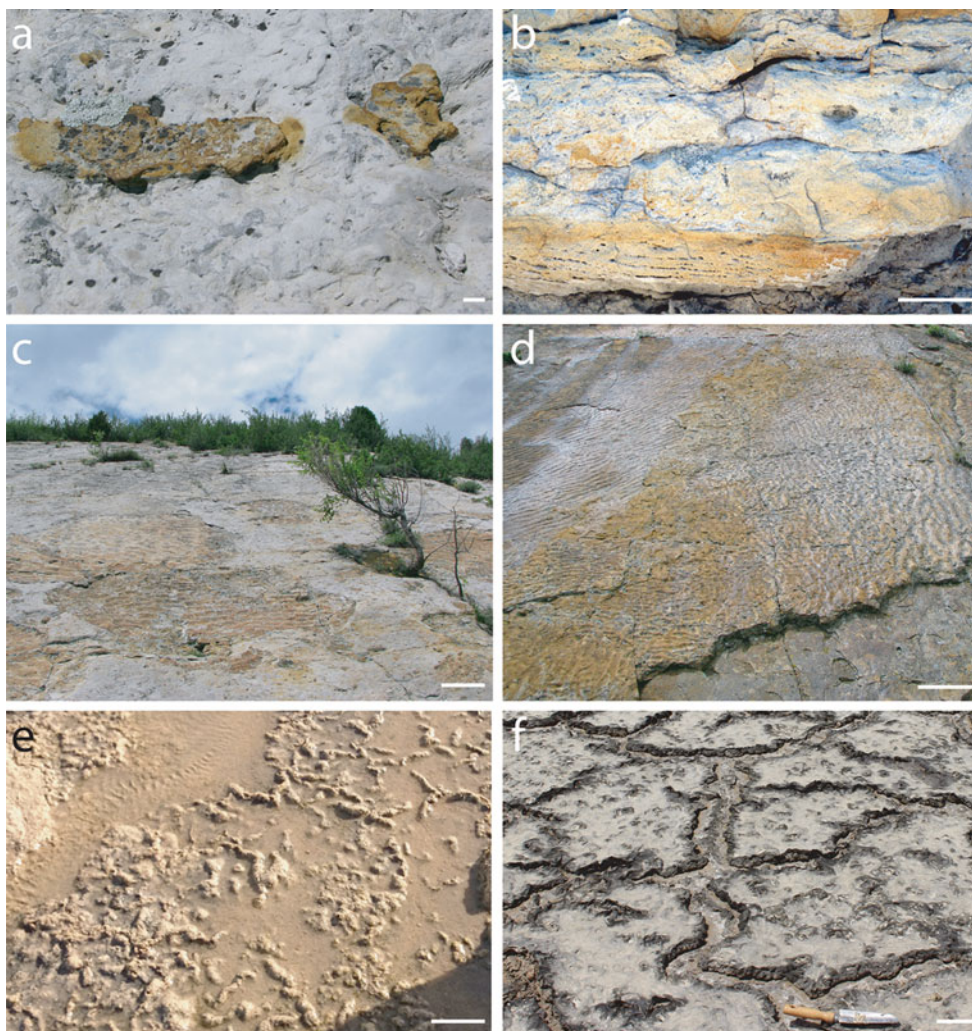
(Paterson 1997), the erosive shear forces of horizontally directed water currents are reduced that otherwise may rip off pieces (=mm- to cm-sized mat chips, Fig. 2a) of microbial mat. Intra-sedimentary gases cannot escape through the EPS-rich microbial mat layer, causing local upheavals (mm- to dm- scale gas domes) or a high porosity (sponge pores, Fig. 2b) in the mat.

Shelf deposits commonly show wrinkle structures (Hagadorn and Bottjer 1997; Noffke 2000) and mat chips. This is different in shallow water facies. Here, erosional remnants and pockets (Fig. 2c), multidirected ripple marks (Fig. 2d), and mat chips are caused by water currents



Microbially Induced Sedimentary Structures, Fig. 1 Typical textures in MISS: (a) Oriented grains (arrow) in mat fabrics, 2.8 Ga Pongola Supergroup,

South Africa; scale: 1 mm. (b) Mat fabrics (dark) in quartzitic fine sandstone, Ordovician, Montagne Noire, France; scale: 0.5 cm. (c) Microsequences, sketch; scale 0.25 mm



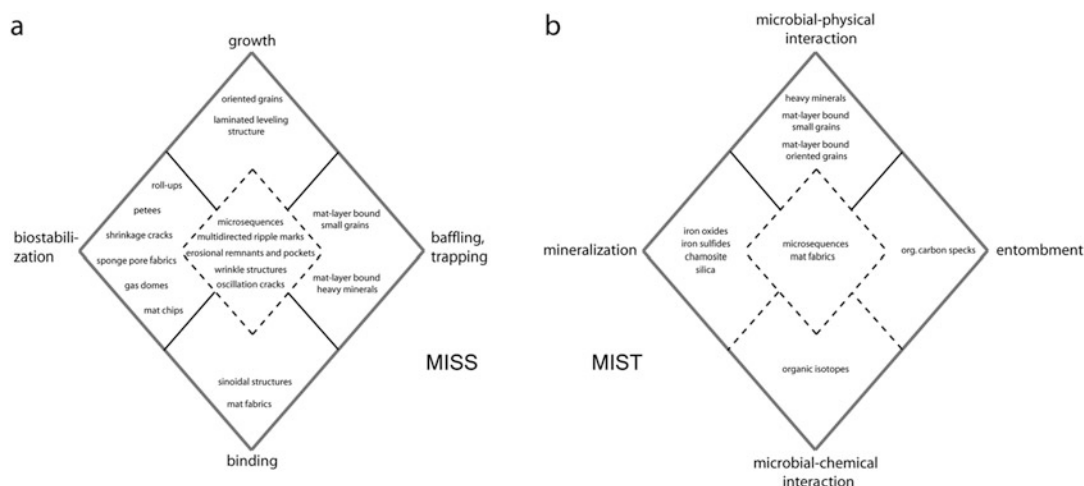
Microbially Induced Sedimentary Structures, Fig. 2 Macroscopic MISS: (a) Mat chips; scale 1 cm. (b) Sponge pore sandstone; scale 5 cm. (c) Erosional remnants and rippled pockets; scale: 50 cm. (d) Multi-directional ripple marks; scale 25 cm in foreground.

Images (a–d) from Dakota Sandstone, Cretaceous, Colorado, USA. (e) Petees, Yalgorup Lake System, Australia; scale 10 cm; image by Alexander Brasier (f) Polygonal oscillation cracks, Abu Dubai tidal flats; scale 5 cm; image by Stephen Lokier

crossing the sedimentary surface. Gas domes may occur during episodes of subaerial exposure. Where evaporation in semi-arid and hot climate zones influence MISS-formation, petees (not: tepees!) and polygonal oscillation cracks develop (Fig. 2e, f). Both structures rise from vertical groundwater migration and periodic desiccation. In terrestrial settings such as interdune areas or flood plains, mat chips and roll-ups are frequent (Eriksson et al. 2000; see contributions on

terrestrial MISS in the volume by Noffke and Chafetz 2012).

In situ precipitation of carbonate minerals, fundamental for stromatolites, does rarely, if at all, take place in MISS-development (Grey and Awramik 2020). However, *in situ* mineralization of microbial mat fabrics by heterotrophic microbes is observed. In thin-section view, MISS include a wealth of various textures lined by pyrite and clay minerals and accompanied by biological



Microbially Induced Sedimentary Structures, Fig. 3 Classification diagrams of MISS (a) and MIST (b)

isotope signals. Organic carbon may still be present in very small amount, even in oldest specimen of Archean ages (Noffke et al. 2013). The microscopic view reveals filaments forming a microbial network, oriented grains, mat-layer bound small-sized grain populations, and microsequences (Fig. 1b, c). Heavy metal concentrations may trace a mat layer as well. MISS and MIST are classified in accordance to their formation (Fig. 3).

Exceptionally well preserved are MISS in the 2.8 Ga Nhlazatse Section (Pongola Supergroup) that crops out along the river Wit Mfolozi, South Africa (Noffke et al. 2008). The 46 m rock succession comprises MISS that change in morphology over time, recording a tidal flat that moved from a position in a moderate to a semi-arid paleoclimate zone. Indeed, the MISS show morphologies, associations, and distribution as known from modern coasts of the North Sea and the Mediterranean Sea. The same is to be said from the internal variation of MIST.

In the Nhlazatse Section, endobenthic microbial mats in the upper intertidal zone display multidirectional ripple marks recording seasonal storms. Mat chips cover rippled surfaces. Thin sections include microsequences that witness cyclicity of sediment dynamics.

Epibenthic microbial mats of the lower supratidal zone have been of three main types (spongy,

tufted, and planar). Spongy mat types were restricted to permanent tidal pools. Their internal construction is identical to that of modern mats in tidal pools of the Bahamas (Fig. 2b). Tufted mats grew in very shallow depressions periodically subaerially exposed. The fossil tufted microbial mats are arranged into polygonal oscillation cracks. In the modern, such cracks are only developing in settings dominated by a semi-arid, hot climate. During the dry season, the microbial mats crack due to desiccation, and mat-polygons form. The margins of the mat-polygons may curl up due to desiccation of the mat. During subsequent seasons of high humidity and/or shallow flooding of the microbial mats, the mat-polygons expand laterally and close the former cracks. The curled-up margins are now overgrown by a new generation of microbial mat. Repetition of this process results in the characteristic polygonal oscillation crack pattern. Due to the thick bulges that mark the former margins of the mat polygons, the former cracks are lined by two parallel running ridges.

The planar mat type at the Pongola site grew in elevated areas between tidal channels that were flooded only episodically. Such microbial mats gave rise to erosional remnants and pockets (Fig. 2c) and gas domes. Erosional remnants and pockets form from partial erosion of a microbial mat. Gas domes witness gas production through metabolic activity as well as mat decay. In the

outcrop, mat chips were produced by both epibenthic and endobenthic microbial mats.

Applications

The significance of MISS lies in the information they provide with respect to paleoenvironments including paleoclimate conditions, the decoding of the evolution of early life, as well as the exploration of other terrestrial planets. Regarding missions to clastic-rich Mars with remotely controlled rovers, the wide variety of MISS on Earth and their vast abundance qualifies them as potentially important biosignatures. That said, martian MISS likely would be of small scale and not include meter-sized structures such as erosional remnants and pockets.

Future Directions

The overall group of MISS is well known by now; however, the many facets of application are still harboring opportunity for further exploration. Given the many clastic deposits on Mars, future missions to Mars will scout for MISS in clastic deposits of ages equivalent to the Archean time on Earth.

Cross-References

- [Archaean Traces of Life](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Biofilm](#)
- [Microbial Mats](#)
- [Moodies Group](#)
- [Moodies Group, Microbial Mats](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)
- [Stromatolites](#)
- [Warrawoona Group](#)

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Microbiome of the International Space Station

Maximilian Mora¹ and Christine Moissl-Eichinger^{1,2}

¹Department of Internal Medicine, Medical University of Graz, Graz, Austria

²Diagnostic and Research Institute of Hygiene, Microbiology and Environmental Medicine, Medical University of Graz, Graz, Austria

Keywords

International Space Station · ISS · Microbiome · Microorganisms · Space travel

Synonyms

Microorganisms on board the International Space Station

Definition

A microbiome is defined as the combined genetic material of microorganisms in a particular environment, here the indoor environment of the International Space Station. It includes information about the identity of the microorganisms as well as their functional abilities.

Overview

Since October 30, 2000, the International Space Station (ISS) has been constantly inhabited by humans and accompanying microorganisms and represents a unique but challenging indoor environment in Earth orbit.

The ISS composes one of the most confined man-made and inhabited environments and

harbors a number of specific physical and chemical parameters: higher radiation levels than on Earth, low nutrient levels due to regular cleaning and reduced introduction of new material, constant temperature (approx. 22 °C), humidity of 36–80%, and microgravity characterize the ISS habitat.

Investigating the ISS microbiome is of utter importance to guarantee safety of the crew and the spacecraft itself, and microbial monitoring is pursued by all involved space agencies (Wilson 2019). The ISS also serves as a testbed for long-term space missions, and insights into microbial dynamics support preparation for such missions.

Crew members are the only constant source of microorganisms onboard the ISS; the input of microorganisms through cargo or other sources is minor. As a result thereof, the composition of the ISS microbiome is very similar to that of a typical human and ground-based indoor environment microbiome, which has been shown by all studies investigating the ISS microbiome so far.

However, within these bounds, the ISS microbiome shows adaptations toward the localization within the ISS, although diversity is fluctuating over time, even over a timespan of 2.5 months (Mora et al. 2019). Metagenomic analyses have shown that these fluctuations also seem to lead to an increase of antimicrobial resistance and virulence genes over time (Singh et al. 2018; Urbaniak et al. 2018).

However, up to date, no health-threatening differences have been found when comparing isolates and/or metagenomic data from the ISS with closely related isolates or metagenomic data from comparable indoor environments or the human microbiome on Earth (Blaustein et al. 2019; Mora et al. 2019). This is also supported by the fact that only a relatively low number of health issues related to pathogenic action of microorganisms onboard the ISS were reported (Crucian et al. 2016).

Nevertheless, studies also show that the ISS environment – while not inducing changes in microbes on a genomic level – seems to select for hardy microorganisms which are specialized to survive under these special environmental conditions. This microbial specialization to spacecraft

environment can also be seen when investigating the interaction of ISS isolates with spacecraft relevant material (SRM). Microbial isolates from ISS have been shown to be able to adhere to different kinds of SRM and to form a biofilm on such material (Mora et al. 2019), and other microbial isolates from ISS, so-called technophilic microorganisms, have also been shown to be able to damage SRM (Alekhova et al. 2005; Wilson 2019). These technophilic microorganisms had become a major problem on the Russian space station MIR (Novikova 2004).

Information on the ISS microbiome is critical to assess the microbial risk of long-term space missions. However, such flight bears even more extreme environmental factors, with complete isolation from the terrestrial biosphere, and it cannot be predicted how the microbiome therein would develop and whether elevated risks for crew and spacecraft material would occur.

Cross-References

- DNA Damage
- International Space Station
- Ionizing Radiation, Biological Effects
- Microgravity
- ‘Omics Technologies
- Orbit
- Survival

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Microfossil Characterization

► Microfossils, Analytical Techniques

Microfossils

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Liège, Belgium

Keywords

Acritarchs · Fossil · Fossilization ·
Morphological fossils

Definition

A microfossil is a microscopic morphological remain of an organism. It may represent a whole or part of a microscopic or macroscopic organism.

The organism may be a unicellular or multicellular prokaryotic or eukaryotic organism, or a virus.

Overview

Microfossils can have a variety of morphologies and chemical compositions, depending on their original properties and the conditions in which they are preserved. Microfossils can have a carbonaceous composition or a mineral composition. The mineral composition can be primary (produced or precipitated by the organism) or secondary (the original carbonaceous or mineral walls or envelopes being in that case partially or completely replaced by other minerals).

Microfossils are studied by micropaleontologists and provide useful information on the evolution of the biosphere, for biostratigraphy (dating sedimentary rocks), and for paleoecology, through most of geological time.

Possible microfossils have simpler morphologies and smaller size as we look further back in time through the early Earth rock record. Moreover, abiotic processes can produce structures resembling microfossils (► **Pseudofossil**). Deciphering the ► **biogenicity** of an object is very difficult even using cutting-edge in situ techniques. Several criteria have been proposed in the literature to test the biogenicity of microstructures preserved three-dimensionally in cherts or silicified carbonates or phosphorites, or flattened in two dimensions in fine-grained siliciclastic rocks. Most criteria underline the importance of a well-characterized geological context as the environmental conditions will determine the conditions of fossilization.

Three criteria need to be reached in order to correctly interpret a particular structure as a microfossil: (1) ► **endogenicity**: the microstructure is within the rock and not a contaminant; (2) syngeneity: the microstructure has the same age as the rock and is not a younger fossilized contaminant such as an organism boring the rock or transported by fluids between pores or veins through the rock; (3) biogenicity: the microstructure has a biological origin. Not only must

biogenicity be demonstrated, but all possible abiotic hypotheses must be excluded before a biological origin can be accepted. Several analytical techniques coupled to observations of the microfossil in situ in sections cut through the rock are used to prove the points above.

Geobiological studies in recent and past environments and laboratory experiments can improve understanding of preservational environments and fossilization processes, and help to recognize morphological (and other) traces of life on early Earth and beyond Earth. This is essential to choose landing sites, instrumentation, and samples to return in exobiological missions.

Cross-References

- [Biogenicity](#)
- [Biomarkers, Morphological](#)
- [Dubiofossil](#)
- [Endogenicity](#)
- [Eukaryote](#)
- [Fossil](#)
- [Fossilization, Process of](#)
- [Microfossils, Analytical Techniques](#)
- [Prokaryote](#)
- [Protists](#)
- [Pseudofossil](#)
- [Syngenicity](#)

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Microfossils, Analytical Techniques

Kevin Lepot

Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, UMR 8187 - LOG Laboratoire d'Océanologie et de Géosciences, F-59000, Lille, France
Institut Universitaire de France (IUF), Paris, France

Keywords

Microscopy · Fluorescence · CLSM · Raman spectromicroscopy · FT-IR spectroscopy · SEM · TEM · EDX · SIMS · ToF-SIMS · Pyrolysis GC-MS · X-ray tomography · X-ray fluorescence · XANES · Biomineralization · Syngenicity · Pseudofossil · Trace metals · Ultrastructure · Biomacromolecules · Isotope ratio

Acronyms

- | | |
|--------|--|
| AFM-IR | Infrared spectroscopy coupled to atomic force microscopy |
| ATR | Attenuated total reflectance |
| CLSM | Confocal laser-scanning microscopes |
| EBSD | Electron backscatter diffraction |
| EDX | Energy-dispersive X-ray (spectroscopy) |
| EELS | Electron energy-loss spectroscopy |
| FIB | Focused ion beam |
| FISH | Fluorescence in situ hybridization |
| FT-IR | Fourier-transform infrared (spectroscopy) |

GC-MS	Gas-chromatography mass-spectrometry
HR-TEM	High-resolution transmission electron microscopy
PIXCT	Ptychographic X-ray computed tomography
SAED	Selected-area electron diffraction
SEM	Scanning electron microscopy
SIMS	Secondary ion mass spectrometry
STEM	Scanning transmission electron microscopy
STXM	Scanning transmission X-ray microscopes
SXM	Scanning X-ray microscopes
S-XRCT	Synchrotron-based X-ray computed tomography
S-XRF	X-ray fluorescence by synchrotron X-rays excitation
TEM	Transmission electron microscopy
ToF-SIMS	Time-of-flight SIMS
XANES	X-ray absorption near-edge structure (spectroscopy)
XRCT	X-ray computed tomography

Synonyms

[Microfossil characterization; Structure and chemistry of microfossils](#)

Definition

Versatile analytical techniques can provide morphological, structural, chemical, and mineralogical (bio)signatures for microscopic fossils. These signatures can be used to distinguish microfossils from pseudofossils, demonstrate their antiquity, identify their parent (micro)organisms (taxonomy), and decipher their activities and host environments. Most of these techniques rely on electromagnetic (X-ray, UV, visible, IR) radiation or particle (electron, ion) beams. They can produce images in two and three dimensions, perform spectroscopy and spectrometry in situ down to the nanometric scale, and generate maps of specific chemical, structural, or crystallographic features.

Overview

Morphological analysis of microfossils can be performed in three dimensions with the following techniques (in order of spatial resolution, from $\sim 1 \mu\text{m}$ to 10's of nm): multiplane transmitted-light microscopy, Raman spectromicroscopy, CLSM, FIB-SEM, and S-XRCT. Nanometric resolution of organic ultrastructures and (bio)minerals can be achieved in 2D at the surface of fossils with SEM and in their cross-sections with TEM. These morphological analyses can help distinguish microfossils from pseudofossils and assess the preservation and taxonomy of microfossils.

Elemental compositions of minerals and organic matter can be analyzed in 2D with EDX, SIMS, and ToF-SIMS, as well as in 3D using S-XRF. This helps further assess biogenicity and conditions of fossilization. Crystallographic characterization can be performed with EBSD and TEM, which can document on fossilization, biomineral formation, and pseudofossil generation processes.

The thermal evolution of carbonaceous matter, in rocks that are sufficiently mature, can be quantified with Raman spectroscopy, thus providing constraints on syngenicity. Organic functional group signatures shown by FT-IR and XANES spectroscopy, and molecular formula obtained by mass spectrometry (Py-GCMS, ToF-SIMS) demonstrate selective preservation of specific types of biomacromolecules in distinct (micro)fossils. Chemotaxonomic constraints and biogenicity indices may thus be derived. Measurements of the isotope ratios (e.g., of C, N, O, and S) can be performed at the microscopic scale with SIMS. These can be used to infer metabolisms and/or conditions of fossilization.

The association of these techniques has proven crucial for investigating microfossils. It can be facilitated by spatially correlative microscopy and microanalyses, currently developed for many of the techniques mentioned herein. An analytical sequence is developed here that copes with the destructive nature of some analyses and some types of sample preparation.

Basic Methodology

Preparation

Microfossils can be analyzed in 30–100 μm -thick polished “petrographic” sections preserving their mineral matrix. Nanoscale focused ion beam (FIB) abrasion allows extraction of ultrathin (usually ~ 100 nm thick, <30 μm wide, <12 μm deep) sections cross-cutting organic fossils and host minerals that can be analyzed at the nanoscale in transmission electron microscopes (TEM) (Brasier et al. 2015; Lepot et al. 2017). Demineralization of organic microfossils (using acid maceration in HCl, acetic acid, HF, and/or HNO_3) allows their analysis without matrix interference and reveals microfossils compacted by sedimentation (Javaux et al. 2004). HNO_3 alters immature-to-mature fossil organic matter, and HCl alters “fresh” biomass (Lepot et al. 2014). Demineralized microfossils can be embedded in glycerol or resins to prepare “palynological” slides. Furthermore, demineralized fossils can be analyzed at the nanoscale when included in polymers and cut using an ultramicrotome into ultrathin (~ 100 nm) sections for TEM (Javaux et al. 2004). Ultrathin samples are also required for transmission of low-energy “soft” X-rays used to analyze light elements (C, N, O, S) with XANES: they can be prepared with FIB (Bernard et al. 2007). Higher energy X-rays such as those used to study trace metal abundances (see S-XRF) can transmit through unglued petrographic sections. For transmitted infrared spectroscopy, best-suited are mineral samples that are at most tens of micrometers in thickness and demineralized organic microfossils. Fluorescence spectromicroscopy techniques operate with petrographic sections or demineralized microfossils, although care should be taken to avoid fluorescent embedding media (Lepot et al. 2014). Raman spectromicroscopy operates on any sample type and can target fossils encapsulated in transparent minerals, hence limiting superficial laser-irradiation damage and preparation artifacts.

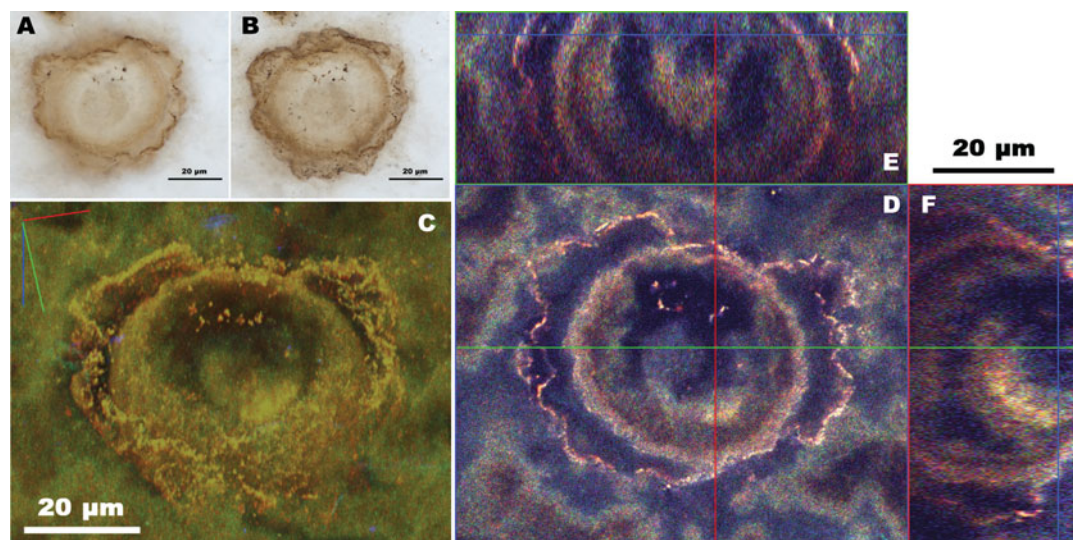
Transmitted Light Microscopy

Transmitted, visible light microscopy allows 3D observation of microstructures. The diffraction

limit on a microscope lateral resolution follows Abbe’s law ($d = \lambda/2\text{NA}$, with λ : wavelength, NA: numerical aperture of the objective). The average lateral resolution is thus ~ 300 nm with a standard objective (NA0.9), and ~ 200 nm with an oil-immersion objective (NA1.4). White light is usually the main light source used, and infrared can also be used to transmit through some opaque phases such as FeS_2 , which is a common postmortem replacement/mineralization of organic anatomy (Wacey et al. 2013; Lepot et al. 2017). The in-focus slice thickness is also proportional to the numerical aperture of the objective used (e.g., >0.6 μm with a 100x NA0.9 objective, >5.6 μm at 10x NA0.3). Additionally, deformation along the optical axis (vertical direction) occurs when the refractive indices of the microfossil matrix (mineral, mounting medium) and those of the media between sample and objective (air, or water, or immersion oil, and/or coverslip) differ. This, combined with the large contribution to the transmitted-light intensity of dark out-of-focus objects, limits the spatial resolution along the optical axis. Stacks of images recorded at different focal depths can be used to render 2D projections of microfossils preserved in 3D by subtracting the low-contrast contributions of out-of-focus parts of the images and combining the remaining contrasted zones (Fig. 1a and b). Similarly, combination of multifocal image stacks acquired using reflected light can help reconstruct images of the topography of thick and/or opaque samples such as (micro)fossils on fracture surfaces. Analyzed polarized transmitted light can reveal mineral microstructures, help identify minerals, and distinguish their respective orientations. Thermally mature organic matter can be tracked over surfaces using reflected light, and quantification of the reflected light intensity can help assess maturity.

Fluorescence (Spectro)microscopy and Confocal Laser-Scanning Microscopy

Fluorescence emission is generated by excitation of electrons by incident photons, followed by non-radiative relaxation (e.g., heat-generating) and radiative relaxation of the excess energy in form of photons of lower energies than that of the



Microfossils, Analytical Techniques, Fig. 1 White-light microscopy and CLSM of a ~407 million-year-old microfossil from the Rhynie chert of Scotland. (a) Single plane photomicrograph. (b) Multiple image resulting of the combination of multiple single focal-plane images. (c) 3D rendering of CLSM image stack. (d) single plane CLSM image and (e, f) orthogonal depth slices extracted along the green and red lines in (d). Blue lines in (e, f) mark the depth

of the single plane slice shown in (d). Sample provided by N. Trewin (U. Aberdeen). CLSM performed by E. Richard (Univ. Lille, CNRS, INSERM, CHU Lille, Institut Pasteur de Lille, US 41 - UMS 2014 - PLBS, F-59000 Lille, France), using 40x NA1.3 objective, color channels (laser excitation, light-collection range): blue (405 nm, 410–513 nm), green (488 nm, 490–606 nm), and red (561 nm, 570–641)

M

incident photons. Fluorescence can arise from in situ autofluorescent molecules such as chlorophylls and carotenoids, minerals (e.g., carbonates), fossil organic matter (Schopf and Kudryavtsev 2010; Lepot et al. 2014), or chemical dyes that can be added to bind to selective classes of molecules such as nucleic acids, proteins, or polysaccharides. Filters allows the selection of specific excitation and emission wavelengths to image distinct components. Fluorescence in situ hybridization (FISH) uses fluorescent probe molecules that can be designed to bind to specific nucleic acid sequences, which allows identification of cells at the gene level, and to visualize the expression of certain genes (e.g., those linked with a specific metabolism). Epifluorescence microscopes share the lateral/vertical resolution limits of white-light microscopy, albeit at increased lateral resolution using UV excitation, following Abbe's equation. Confocal laser-scanning microscopes (CLSM) provide increased resolutions in 3D using lasers of various wavelengths to induce specific fluorescence emissions.

A focused laser beam is raster-scanned on the sample and out-of-focus fluorescence emission is removed by a pinhole. This produces confocal images with a focalized slice thinner than 0.5 μm , and with a lateral resolution of ~200 nm or better. Depth series of 2D images can be combined to reconstruct 3D projections and orient virtual slices in any direction (Fig. 1c–f; Schopf and Kudryavtsev 2010). CLSM can acquire hyperspectral stacks of fluorescence maps over a range of wavelengths, from which fluorescence spectra can be extracted in specific regions of interest that may indicate the origin of autofluorescence (Lepot et al. 2014).

Raman Spectromicroscopy

Raman spectroscopy uses monochromatic beams of photons (from X-ray to near-infrared wavelengths) to excite molecules to virtual energy states. The molecules then relax to various final energy states (e.g., vibrational, see next section). In doing so, they backscatter photons with energies equating that of the absorbed photons minus

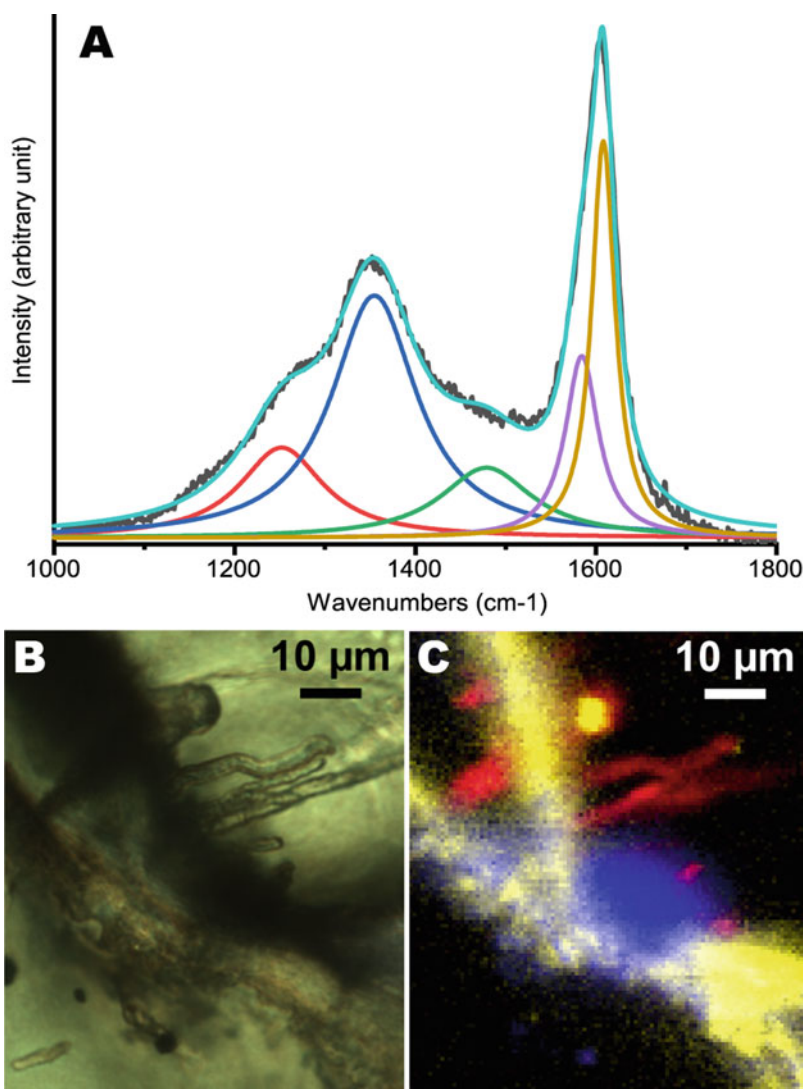
the various energy differences between initial and final states of the molecules. The differences between the energy of the incident laser and the energies of the backscattered photons are named Raman shifts, expressed in wavenumbers (cm^{-1}). They are mostly independent of the incident wavelength, and are measured as bands with spectrometers. Minerals and organic molecules generally produce spectra with multiple characteristic bands. Minerals (and their polymorphs) and plastics are readily identified by automated comparison of Raman spectra with databases. Various functional groups (e.g., C=O, O–H) can be distinguished in living/fresh organic matter, and

some biomolecules such as pigments, which can survive for thousands of years in sediments, display intense Raman spectra with characteristic fingerprints (Lepot et al. 2014). Fluorescence emission may generate large humps in Raman spectra in some organic and/or inorganic materials. Immature fossil organic matter and carbonates can be highly fluorescent, and functional groups are best detected in immature fossil organic matter using near-IR excitation (Olcott Marshall and Marshall 2015). Mature fossil organic matter mainly yields broad and intense bands (Fig. 2a), the shape of which reflects the structure of the macromolecular aromatic network

Microfossils, Analytical Techniques,

Fig. 2 Raman

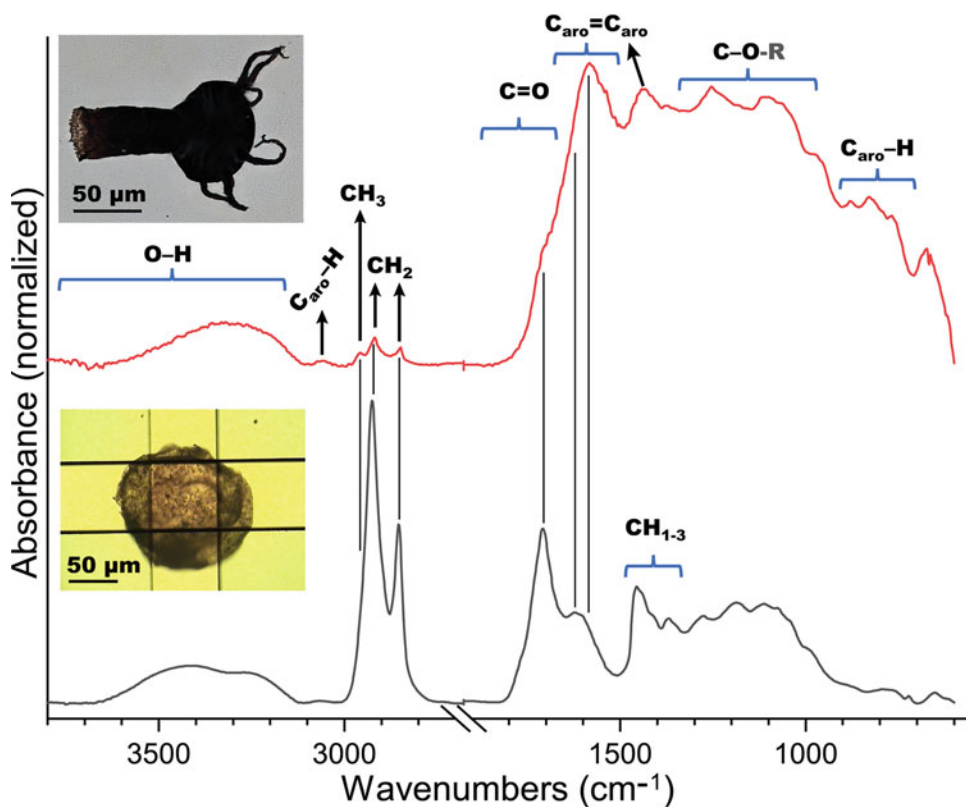
spectromicroscopy. (a) Raman spectrum of carbonaceous matter in a microfossil of the 1.88 Ga Gunflint Formation (see Fig. 5a). Data in dark brown, and total fit in blue generated using 5 Lorentzian bands. (b) Photomicrograph of titanite (CaTiSiO_5) microtubes in metamorphosed volcanoclastic material of the 2.72 Ga Tumbiana Formation. (c) Raman spectromicroscopy of (b) showing carbonaceous matter (yellow), titanite (red), and TiO_2 (blue). ((b–c) Reprinted from Earth and Planetary Science Letters, 312, Kevin Lepot, Karim Benzerara, Pascal Philippot, Biogenic versus metamorphic origins of diverse microtubes in 2.7 Gyr old volcanic ashes: Multi-scale investigations, 37–47, Copyright (2011), with permission from Elsevier)



(Henry et al. 2019). Although these bands may not bear diagnostic fingerprints of molecular groups, they can be used to assess the maturity of the fossil organic matter through deconvolution of the band profiles (Fig. 2a; Henry et al. 2019). Using automated sample displacement or raster-scanning of the laser position, hyperspectral mappings can be acquired in Raman spectromicroscopes in 2D (Fig. 2b and c) or 3D (Schopf and Kudryavtsev 2010) with resolutions of ca. 300 nm. Similar to CLSM, the high resolution in depth is achieved by use of a focused laser and sorting of backscattered beams by a pinhole. Due to its intense resonant signal, thermally mature fossil organic matter is easily mapped in most transparent mineral matrices.

FT-IR Spectromicroscopy

Infrared photons of specific wavelengths can be absorbed by a given chemical bond type, raising the energy of such bonds to vibrational states. Similar to Raman spectroscopy, Fourier-transform infrared (FT-IR) spectroscopy thus allows identification and semi-quantification (band area ratios) of types of chemical bonds in minerals and organics. Microfossils have been analyzed in the mid-infrared domain ($500\text{--}4000\text{ cm}^{-1}$, that corresponds to wavelengths of $20\text{--}2.5\text{ }\mu\text{m}$), as shown in Fig. 3. Mid-infrared absorption bands of minerals overlap those of many organic functional groups, which can be overcome by complete demineralization



Microfossils, Analytical Techniques, Fig. 3 FT-IR spectra of Silurian microfossils. Upper spectrum recorded on a chitinozoan, lower spectrum on an acritarch. Note the square drawn by IR-opaque windows used to select the analyzed area of the acritarch specimen. The chitinozoan is enriched in aromatic functional groups ($C_{\text{aro}} = C_{\text{aro}}$ and $C_{\text{aro-H}}$) and displays little, short aliphatic chains

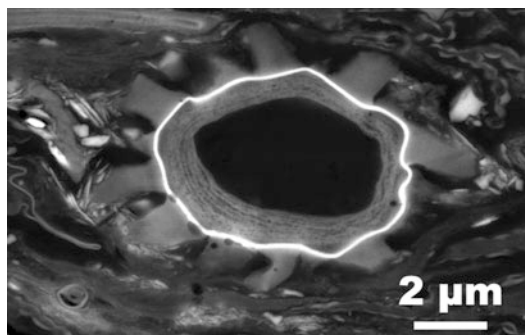
(characterized by the abundance of CH_3 relative to CH_2 groups). The acritarch is dominated by CH_2 groups, indicating relatively longer aliphatic chains, and carboxyls ($\text{C}=\text{O}$). Microfossils provided by T. Vandenbroucke (U. Ghent), analysis carried by I. De Waele (LASIR, U. Lille)

of organic microfossils (Olcott Marshall and Marshall 2015). In contrast with Raman spectroscopy, functional groups can be distinguished in FT-IR spectroscopy of organic matter up to the anthracite maturity rank, and can be used to assess the origin and thermal maturity of the organics using semi-quantification of functional groups (Chen et al. 2015). Metamorphosed organic matter usually displays little infrared absorption bands. Spectromicroscopy can be performed on plurimicrometric targets in three main modes in standard micro-FT-IR instruments (Chen et al. 2015). First, infrareds condensed through a reflective objective onto the sample and transmitted toward a second objective can be analyzed on the spectrometer. Depending on their compositions, the thickness of microfossils should not exceed a few micrometers. Analysis using transmitted FT-IR of organic microfossils embedded in a transparent mineral matrix can be performed in unglued petrographic sections $\sim 40\text{ }\mu\text{m}$ thick, but is limited to the bands of organic functional groups absorbing in the $2000\text{--}3000\text{ cm}^{-1}$ domain, which are little affected by host minerals (Chen et al. 2015 and references therein). Second, reflected infrareds can also be analyzed, although reflectance spectra display differences in shape and intensity with transmittance spectra. Third, the attenuated total reflectance (ATR) technique uses a crystal put in direct contact with samples, probing a thickness of a few hundred nanometers to a few micrometers. In all three techniques, analyses can be carried on single spots. The spot size obtained with a 36x NA0.5 objective is ca. $60\text{ }\mu\text{m}$ large. The analyzed area can be reduced down to $\sim 5\text{ }\mu\text{m}$ using adjustable IR-opaque windows (Fig. 3) forming a “pinhole” above the collecting objective, but at the expense of spectral quality. Hyperspectral mappings can be performed for all three techniques where FT-IR spectra are recorded simultaneously at each pixel of a detector. The lateral resolution of micro-FT-IR imaging is limited by diffraction to 1λ (36x NA0.5 objective), that is $2.5\text{--}20\text{ }\mu\text{m}$ in the mid-infrared. Additional optics may enable $\sim 1\text{ }\mu\text{m}$ resolution. Synchrotron infrared sources also help increasing the resolution to a few micrometers with spatial filtering and multibeam techniques.

Finally, infrared spectroscopy coupled to atomic force microscopy (AFM-IR), whereby the nanoscale displacement of an ultrasharp tip by the thermal expansion generated through IR absorption by the sample is measured, which allows spatial resolution $<20\text{ nm}$ (Dazzi and Prater 2017).

Scanning Electron Microscopy

Scanning electron microscopy (SEM) scans a thin primary beam of electrons over the surface of a sample. The interactions between primary electrons and materials generate electrons (backscattered, secondary and Auger electrons) and photons (X-ray, cathodoluminescence) that can be analysed with specific detectors. Secondary electrons generate images that are strongly influenced by sample topography. Backscattered electron intensity is proportional to the average atomic number of the material, producing images with contrast linked to chemical heterogeneity. The spatial resolution of secondary and backscattered electron imaging can reach $\sim 1\text{ nm}$. Cellular components and textures (ultrastructures) of organic and mineral microfossils can be imaged both in cross-sections (Fig. 4) or at the surface of microfossils (Javaux et al. 2004; Cohen et al. 2017; Wacey et al. 2017). Electron backscatter

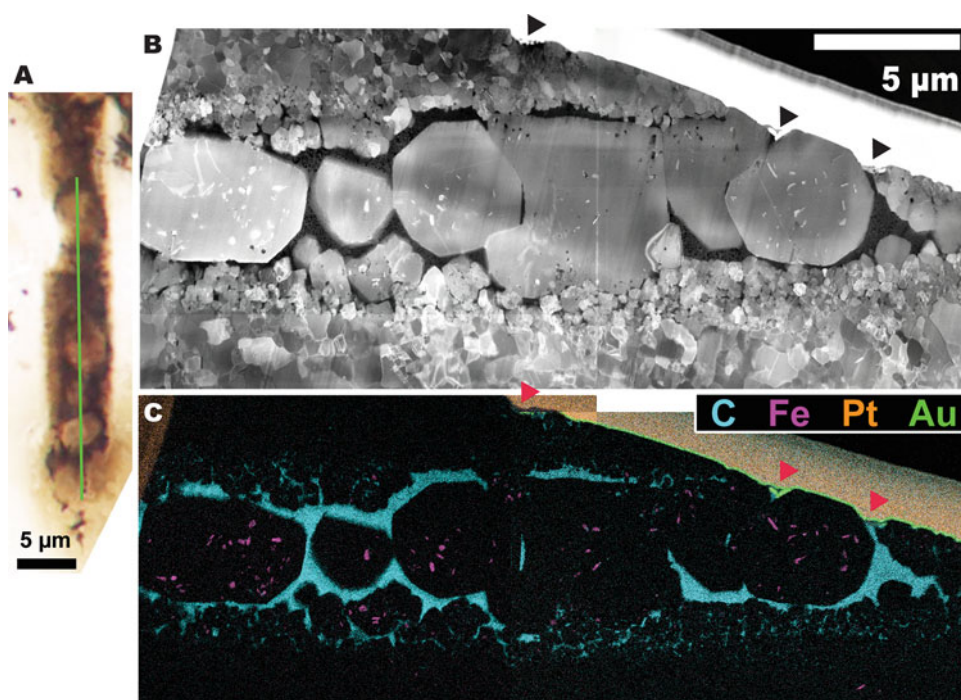


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Fig. 4 Ultrastructures in SEM BSE image (polished section) of a *young* fossil unicellular eukaryote buried under 126 cm of sediments, Antarctic lake O-Ike. Most of the chemical contrast in this image arises from differential fixation of uranium (white layer) and osmium (shades of gray) to the different ultrastructures of the microorganism after heavy-metal staining preparation. Light gray to white angular particles are minerals

diffraction (EBSD) can be used to identify mineral crystallographic systems (hence distinguishing CaCO_3 polymorphs such as calcite and aragonite), to evidence the boundaries of crystal/grains of similar chemistry in petrographic sections, and to determine and map crystallographic orientations, e.g., in biominerals (Cusack 2016). Although SEM characterizes surfaces, it can be coupled to a FIB that ablates ultrathin superficial layers of materials. Sequences of FIB ablations and SEM imaging (and/or SEM-EDX, see below, and/or EBSD mapping) can be used to record image stacks in order to reconstruct 3D images of microfossils (Brasier et al. 2015; Wacey et al. 2017). FIB-SEM can also document targeted cross-sections of microfossils (Wacey et al. 2017), which can be more pristine than the surface of mechanically polished sections (Fig. 5, arrows).

Transmission Electron Microscopy

Transmission electron microscopy (TEM) can image ultrastructures with true nanometric resolution in ultrathin (<100 nm) samples. Illuminating samples with a beam of parallel electrons generates images displaying contrasts related to crystallographic orientation, crystal defects, chemical composition, and sample thickness. Selected area electron diffraction (SAED) of parallel electron beams can be used to identify crystal systems in regions larger than ~ 50 nm (Lepot et al. 2017). High-resolution TEM (HR-TEM) can image atomic structures with a resolution down to 0.07 nm, for example, to identify nanocrystals in (bio)minerals (Lepot 2020) or to assess the stacking of polyaromatic structures during metamorphism (Bernard et al. 2007). Electron beams can be focused to less than 0.1 nm and scanned over the samples in a fashion similar to SEM,



Microfossils, Analytical Techniques, Fig. 5 Analytical TEM, microfossil of the 1.88 Ga Gunflint microbiota. (a) Photomicrograph. (b) Dark-field STEM image of the FIB section cut along the green line in (a). (c) STEM-EDX mapping of (B) showing carbonaceous matter (carbon in blue), Fe-minerals (Fe, pink), and preparation artifacts of

Pt and Au. Arrowheads in (b–c) show the nanoscale removal of organic matter at grain boundaries at the surface of the petrographic thin section from which the FIB section was extracted. ((a–c) Reprinted from Lepot et al. (2017), under a Creative Commons Attribution 4.0 International License: <http://creativecommons.org/licenses/by/4.0/>)

hence providing scanning-TEM (STEM) images (Lepot et al. 2017). Bright-field and dark-field STEM imaging (Fig. 5a) displays contrasts generated by sample thickness, chemical composition, and crystal structure/orientation (diffraction contrast), whereas high-angle annular dark field (HAADF) STEM shows mainly chemical and thickness contrasts. Nanodiffraction mapping can be performed by scanning a focused transmitted electron beam over the sample surface, which provides crystallographic data in a fashion similar to EBSD, but with nanometric resolution. Finally, electron energy-loss spectroscopy (EELS) can be used in STEM to measure atomic compositions, to distinguish chemical bonding types and oxidation states, and to map such chemical speciation down to the sub-nm scale (Lepot et al. 2017).

Elemental Compositions with EDX

Upon electron impact, X-rays are produced from a superficial zone $\sim 0.2\text{--}1\text{ }\mu\text{m}$ large and deep in SEM, and $< 20\text{ nm}$ large in STEM for samples $< 100\text{ nm}$ -thick. Elemental compositions can be measured by energy-dispersive X-ray (EDX) spectroscopy with a sensitivity $> 0.1\%$ and a precision of $2\text{--}30\%$. Light elements such as C, O, and N are very difficult to quantify in organic matter. EDX can be used to map distributions of chemical elements (Fig. 5). The spatial resolution of EDX is limited by the generation zones discussed above.

Dynamic SIMS

Dynamic secondary ion mass spectrometry (SIMS) uses primary, focused beams of ions (e.g., Cs^+ or O^-) to sputter materials from multiple atomic/ionic/molecular layers at the surface of samples. Sputtered secondary ions are then separated by mass, and each mass window is counted using individual detectors. This allows the measurement of isotope ratios with sub-permil precision and of major to trace element compositions (Orphan and House 2009). Analyzed (that is, sputtered) pits are 50 nm to $\sim 40\text{ }\mu\text{m}$ large and a few nanometers to several micrometers in depth. Variable bias named “instrumental mass fractionations” arise in SIMS that depend on the geometry of the instrument (ion path), its tuning, the age of the detectors, and sample topography. Variations

in chemical compositions of the matrix (e.g., C_xH_y) hosting the analytes (e.g., ^{13}C and ^{12}C) may generate additional bias (Orphan and House 2009; Williford et al. 2013). Instrumental and matrix-induced biases have to be evaluated through repeated analysis of standard materials. Quantitative (or semi-quantitative) mapping of isotope ratios or chemical elements can be performed by raster-scanning the primary ion beam over the sample surface with a spatial resolution down to $\sim 50\text{ nm}$ (Orphan and House 2009).

Time-of-Flight SIMS

In time-of-flight SIMS (ToF-SIMS), ions are sputtered in vacuum by a primary focused ion beam during a short-timed pulse (Thiel and Sjövall 2015). The sputtered ions are accelerated in an electrical field, after which they travel in a time-of-flight tube at velocities proportional to their mass/charge ratios, that are in turn quantified by the time of arrival of the ions on the terminal detector. Hence, full mass spectra can be recorded from 0 to 1000+ atomic mass units (Thiel and Sjövall 2015). In contrast to dynamic SIMS, ToF-SIMS instruments usually operate in static conditions defined by relatively low primary ion dose densities (10^{12} to 10^{13} ions. cm^{-2}). This, together with the use of primary beams of clustered atoms (e.g., Bi_3^+ , C_{60}^+ , Au_n^+ , Ar_{2500}) that deposit their energy at much shallower levels than monoatomic sources (e.g., Ga^+ , Cs^+ , Ar^+) allows the release of high molecular-weight ions from the extreme surface (monolayer to $< 10\text{ nm}$) of samples (Thiel and Sjövall 2015). Lateral resolution down to $\sim 100\text{ nm}$ can be obtained, and high-resolution maps of organic and inorganic ions are acquired by raster-scanning the primary ion beam. Depth profiles can be obtained in 3D by progressive ion-sputtering of layers from the sample surface in a fashion similar to FIB-SEM. ToF-SIMS has been used to analyze various classes of biomarkers and biopolymers in environmental samples, fossils and sedimentary rocks, to analyze oily fluid inclusions or extraterrestrial organic matter (Thiel and Sjövall 2015). An important difficulty in ToF-SIMS arises from relatively large inaccuracy on measured masses (and lower mass resolution) caused by sample

topography (Thiel and Sjövall 2015). Polishing can level topography but specific methods are required to avoid or minimize contaminants (Fadel et al. 2020). With a mass resolution of 2,000–10,000 $m/\Delta m$, ToF-SIMS may not distinguish molecules of medium-to-high molecular weight in complex mixtures where multiple fragmentation patterns overlap, which may be overcome by additional tandem mass spectrometry available on some instruments (Thiel and Sjövall 2015).

Pyrolysis GC-MS

Gas-chromatography mass-spectrometry (GC-MS) provides an additional mode of molecule separation using a chromatographic column prior to analysis by mass spectrometry. This technique, compared with ToF-SIMS, requires large sample volumes to extract soluble molecules. The latter can also be analyzed by thermal desorption, and higher (pyrolytic) temperatures can fragment the insoluble macromolecular fraction (kerogen) associated with microfossils. Pyrolysis GC-MS has been enabled by handpicking of a few hundred similar microfossils (Dutta et al. 2007) or by laser-pyrolysis of one (large) to several microfossils (da Silva et al. 2016).

X-ray Nanotomography

X-ray computed tomography (XRCT) enables nondestructive 3D imaging even in thick and opaque matrices that could limit 3D CLSM imaging (Wacey et al. 2017). Microfossil analysis requires sub-micrometric resolution. Synchrotron-based instruments (S-XRCT) can achieve ~200 nm spatial resolution (Little et al. 2021). Ptychographic X-ray computed tomography (PIXCT) computes diffraction patterns generated using synchrotron X-rays to achieve ~50 nm resolution in 3D together with electron density estimates (Maldanis et al. 2020).

Synchrotron X-ray Fluorescence

X-ray fluorescence produced by synchrotron X-rays (S-XRF) allows mapping and quantification of the abundances of elements larger than sodium with ppm sensitivity and lateral resolution down to ~30 nm (Lemelle et al. 2020).

XANES Spectromicroscopy

Absorption of X-rays can delocalize inner-shell electrons to weakly bound states such as molecular orbitals. This generates absorption spectra with step-like (edge) increases displaying one, or multiple bands that are characteristic of the chemical bond types, the crystallographic environments, and the redox states of the elements. These spectral features are studied by X-ray absorption near-edge structure (XANES) spectroscopy (Bernard et al. 2007; Lepot et al. 2017) which can be performed in scanning transmission X-ray microscopes (STXM) and in scanning X-ray microscopes (SXM, also used for S-XRF, see above). STXM reaches ~25 nm spatial resolution but requires ultrathin samples, and SXM can reach <500 nm resolutions. In contrast with electrons used in EELS (see TEM), X-rays produce much less irradiation damage to sensitive minerals and organics.

Key Research Findings

Biom mineralization

Biom mineralization (or bioprecipitation) can be induced by the presence of reactive surfaces on (or secreted by) microorganisms, be induced by their metabolic activity, or result from genetically controlled processes. Most of the techniques described above have contributed to the understanding of biom mineralization. The association of multiple methods is necessary to clearly distinguish the signals generated by minerals and those by cells and/or organic molecules. At the ~0.1–1 μm scale, fluorescence spectromicroscopy can be efficiently associated with SEM and Raman spectromicroscopy in modern (Lepot et al. 2014) and fossil (Schopf and Kudryavtsev 2010) biom mineral-forming systems. At the same scale, ToF-SIMS can locate molecular biomarkers in association with single biom mineralized microorganisms (Thiel and Sjövall 2015). The coupling of synchrotron-based techniques and analytical TEM provide insight into biom mineralization at the nanometer scale.

The oldest record of controlled biom mineralization consists of phosphatic scales ~810 million

years old that have been attributed to unicellular eukaryotes (Cohen et al. 2017). In these scales, HR-TEM showed interwoven nanofibers that are elongated along a preferential direction, a crystallographic feature that is confirmed with SAED (Cohen et al. 2017). In this study, EDX spectroscopy demonstrated that the phosphate is a primary hydroxyapatite and abundant F and Cl substitutions indicative of diagenetic recrystallization were not detected. In older rocks, microbial calcification in 2.72 Ga stromatolites has been inferred by analysis of nanocrystalline CaCO_3 nanospheres using HR-TEM and XANES of associated organic matter (Lepot 2020).

Fe-mineralizations have been documented in close association with microfossils of the Paleoproterozoic. In a 1.74 Ga Fe-oxide-silica deposits, branching filaments were imaged in 3D with S-XRCT and STEM showed their tubular structures with walls of Fe-oxide nanoparticles (Little et al. 2021). These are interpreted as (recrystallized) products of Fe-oxidizing bacteria (Little et al. 2021). STEM showed that specific microfossil morphospecies in 1.88 Ga stromatolites display intracellular concentrations of nano- Fe^{2+} -minerals (Fig. 5). These were identified using a combination of EDX, nanodiffraction, EELS (that distinguished crystallographic environment of Si and the redox of associated Fe), and XANES (identifying CO_3^{2-} groups in Fe-carbonates) (Lepot et al. 2017). These Fe-minerals, in conjunction with the anatomy of the microfossils, were interpreted as the products of intracellular Fe^{3+} -mineralization by oxygenic phototrophs that have suffered postmortem reductive transformation (Lepot et al. 2017). Postmortem mineralization of organic ultrastructures of microfossils by Fe^{2+} -sulfides (Wacey et al. 2013; Lepot et al. 2017) and Fe^{2+} -carbonates (Fadel et al. 2017) was studied with STEM. Additional SIMS of S-isotope ratios supported an implication of heterotrophic sulfate-reducing microorganisms in the formation of the Fe-sulfides and the degradation of the associated microfossils (Wacey et al. 2013). In the Fe^{2+} -carbonate mineralization example, Fe-isotope ratios indicated a formation through reduction of Fe^{3+} -minerals, which may have been biomineralized initially by the

microorganisms represented by the observed fossils (Fadel et al. 2017).

Syngenicity of Organic Matter in Microfossils

Combined in situ characterization techniques have been used to seek textural relationships that demonstrate syngenicity, that is: a contemporaneous origin of microfossils with the earliest fabrics of the encapsulating rock. To this end, mapping of carbonaceous matter and associated minerals with Raman spectromicroscopy (Fig. 2) is useful. Contamination of the rocks postdating the most intense metamorphic (or deepest burial) history of the rock can be assessed variously. The color of organic matter evolves from near-transparent (fresh) to yellow (immature), to orange/brown (mature), and to black (metamorphic). Although colors may vary among taxa within a microfossil assemblage due to distinct molecular compositions and/or thicknesses (Fig. 3), they can be used to identify recent contaminants (bacteria, fungi, sample-mounting resins). In reflected white-light microscopy, the yellow-green/gray color of mature organic matter (Chen et al. 2015) is readily distinguished from organic contaminants and from oxide and sulfide minerals. In metamorphic carbonaceous matter, the presence and structure of atomic-scale ordering in HR-TEM images (e.g., Bernard et al. 2007) confirms pre-metamorphic precursors. Raman spectra can be used to quantify the maturity of organic matter, which is linked with burial conditions (Henry et al. 2019). The latter can also be estimated with mineral proxies. The agreement between organic and mineral “geothermometers” indicates that organic matter predates the most intense burial conditions.

Pseudofossils

Abiotic mineral and/or organic microstructures mimicking microfossil morphologies (such as filaments, spheres) and organizations, named biomorphs or pseudofossils, can be observed in rocks (Lepot 2020). Discriminating putative microfossils (dubiofossils) from abiotic biomorphs is difficult, as exemplified by the debate over the oldest candidate carbonaceous microfossils from the 3.46 Ga Apex Chert.

Based on 3D Raman and CLSM imaging, microfossils were inferred (Schopf and Kudryavtsev 2010). However, evidence that the reported carbonaceous filaments are associated with a continuum of shapes, which likely include, mineral mimics coated/impregnated with migrated organic matter, was shown by a combination of multiplane optical microscopy and TEM (Brasier et al. 2015 and references therein).

A number of criteria have been identified that can be combined with (often not individually) the textural features to help assess putative cellular microfossils (Lepot 2020). (1) A geological context allowing preservation of fossils. (2) The absence/presence of common biomorph templates such as quartz spherulites, or volcanic vesicles, which are best studied with optical microscopy. (3) The preservation of organic microstructures seen in petrographic sections (Fig. 1) and through demineralization of the host rock (observed with optical microscopy, Fig. 3, and SEM, e.g., Javaux et al. 2004), arguing for microfossils. (4) The identification of features such as folding/wrinkling that highlight postmortem deformability (e.g., lower picture in Fig. 3). These are best seen in SEM in demineralized, compressed or deflated microfossils, or in situ with CLSM in 3D microfossils (Fig. 1) (Schopf and Kudryavtsev 2010). (5) Continuous to sub-continuous organic matter that is disposed at the grain boundaries of its mineral matrix and that displays morphologies consistent with anatomic features such as cell walls and/or sheaths (Fig. 5) (Brasier et al. 2015; Lepot et al. 2017). The study of the textural relationship between minerals and organics can be assessed at the micrometer scale with Raman spectromicroscopy (Fig. 2). However, Raman spectromicroscopy cannot readily show the boundaries of adjacent grains/crystals with similar compositions and their relationships with carbonaceous matter. EBSD and/or a combination of STEM (Fig. 5a) and TEM-nanodiffraction mapping can outline adjacent crystals of similar compositions. Microtubular textures exemplified in Fig. 2, initially interpreted as the etching marks left by microorganisms (thus termed ichnofossils) in basaltic glass, have been reevaluated as metamorphic mineral textures using a combination of

Raman spectromicroscopy, NanoSIMS, and TEM (Lepot 2020). Finally, (6) observation of diagnostic cellular ultrastructures as detailed below can demonstrate microfossils.

Metals in Fossil Organic Matter

ToF-SIMS revealed increased metal concentrations in some early Paleozoic assemblages of chitinozoans, which coincides with, and may explain the malformations observed in the microfossils (Vandenbroucke et al. 2015). ToF-SIMS characterizes the surface of microstructures, although depths-profiles can be measured. Nano-S-XRF can characterize trace metals in the complete volume of cells (Lemelle et al. 2020). The presence of metals associated with fossil organic matter can partly explain contrasts in TEM images between distinct ultrastructures (in addition to variations in density), as discussed below. It also makes organic matter visible in TEM without requiring heavy-metal staining like that used for fresh/recent organic matter (Fig. 4, Lepot et al. 2014).

High-Resolution Morphological and Ultrastructural Information

Several morphological features can further demonstrate anatomical/cellular microstructures and assess their taxonomic relationship to extant or younger (micro)organisms. Combined thick and multilaminar cell walls can be seen in some demineralized organic microfossils with TEM (Javaux et al. 2004), but also in some organic microfossils preserved in their mineral matrix with CLSM (Fig. 1), SEM (Fig. 4; Wacey et al. 2017), or TEM. Such ultrastructures have been used to demonstrate an eukaryotic affinity. Cell-wall textures, for example, regular ornamentations and/or protrusions (processes) can be seen in optical microscopy, or highlighted with SEM (surface, or cross-section: Fig. 4) and CLSM, and are also diagnostic of eukaryotes (Javaux et al. 2004). Internal structures can be highlighted – in particular when the wall is dark – with CLSM in 3D (Fig. 1). CLSM and Raman imaging have been used, for example, to reveal the internal structure diagnostic of a comb-jelly (animal) embryo in 540 Ma phosphates (Schopf and Kudryavtsev 2010).

Evidence for Selective Molecular Preservation

The selective preservation of derivatives of various biomacromolecules is demonstrated by chemical heterogeneities between distinct taxa in the same rock analyzed by micro-FT-IR spectroscopy (Fig. 3). It is also supported by chemical heterogeneities shown by XANES at the nanoscale in a single microfossil (Bernard et al. 2007). NanoSIMS has been used to reveal organic N and S in 850 Ma-old microfossils (Oehler et al. 2006) that are usually not detected as functional groups in FT-IR spectra of microfossils (Fig. 3), possibly due to low abundances, or the high sensitivity of SIMS to these heteroatoms. Moreover, these NanoSIMS analyses documented distinct N/C ratios in filamentous versus spheroidal forms that might reflect different biological precursor, such as extracellular polysaccharide sheaths in filaments and cell walls in spheroids (Oehler et al. 2006).

These molecular compositions may represent a combination of biomacromolecules that evolved during burial diagenesis and metamorphism (if any), possibly with an addition through polymerization of free molecules such as lipids (Versteegh et al. 2004), hence forming “geomacromolecules.” Some molecular heterogeneities in rocks may be inherited from microscopically heterogeneous diagenetic conditions, such as sulfurization of organic matter linked with microbial metabolism, as evidenced with XANES and SIMS (Lepot 2020). Such heterogeneities in diagenetic conditions can be evaluated by the characterization of the petrographic context of the matrix hosting the microfossils, e.g., using SEM (Fig. 4) and Raman spectromicroscopy (Fig. 2).

Several examples of the use of molecular compositions to constrain the origin of specific groups of microfossils follow. The coupling of pyrolysis GC-MS and FT-IR ruled out the possibility that the dark-wall preserved in chitinozoans (Fig. 3) is derived from chitin, but is rather an aromatic-rich macromolecule for which the precursor remains unknown (Dutta et al. 2007). The preservation of derivatives of the biomacromolecule sporopollenin is shown in FT-IR spectra of spores of Silurian land plants, which contain a combination of strong aromatic and aliphatic signals together with

a specific band of aromatics only known in spores, peat, and lignite (Steemans et al. 2010). In contrast, some marine acritarchs, likely planktonic unicellular eukaryotes, display a dominance of long aliphatic chains in FT-IR (Fig. 3b), which are likely related to the preservation of algal macromolecules produced by algae (Steemans et al. 2010; Olcott Marshall and Marshall 2015). The CH_3/CH_2 ratio analyzed with FT-IR in microfossils of the Proterozoic preserved in their quartz matrix has been used to support the preservation of lipids produced by bacteria rather than archaea or eukaryotes (Igisu et al. 2009).

In all the cases above, molecular compositions appear useful for taxonomy in association with morphological/ultrastructural constraints. However, the detection of organic heteroatoms (N, S, O, P), of organic functional groups, or the identification of molecular formula may not be sufficient to rule out pseudofossils. Indeed, complex organic molecules may form abiotically, and migration of bio-sourced bitumen may form pseudofossils or coat mineral biomorphs (Lepot 2020). Association of distinct molecular compositions with specific morphospecies from a single rock (e.g., Fig. 3) can help demonstrate microfossils.

Constraints from C Isotope Ratios of Organic Matter

Organic carbon-isotope ratios ($^{13}\text{C}/^{12}\text{C}$) have been measured with SIMS for several microfossil assemblages and have been linked to the metabolic activity of the organisms (Orphan and House 2009; Williford et al. 2013; Lepot 2020). Heterogeneities in organic carbon isotope ratios measured between microfossils of the same taxon displaying different ultrastructural preservation (Williford et al. 2013) indicate that selective preservation may to some extent bias their C-isotope signature. Some C-isotope differences recorded among distinct microfossils preserved in the same rock are nevertheless too large to be explained by selective preservation and pointed to a distinction between eukaryotic and cyanobacterial precursors for two of the most common microfossils of the Neoproterozoic (Williford et al. 2013). It moreover implies that

the organic matter in these distinct microfossils could not have formed by filling of empty mineral molds by bitumen and that distinct macromolecules may be preserved in these fossils. C-isotope ratio heterogeneities distinguished among some of the oldest candidate microfossils (~ 3 and ~ 3.4 Ga) support their interpretation as anatomical remains and argue against an all-abiotic origin for the bulk of the carbonaceous matter in their host rocks (Lepot 2020).

Applications

As detailed above, three of the main applications of analytical techniques to microfossils target the link between organic matter and minerals (matrix, biominerals, diagenetic replacements). They help distinguish microfossils from pseudofossils, inspect the textural relationship between anatomy and candidate biominerals, and investigate post-mortem processes (e.g., mineral growths) leading to modifications of microfossil ultrastructures. Complete analysis of organic-mineral associations is achieved in TEM/STEM at the nanoscale in 2D following destructive sample preparation. CLSM and S-XRCT are particularly efficient for nondestructive 3D imaging of organics and minerals, respectively. It appears in turn necessary to combine multiple techniques on the same sample to investigate organic-mineral relationships in 3D. This is enabled by the advent of correlative microscopy, where all techniques record spatial coordinates and use automated sample displacements, together with spatially resolved analyses and novel sample preparation methods. These investigations can be further coupled with isotope-ratio microanalysis, and in situ mass-spectrometry of the molecular composition of fossils.

Future Directions

Optical microscopy and CLSM, followed by SEM provide nondestructive imaging. The analysis of mineral chemistries can be performed destructively in 3D with FIB-EDX (elemental mapping

by EDX during sequential ablation of a sample) or with nano-S-XRF, which is nondestructive. Observation of the disposition of grain boundaries is crucial in assessments of organic-texture templating, and the orientations of crystals can inform on (bio)mineral growth processes. These features can be imaged with EBSD in 2D and FIB-EBSD in 3D during sequential FIB ablation. In parallel, TEM can be performed on destructively prepared targets. This combination is expected to provide the highest level of textural-mineralogical information on microfossils.

Isotope ratio of C, N, and S can constrain metabolisms (Lepot 2020) and be measured with SIMS at the microscale by ablation of a few hundred nanometers of sample surfaces. This would be optimally performed between the nondestructive and the more destructive analyses listed above.

Spectroscopy including XANES and FT-IR demonstrate the preservation of distinct molecular signatures in some microfossils. Spectroscopy can thus be used in conjunction with SIMS of C, N, O, H isotope ratios to evaluate possible biases imparted by selective preservation processes on metabolic signatures. AFM-IR can investigate functional groups and ToF-SIMS the chemical formula of organics down to the nanoscale. These two techniques are essentially nondestructive beyond the initial preparation of ultra-flat sections, unlike the extraction of FIB sections for XANES or demineralization for FT-IR. As such, they can be the first analyses to be performed after initial microscopy, and can be followed by the 3D and/or destructive investigations. Nevertheless, initial preparation of ultra-flat rock surfaces requires stringent protocols to minimize contaminations (Fadel et al. 2020). ToF-SIMS has identified some bio(macro)molecules in macrofossils (Thiel and Sjövall 2015). Developments in the application of ToF-SIMS to microfossils is currently focused on overcoming the coupled limitations of superficial contaminations, topographic biases, and small amounts of organic matter. The combination of spatially resolved spectroscopies (XANES, FT-IR) and mass spectrometry (ToF-SIMS) is expected to provide important constraints on fossilization processes and the taxonomy of microfossils.

Inorganic species can be detected and semi-quantified with ToF-SIMS, and quantified with nano-S-XRF. This could help document trace metals in fossil-forming geomacromolecules, in order to provide clues on the enzymatic machinery of parent microorganisms and/or on environmental stressors (Vandenbroucke et al. 2015).

Cross-References

- ▶ Acid Maceration
- ▶ Acritarch
- ▶ Aliphatic Hydrocarbon
- ▶ Apex Chert, Microfossils
- ▶ Archaea
- ▶ Archaean Traces of Life
- ▶ Aromatic Hydrocarbon
- ▶ Bacteria
- ▶ Barberton Greenstone Belt, Traces of Early Life
- ▶ Biogenicity
- ▶ Biomarkers
- ▶ Biomarkers, Morphological
- ▶ Biomineralization
- ▶ Biomorphs
- ▶ Biopolymer
- ▶ Bioprecipitation
- ▶ Biosignatures, Effect of Metamorphism
- ▶ Bitumen
- ▶ Cell Wall
- ▶ Chert
- ▶ Dubiofossil
- ▶ Eukaryotes, Appearance and Early Evolution of
- ▶ Fluid Inclusions
- ▶ Fluorescence
- ▶ Fossil
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- ▶ Ga
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- ▶ Infrared Spectroscopy
- ▶ Isotope Biosignatures
- ▶ Kerogen
- ▶ Ma
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- ▶ Microorganism
- ▶ Organic Molecule
- ▶ Oxygenic Photosynthesis
- ▶ Photon
- ▶ Pseudofossil
- ▶ Pyrolysis GC/MS
- ▶ Raman Spectroscopy
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- ▶ Strelley Pool Formation
- ▶ Stromatolites
- ▶ Synchrotron Accelerator
- ▶ Synchrotron Radiation
- ▶ Syngenicity
- ▶ Taxonomy
- ▶ Trace Metals
- ▶ Traces of Life in Basaltic Crust
- ▶ Ultrastructure
- ▶ Visible Light
- ▶ Wave Number
- ▶ Wavelength
- ▶ XANES

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MicroFUN

► [Microlensing Follow-Up Network](#)

μg

► [Microgravity](#)

Micro-g

► [Microgravity](#)

Microgravity

David M. Klaus
Aerospace Engineering Sciences, University of
Colorado, Boulder, CO, USA

Keywords

Spaceflight · Spacecraft · Parabolic flight ·
Drop tower · Gravity · Gravitational
acceleration

Synonyms

[Freefall](#); [Micro-g](#); [Weightlessness](#); [Zero-G](#); [μg](#)

Definition

“Microgravity” (also commonly referred to as “Zero-G”) is broadly accepted as describing the condition of weightlessness experienced during spaceflight. More precisely, this unique physical state arises from an apparent lack of gravitational acceleration occurring relative to a local inertial reference frame, but does not necessarily refer to a reduced level of gravity in an absolute sense. The root term “gravity” in this case is actually a unit of acceleration, with Earth’s gravitational attraction of 9.8 m/sec^2 defined as $1 g$. The prefix “micro” can specifically indicate a factor of 10^{-6} or, more generally, just imply being very small.

Overview

“Microgravity” (also commonly referred to as “Zero-G”) is broadly accepted as describing the condition of weightlessness experienced during spaceflight, on a parabolic aircraft trajectory, or in a vertical drop tower. More precisely, this unique physical state arises from an apparent (or real) lack of gravitational acceleration that exists on a given mass relative to its local inertial reference frame (e.g., the spacecraft).

The root term “gravity” in this context refers to a unit of acceleration, with Earth’s gravitational attraction of 9.8 m/sec^2 defined as $1 g$. The prefix “micro” can specifically indicate a factor of 10^{-6} or, more generally, just imply being very small. Any multiple or fraction of this unit of acceleration can be expressed in relative terms of g , for example, an astronaut might experience $3 g$ ’s of acceleration during launch or $0.17 g$ on the lunar surface.

It is important to note that “microgravity” does not necessarily imply a reduction of the presence of gravity itself nor any change to the gravitational constant ($G = 6.672 \times 10^{-11} \text{ N}\cdot\text{m}^2\cdot\text{kg}^{-2}$), which is neither a force nor an acceleration per se, rather a physical constant used to dimensionally derive the force (F_{12}) resulting from the attraction of a mass (m_1) on another mass (m_2) a distance (r) away, defined as

$$F_{12} = (G m_1 m_2) r^{-2}$$

As a result of this force, gravity can produce two effects on an object – motion and weight. The familiar force (F) equation derived from this relationship, taking into account the acceleration (a) that acts on a given mass (m), reduces to

$$F = ma$$

When a mass (m) is resisted by an equal and opposite reaction, this force (F) defines weight. When an equal and opposite reaction is negligible, however, as occurs during orbital spaceflight or linear freefall in a vacuum, gravity instead gives rise to unimpeded (i.e., accelerated) motion, which is governed by either centripetal or linear

acceleration, respectively. As a consequence, no weight is imparted to the mass and, within its inertial reference frame, it experiences a state of weightlessness attributed to the lack of relative acceleration, termed microgravity. In contrast, a body falling through a viscous medium such as air or water reaches a state of terminal velocity where the force due to gravity is balanced by the resisting drag, at which point the body achieves a constant speed and experiences its full weight. For a spacecraft on a hyperbolic escape trajectory sufficiently far (r) from any dominant mass (m_1) such that no significant gravitational acceleration is affecting it, Newton's first law of motion dictates that it will continue moving at a constant velocity until acted on by an external force. In this unique case, the absolute presence of gravity theoretically approaches zero.

The microgravity environment experienced in Earth orbit has been used since the early 1960s to conduct studies on living organisms ranging from plants and microbes to humans. A wide variety of physical and biological responses to weightlessness have been characterized by this research.

Cross-References

- [Gravitation](#)
- [Gravitational Biology](#)
- [Planetary and Space Simulation Facilities](#)
- [Space Biology](#)
- [Space Environment](#)

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Microkrystite

- [Spherules](#)

Microlensing Follow-Up Network

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[MicroFUN](#)

Definition

MicroFUN (Microlensing Follow Up Network) is an informal consortium of observers dedicated to photometric monitoring of interesting microlensing events in the Galactic bulge. The primary scientific objective of MicroFUN is to observe high-magnification microlensing events in order to detect the signatures of exoplanets orbiting the primary lens. MicroFUN is somewhat unusual in that over half its members are amateur astronomers. MicroFUN has contributed to the discovery of the majority of the planets detected by microlensing. In 2008, MicroFUN announced the discovery (along with other collaborations) of the first planetary system discovered by microlensing, ► [OGLE-2006-BLG-109Lb,c](#). This system of two planets closely resembles a scaled analog of Jupiter and Saturn.

Cross-References

- [Exoplanets, Discovery](#)
- [OGLE-2006-BLG-109Lb,c](#)

Microlensing Observations in Astrophysics

David W. Latham¹ and B. Scott Gaudi²

¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

²Department of Astronomy, Ohio State
University, Columbus, OH, USA

Synonyms

MOA

Definition

MOA (Microlensing Observations in Astrophysics) is a collaboration of astronomers from New Zealand and Japan that employs the microlensing technique to search for dark matter and exoplanets. The Principal Investigator of the MOA collaboration is Yasushi Muraki of Nagoya University. MOA has contributed to the discovery of nearly all of the planets discovered by microlensing. The MOA 1.8 m telescope is located at Mt. John Observatory on the south island of New Zealand.

Cross-References

► [Exoplanets, Discovery](#)

Micrometeorites

Emmanuel Jacquet and François Robert
Institut de Minéralogie, Physique des Matériaux
et Cosmochimie (IMPMC), Sorbonne Université
et Muséum National d'Histoire Naturelle, UMR
7590 CNRS, Case 52-61 rue Buffon, Cedex
05 Paris, France

Definition

A micrometeorite is the remnant, on a planetary surface (e.g., Earth), of an interplanetary submillimeter-size dust particle.

Overview

The arrival on Earth of microscopic extraterrestrial grains has been discussed since the late nineteenth century for example, with the discovery of cosmic spherules by the Challenger oceanographic mission in 1872. These spherules were collected with a magnet by dragging the surface of marine sediments. The extraterrestrial origin of these spherules was nevertheless a subject of debate and was not accepted until the advent of ion microprobes in the late 1980s. Laboratory measurements of implanted rare gases, solar flare tracks, and isotope abundances confirmed that the collected particles are indeed extraterrestrial and that, prior to atmospheric entry, they spent up to several million years as small particles orbiting the Sun. Starting in 1982, micrometeoroids were collected in the Earth's stratosphere using plate collectors under the wings of NASA airplanes. These are referred to as *Interplanetary Dust Particles* (IDPs) in contradistinction to micrometeorites which have reached the ground. In the same decade, Michel Maurette pioneered the collection of micrometeorites in polar regions from melted ice and snow, first in Greenland and then in Antarctica, with present-day collections in Concordia snow (by his successor team in Orsay, now at the Muséum national d'Histoire naturelle) yielding the most pristine micrometeorites to date (if IDPs, which have only spent hours to weeks in the atmosphere, are set aside). Less favorable environments such as urban rooftops (e.g., Suttle et al. 2021) have also been more recently evaluated.

For Antarctic collections, knowledge of the melted volume and the snow precipitation rate allows to estimate the micrometeorite flux, typically on the order of 5 kt/a when extrapolated worldwide (e.g., Rojas et al. 2021). This is smaller than the 36 kt/a estimated from the space-based Long Duration Exposure Facility (Zolensky 2021) presumably because of ablation during

Keywords

Extraterrestrial matter · Meteorites · Comets ·
Interplanetary dust particles

atmospheric transit. In their size range (typically around 0.1 mm), micrometeorites can survive (depending on entry velocity and angle) because they are decelerated at high altitudes and thus suffer less heating and ram pressure than their macroscopic counterparts (because of the lower air densities). *Cosmic spherules* have entirely melted during atmospheric transit, but *fine-grained* (compact or fluffy) or *coarse-grained* (or crystalline) micrometeorites may show little evidence of thermal alteration during atmospheric transit; *scoriaceous* micrometeorites show an intermediate degree of melting. Micrometeorites should not be confused with (generally more oxidized) ablation spherules detached from macroscopic meteorites during atmospheric entry (e.g., Van Ginneken et al. 2010).

Most micrometeorites are chondritic and show affinities to carbonaceous chondrites even though the latter represent only 4% of meteorite falls. Indeed, micrometeorites are not biased toward the asteroid main belt between Mars and Jupiter as macroscopic meteorites are, because Poynting-Robertson drag (due to the recoil of impinging solar photons, Doppler-shifted because of orbital motion may incur inward drift from more distant regions (e.g., the Kuiper belt). Individual mineral grain sizes range from micrometers (primarily pyroxenes and olivines) to nanometers, with the predominant size for all phases less than 100 nm. IDPs, which are generally more pristine than micrometeorites fallen on the ground, have been classified into two main groups: Chondritic-Smooth (CS) IDPs, which show phyllosilicates, and Chondritic-Porous (CP) IDPs (corresponding to the “fine-grained fluffy” micrometeorites) which show anhydrous silicates (olivine, pyroxene). Both types of silicate assemblages are nevertheless sometimes observed together. CP IDPs contain submicron Glasses with Embedded Metals and Sulfides (GEMS) which have been entertained to be of presolar origin, although only a minority display anomalous isotopic signatures. Carbonaceous phases present in aggregates are disorganized organic polymers sometimes regarded as the products of a low-temperature organosynthesis in space such as Fischer-Tropsch synthesis (~530 °C). Some Antarctic micrometeorites are

dominated by organic matter and referred to as →UltraCarbonaceous Antarctic MicroMeteorites (UCAMMs).

Based on estimated entry velocities, it has long been believed that many CP IDPs are cometary. They are released into space by comets when they enter the inner solar system. Comets are made of up to 50% water ice that sublimates when they come closer and closer to the Sun, causing an increase in their surface temperature. This massive sublimation of water – along with many other volatile species – causes the injection of cometary dust into interplanetary space. Comets may have formed too late for radiogenic heating to bring about ice melting and aqueous alteration, which is consistent with the lack of hydrated phases in CP IDPs and fine-grained fluffy micrometeorites. Earth-crossing comets are known to produce annual meteor showers (such as the Perseids in mid-August), superimposed on background sporadic meteors. Some IDP collections have targeted such time windows in the hope of sampling the micrometeorite end of the size distribution of these cometary debris.

One space mission – *Stardust* – has collected particles directly from the coma of comet 81P/Wild 2 and has returned them to Earth. It was thus possible to study for the first time bona fide cometary grains from a known parent body with laboratory instruments that have better performances than instruments flown on spacecrafts (such as those which attended the 1986 return of the Halley comet). The Wild 2 grains bear resemblances to carbonaceous chondrites, and with some specific micrometeorites. Little evidence for aqueously altered material has been found, although the high-velocity capture would have preferentially destroyed that material. Since the available amount of micrometeorites greatly outweigh that of *Stardust* returned samples, they of course remain the chief resource for cometary matter research.

Cross-References

- ▶ Comet
- ▶ Fischer-Tropsch-Type Reaction
- ▶ Kuiper Belt

- [Meteorites](#)
- [Stardust Mission](#)
- [Ultra-carbonaceous Antarctic Micrometeorites](#)

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Micronutrients

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Trace elements](#)

Definition

Micronutrients are elements, in general metals or metalloids, required in small amounts for cell growth. Micronutrients generally play a critical role as components of specific enzymatic activities. Not every micronutrient is required by all cells. The best known micronutrients are the following: chromium, cobalt, copper, manganese, molybdenum, nickel, selenium, tungsten, vanadium, zinc, and boron. For instance, boron is an inducer of quorum sensing; copper is required for photosynthesis or the activity of the enzyme cytochrome c oxidase and some superoxide dismutases; manganese is present in certain superoxide dismutases and in oxygenic photosynthetic systems; nickel can be found in most hydrogenases and in urease; selenium is present in formate dehydrogenases and in the amino acid selenocysteine; and zinc can be found associated to ► [RNA](#) and ► [DNA](#) polymerases and many DNA-binding proteins.

Cross-References

► [Cofactor](#)

Microorganism

José Luis Sanz
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Germ](#); [Microbe](#)

Definition

Etymologically, microorganisms are small organisms whose size is too small to be observed by the naked eye. The resolution of the human eye is 0.2 mm, and this establishes 1 mm as an artificial limit

for the maximum size of microorganisms. Taxonomically, “microorganism” lacks a precise meaning, and the term includes prokaryotes (► [Bacteria](#) and ► [Archaea](#)) and eukaryotes (protists, microscopic algae, and fungi), which are all unicellular or lacking true tissues. Exceptionally, ► [virus](#) should be included in the definition of “microorganisms,” even though they lack cellular arrangement. Microbiology is the area of biological sciences that studies microorganisms. Prokaryotes are the main focus of study in Microbiology. All are unicellular and lack a nucleus (pro-karion); their response to oxygen is very diverse; they can be auto- or heterotrophic and they employ the entire range of energy-obtaining systems found in living beings: anaerobic or aerobic respiration, ► [fermentation](#), chemolithotrophism, and oxygenic or anoxygenic photosynthesis. Phylogenetically they are divided into two Domains: *Archaea* and *Bacteria*.

Cross-References

- [Anaerobe](#)
- [Bacteria](#)
- [Eukarya](#)
- [Virus](#)

Microorganisms on Board the International Space Station

- [Microbiome of the International Space Station](#)

Microsome

- [Ribosome](#)

Microtektite

- [Spherules](#)

Mid-Ocean Ridge

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Acronyms (Optional)

MOR

Definition

A midocean ridge is a submarine mountain range with a valley (rift) at its center. It corresponds to the divergent boundary between two tectonic plates (divergent plate boundary). Here the Earth’s crust is spreading, forming new ocean floor that gradually moves away from the ridge at a speed between 1 and 10 cm per year. Beneath the ridge, rising mantle material partially melts in response to reducing pressure. Produced ► [magma](#) is collected in a magmatic chamber a few kilometers below the seafloor. Much of the magma eventually freezes in place forming the bulk of the new ► [oceanic crust](#) composed of MOR ► [basalts](#) (or MORBs), ► [gabbros](#), and residual ultramafic rocks (harzburgite, dunite). Seawater circulates actively, reacting with the volcanic rock, dissolving out metals, and depositing them around seafloor high-temperature springs (black and white smokers). Midocean ridges are the main source of acidity for the ocean. Fractures filled with heated water act as incubators for microbes that live in some of the harshest conditions ever discovered to support life. Conditions typical at MOR have been often depicted as one of the possible environments where life flourished on the Earth during the ► [Hadean](#).

Cross-References

- [Basalt](#)

- [Black Smoker](#)
- [Black Smoker, Organic Chemistry](#)
- [Extremophiles](#)
- [Gabbro](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [MORB](#)
- [Oceanic Crust](#)
- [Plate Tectonics](#)
- [White Smoker](#)

Mid-Ocean Ridge Basalt

- [MORB](#)

Mie Scattering

Emmanuel Marcq
LATMOS/IPSL, UVSQ Université Paris-Saclay,
Sorbonne Université, CNRS, Guyancourt, France

Keywords

Scattering: Elastic · Far field · Polarizing

Synonyms

[Lorenz-Mie-Debye scattering](#); [Lorenz-Mie-Debye solution](#); [Mie solution](#)

Definition

Solution to the problem of radiation scattering by a homogeneous dielectric sphere. It yields a realistic model of scattering by spherical (e.g., liquid) droplets found in some atmospheric clouds, as well as a convenient first-order approximation for nonspherical scatterers also found in planetary clouds and/or hazes, bridging the gap between the small scatterer approximation (Rayleigh scattering) and large scatter approximation (geometric optics). Compared to Rayleigh scattering, Mie

scattering is weakly wavelength dependent and weakly polarizing.

Overview

Hypotheses

Mie scattering (more properly known as *Lorenz-Mie-Debye theory of light scattering*) relies on the following assumptions:

- The scattering particle is a homogeneous, dielectric sphere of radius r .
- Incident radiation is a monochromatic plane wave of wavelength λ .
- Only *far field* solutions are considered (terms vanishing faster than d^{-2} are discarded).

August Mie, based on previous work by Lorenz and others, showed (Mie [1908](#)) that the formal solution for the scattered electromagnetic could be expressed as an infinite series depending only on:

- The *size parameter* x defined as $x = \frac{2\pi r}{\lambda}$
- The scattering angle Θ , due to the axisymmetry of the problem
- The complex refractive index $m = m_r + i \cdot m_i$ of the dielectric sphere (relative to the surrounding medium)

The exact expression and mathematical derivation are highly technical and can be found in several radiative transfer textbooks (Liou [2002](#)). They are beyond the scope of this short overview.

Limits

Assuming $m_i = 0$ and keeping the first order of the Taylor expansion with respect to x (which is valid for small particles $r \ll \lambda$) yields back all results from the ► [“Rayleigh scattering”](#) model (see linked entry). Mie scattering can therefore be thought as one possible way to generalize Rayleigh scattering for arbitrary scatterer sizes and imaginary refractive index.

The other limit $x \gg 1$ yields back the results from *geometrical optics* (raytracing multiple reflections and refractions found in, e.g., rainbows).

Extinction

Extinction Efficiency

Defining the *extinction efficiency* coefficient as $Q_{\text{ext}} = \sigma_{\text{ext}}/\pi r^2$ (i.e., the ratio between the extinction and geometrical cross sections), Mie theory yields the values of Q_{ext} plotted in Fig. 1.

Several features are especially noteworthy:

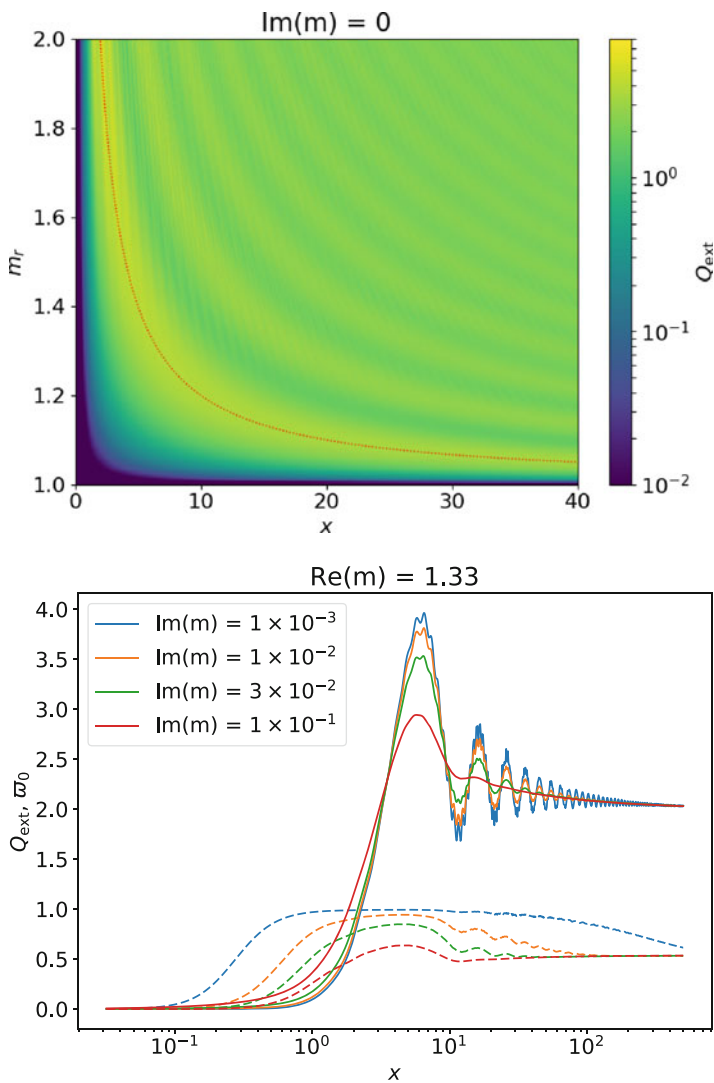
- The maximal value of Q_{ext} is reached for $x \approx \frac{2}{m_r - 1}$, and can reach values well above unity. In other words, and for usual values of m_r , **Mie extinction is most efficient when the**

radius of the particles is similar to the incident wavelength.

- The Rayleigh limit ($x \ll 1$) yields the familiar $Q_{\text{ext}} \propto \lambda^{-4}$ dependency. For larger values of x , this slope disappears, resulting in a more or less “grey” scattering as opposed to the typical “blue” prevalent in Rayleigh regime.
- The geometrical optics limit ($x \gg 1$) yields $Q_{\text{ext}} \rightarrow 2$, which seems counterintuitive. This is because, as previously mentioned, Mie solution is a far field solution, so that the angular size of the scattering particle is kept small relative to the observer. Therefore, diffraction

Mie Scattering,

Fig. 1 Left: extinction efficiency vs. size parameter and real refractive index according to Mie theory. The dotted red line follows $r = \frac{\lambda}{\pi(m_r - 1)}$. Right: extinction efficiency (solid) and single scattering albedo (dashed) vs. size parameter for several imaginary refractive indices



cannot be neglected, and results in doubling the purely geometrical cross section.

- Increasing imaginary refractive index smoothes the $Q_{\text{ext}} = f(x)$ function, since higher-order interferences are suppressed with increasing absorption in the dielectric medium.

Finally, for realistic size distributions of scattering particles, the convolution of the interference pattern by the size distribution results in smoothed variations of the Mie parameters (Q_{ext} , ϖ_0 , phase function, etc.). Actually, size distributions sharing a given modal radius and variance yield very similar Mie computations, the influence of higher-order size distribution moments becoming negligible.

Single Scattering Albedo

Without any absorption within the dielectric sphere ($m_i = 0$), Mie theory yields $\varpi_0 = 1$ as expected. As can be seen in Fig. 1, increasing m_i causes absorption, and therefore $\varpi_0 < 1$ in this case. Actually, $m_i > 0$ yields $\varpi_0 \rightarrow 1/2$ for $x \gg 1$: in the geometrical optics limit, the particle acts as an absorber over its geometrical cross section, leaving only the diffracted component. Also, $\varpi_0 \rightarrow 0$ for $x \ll 1$ provided $m_i > 0$.

Phase Function

As can be seen in Fig. 2, the phase function behavior is highly dependent on the size parameter. For small values of x , Rayleigh phase function is recovered with an asymmetry parameter $g = 0$ (refer to ► “Radiative Transfer” entry for a definition of asymmetry parameter g), then g increases with increasing x , with the appearance of a strong forward scattering peak (near $\Theta = 0^\circ$) as well as increasingly complex interference patterns. In the geometrical optics limit, these interference patterns yield successive rainbow orders (single or multiple refraction/reflection of incident rays within the spherical droplet).

Polarization

Mie scattering, like Rayleigh scattering, can induce linear polarization of the scattered radiation, as can be seen in Fig. 2. Here also, $x \ll 1$ yields back the familiar Rayleigh polarization

pattern ($\approx 100\%$ for $\Theta = 90^\circ$), whereas more complex, interferential patterns in polarization appear at larger values of x . Especially, the negatively polarized backscattering peak centered on $\Theta > 150^\circ$ and $x > 2.5$ is known as the *glory* phenomenon.

Finally, one should note that multiple scattering tends to blur and reduce polarization in the scattered radiation, due to the uncorrelated random geometries of successive scattering events.

Applications in Planetary Atmospheres

Although the Mie solution was discovered in the early twentieth century, using it in practice was only possible once computers allowed for a summation of a large enough number of terms among the infinite series. Moreover, since the angular dependency of the terms is already expressed by Legendre polynomials, it is especially suitable for use in a discrete ordinate radiative transfer model. A well-known Fortran implementation of Mie solution is due to Bohren and Huffman (1983).

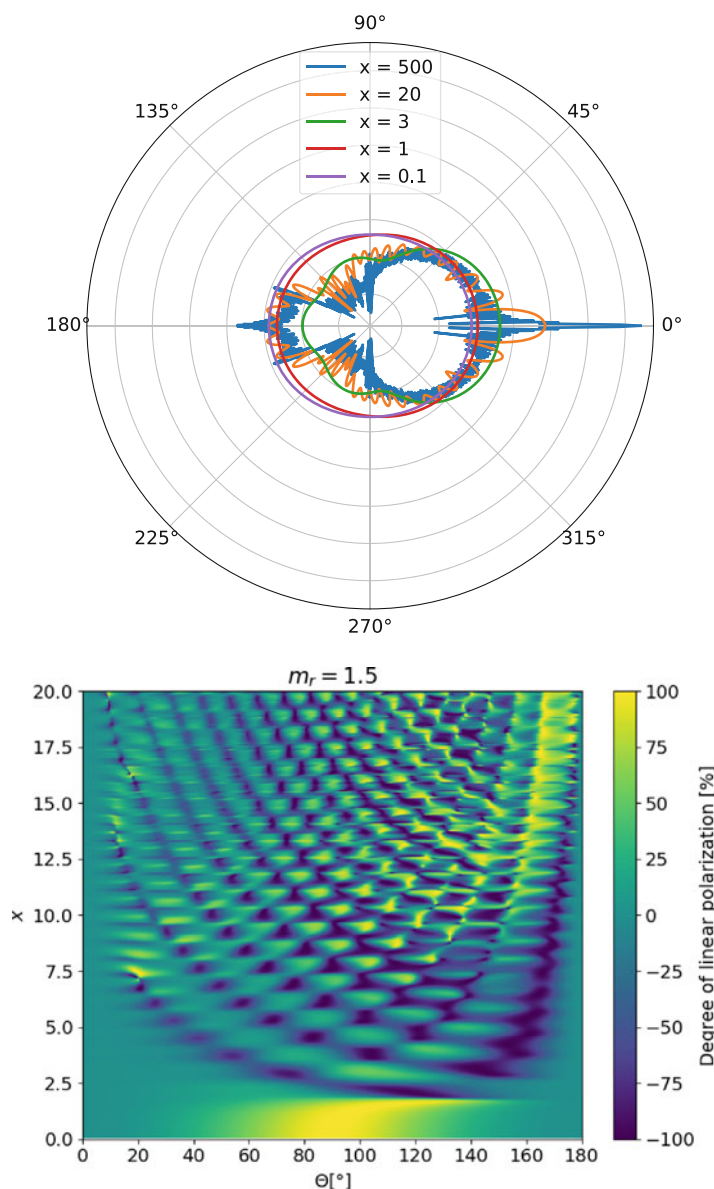
In Solar System

Spectropolarimetry is an especially valuable tool to investigate the scattering properties of a planetary atmosphere, since it allows for the exploration of a larger parameter space (Θ and x , thanks to varying wavelength), as well as accessing both intensity and (at least) the linear degree of polarization. Comparison of these observations with Mie theory then leads to useful constraints on both scatterers size distribution and refractive index (and therefore composition). Taking polarization into account (as opposed to the only scalar intensity) leads to an increased sensitivity to the microphysical properties of the scattering particles, since polarization depends mainly on the first few scattering orders.

As an illustration, a famous successful application of Mie theory, Hansen and Hovenier (1974) was the identification of the clouds of Venus as primarily composed of $1\text{ }\mu\text{m}$ liquid droplets of a highly acidic $\text{H}_2\text{SO}_4\text{--H}_2\text{O}$ solution ($>75\%$ H_2SO_4). Similar ground-based studies of the scattering phase function of outer planets are hampered by the small variation range of Θ as seen from Earth.

Mie Scattering,

Fig. 2 Left: logarithmic polar plots of Mie phase function for some size parameter values, $m = 1.5$ and unpolarized incident beam; right: degree of linear polarization with respect to scattering angle and size parameter for an unpolarized incident beam



M

For Exoplanetary Atmospheres

In transit spectroscopy, Mie scattering manifests itself as a more-or-less spectrally uniform transit depth “floor” in cloudy atmospheres. It is especially noticeable at larger wavelengths (near IR onwards), since Rayleigh scattering by the gaseous atmosphere tends to dominate at smaller wavelengths.

In the near future, (spectro) polarimetry could be a valuable tool for detecting highly scattering exoplanetary atmospheres in the Rayleigh-Mie

regime, since the scattered component would exhibit periodic variations of its polarization as a function of orbital phase angle, whereas the stellar component would be only weakly polarized.

Limitations

Mie scattering is a powerful tool for computing light scattering by spherical particles, but not all aerosols match this assumption: ice crystals, mineral dust, and photochemical hazes are sometimes far from spherical. In such a case, other, more

sophisticated calculation methods should be used for a quantitative analysis (*T*-matrix, discrete dipole approximation, finite elements, etc.), although Mie theory may still be used as a convenient, first-order approximation to derive, for example, the typical size of scattering particles.

Cross-References

- [Atmospheric Retrieval for Exoplanets](#)
- [Greenhouse Effect](#)
- [Radiative Transfer \(Atmospheres\)](#)
- [Rayleigh Scattering](#)

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Mie Solution

- [Mie Scattering](#)

Mildly Reducing Atmosphere

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

A mildly reducing atmosphere is an atmosphere containing small but significant amounts of

reduced gases, for example, H₂, CH₄, NH₃, H₂S, or CO, and not containing a counterbalancing excess of oxidized species such as O₂. Many believe that the prebiotic Earth's atmosphere may have been mildly reducing due to mantle outgassing prior to the advent of biological oxygenic photosynthesis. In general, reducing atmospheres appear to be more favorable for the abiotic synthesis of organic compounds.

Cross-References

- [Abiotic](#)
- [Chemical Evolution](#)
- [Prebiotic Chemistry](#)

Milky Way

Leticia Carigi
 Instituto de Astronomía, Universidad Nacional
 Autónoma de México, Ciudad de México,
 Mexico

Keywords

Spiral galaxy · Disk · Halo · Bulge

Synonyms

[Our galaxy](#); [The galaxy](#)

Acronyms

MW

Definition

The Milky Way is the galaxy where our Solar System is located. It consists of baryonic matter (stars, gas, and dust) but mainly of dark matter that is gravitationally bound to the baryonic matter.

Overview

The Milky Way (MW) is a spiral galaxy with an approximate mass of $1.3 \times 10^{12} M_{\odot}$, where roughly $10^{11} M_{\odot}$ is baryonic matter ($\sim 6 \times 10^{10}$ in stars and the rest in gas and dust), distributed in three main visible components: disk, bulge, and halo, all of them centered at the nucleus of the MW.

The disk is a flat rotating structure made up of stars and gas and present two main substructures: a thin disk and a thick disk. The thin disk is where the cold gas and dust are located and the new stars form, these new young stars form spiral arms (S shaped) that are bright relative to the disk, and they inspired the name of spiral galaxy. For this disk, the stellar and gas masses are $3.5 \times 10^{10} M_{\odot}$ and $1.2 \times 10^{10} M_{\odot}$, respectively; its maximum radius may be 30 kpc and its height from the galactic plane decreases with the radius, being 300 pc height at the galactocentric radius where the Sun is situated. The Sun is located at 8.2 kpc from the Galactic center and 25 pc height, inside the interior edge of the Orion-Cygnus spiral arm. The vast majority of thin-disk stars are younger than 9 Gyr and metal rich, show iron abundances (Fe/H) larger than 1/4 of the solar value and lower α /Fe ratios, and move in coplanar and circular orbits. The thick disk is more diffuse, thicker, and shorter than the thin disk. Its stellar mass is $6 \times 10^9 M_{\odot}$, the mean height at the solar position is ~ 900 pc, and its length is still unknown. This disk is formed only by stars older than 9 Gyr that move with less organized orbits. The iron abundances are higher than one tenth of the solar one, and for similar thin-disk Fe/H values, stars in the thick disk show higher α /Fe values.

The bulge is a dense quasi-box structure of 1.5 kpc in height contained within a radius of 3 kpc about the center of the MW. Its baryonic mass is $1.5 \times 10^{10} M_{\odot}$ and is made of metal-rich stars older than 11 Gyr with a mean iron abundance one quarter higher than the solar value and α /Fe similar to the thick disk stars. Most of these stars move in box/peanut orbits shaping the bulge.

The halo is a quasi-spherical structure formed by an inner stellar component and an outer

gaseous one. The stellar halo contains several substructures, extends beyond the thick disk to ~ 30 kpc radius, and presents a stellar mass $\sim 1.3 \times 10^9 M_{\odot}$. The halo stars show chaotic orbits in different directions and orientations and are metal poor with ages higher than 10 Gyr, with iron abundances lower than one tenth of the solar value and α /Fe similar to the thick-disk and the thin-disk stars. The gas halo extends farther than the stellar halo and is made of a hot and diffuse gas with an estimated mass of $2.5 \times 10^{10} M_{\odot}$ inside 280 kpc radius.

Inside the thick disk, halo, and bulge, there are globular clusters. These stellar clusters are small groups of high concentration with typical radii and masses of ~ 4 pc and $\sim 5 \times 10^5 M_{\odot}$, respectively. Most of them are formed by old and metal-poor multiple populations that present peculiar chemical abundance patterns.

All the previous baryonic structures are contained inside a $1.2 \times 10^{12} M_{\odot}$ dark matter halo, that is, a spherical hypothetical structure which extends beyond the stellar halo, probably up to ~ 300 kpc. This halo is made of non-baryonic matter whose nature remains unknown and which only interacts with itself and the baryonic matter through gravitation.

Up to date, it is unknown how the MW formed. For the most accepted theories based on mergers of small galaxies at different evolutionary stages, within the cosmological theory of cold dark matter, see →Galactic Archaeology.

Cross-References

- [Chemical Evolution](#)
- [Galaxy](#)
- [Galactic Archaeology](#)
- [Metallicity](#)
- [Solar Neighborhood](#)

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Miller, Stanley

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

History

In 1953, the young chemist, Stanley Miller (1930–2007), published in *Science* a paper entitled “A production of Amino Acids Under Possible Primitive Earth Conditions.” His work was based on Harold Urey’s assumption about the reducing composition of the primitive atmosphere as well as on Oparin’s and Bernal’s previous suggestions.

In an apparatus built to circulate a mixture of CH₄, NH₃, H₂O, and H₂ exposed to electric discharges during 1 week, he noticed the production of amino acids (glycine, α alanine, and β alanine).

Miller’s paper constituted one of the most important events in the history of the researches on the origins of life. Miller’s result found an important audience in the scientific community as well as in the public opinion. His discovery was said to be the first step of the process of origins of life in earth.

Along with Urey, Miller’s was considered as one of the main inventors of prebiotic chemistry. During at least two decades, his work influenced conceptions of prebiotic conditions in which all experiments had to be done, and especially it imposed the idea of the reductive primitive atmosphere, without CO₂. Miller’s career was one of

the most active on the topic of the origins of life during the second part of the twentieth century.

Cross-References

- [Bernal’s Conception of Origins of Life](#)
- [Oparin’s Conception of Origins of Life](#)
- [Urey’s Conception of Origins of Life](#)

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Mimas

Therese Encrenaz

XLESIA, Observatoire de Paris - Section de Meudon, Meudon, France

Definition

Mimas, the innermost mid-sized satellite of ► [Saturn](#), was discovered by William Herschel in 1789. Its distance to Saturn is 185,600 km or only 3 Saturnian radii. The diameter of Mimas is 400 km and its density is 1.14 g/cm³, consistent with a body dominated by water ice. Mimas is heavily cratered; its largest impact crater, named Herschel, has a diameter of 130 km, or about a third of the satellite’s diameter. The perturbations induced by Mimas are believed to be responsible for the clearing of the Cassini division in Saturn’s rings. Mimas was first explored by the Voyager mission in 1980–1981 and later by the ► [Cassini](#) orbiter, which began to monitor the Saturn system in 2005.

Cross-References

- [Planetary Rings](#)
- [Saturn](#)
- [Voyager, Spacecraft](#)

Mineral

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

- [Sedimentary Rock](#)
- [Serpentinization](#)
- [Siderite](#)
- [Silicate](#)
- [Suevite](#)
- [Sulfate Minerals](#)
- [Zircon](#)

Definition

A *mineral* is a naturally occurring solid of inorganic origin, with a definite chemical composition and in most cases an ordered atomic arrangement. Compositions range from pure elements like gold (Au), diamond (C), or native copper (Cu) to simple oxides (SiO_2 – quartz; TiO_2 – rutile) or carbonates (CaCO_3 – calcite) to highly complex silicate minerals (e.g., tectosilicate such as K-bearing feldspar KAlSiO_3). Silicate minerals dominate most parts of the solid Earth, the exception being the core which is composed mainly of Fe-Ni alloy. Most minerals are crystalline, but some, like chalcedony or opal, are amorphous. Assemblages of different minerals compose a rock.

Cross-References

- [Alunite](#)
- [Banded Iron Formation](#)
- [Basalt](#)
- [Evaporite](#)
- [Gabbro](#)
- [Goethite](#)
- [Granite](#)
- [Hematite](#)
- [Igneous Rock](#)
- [Iron Oxyhydroxides](#)
- [Mafic and Felsic](#)
- [Magma](#)
- [Magnetite](#)
- [Mantle](#)
- [Metamorphic Rock](#)
- [Ophiolite](#)
- [Pyrite](#)
- [Quartz](#)
- [Rock](#)

Mineral Self-Assembling Structures

- [Chemical Gardens](#)

Mineral Vesicles

Raffaele Saladino

Department of Ecological and Biological
Sciences, University of Tuscia, Viterbo, Italy

Keywords

Mineral vesicles · Abiotic mineral
precipitation · Heterogeneous catalysis ·
Prebiotic chemistry

Synonyms

[Silica metal oxide vesicles](#)

Definition

Mineral vesicles are self-organized biomimetic structures that form via abiotic mineral precipitation.

History

Mineral vesicles are self-organized biomimetic membranous structures that form in serpentinization-driven silica-rich water via fluid-rock interaction and mineral precipitation (Getenet et al. [2020](#)).

This process is expected to be a common phenomenon on primitive Earth and Earth-like planets characterized by alkaline environments García-Ruiz et al. (2017). In addition, mineral vesicles may resemble the geochemical conditions of Hadean Earth, when alkaline silica-rich oceans evolved from the early atmosphere and hydrosphere (García-Ruiz and Otálora 2015). These vesicles are able to catalyze prebiotic reactions, including the synthesis of molecules of biological relevance from simple chemical precursors such as formamide (Mattia Bizzarri et al. 2018). In this latter case, they act as heterogeneous catalysts more efficient than their “chemical garden” counterparts (Saladino et al. 2016), highlighting the beneficial role of the surface/volume ratio on the control of the overall kinetics of the reaction (Saladino et al. 2019). During the prebiotic reaction, mineral vesical growth and collapse release their molecular content in the bulk of the solution.

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Minimal Autonomy

- [Autopoiesis](#)

Minimal Gene-Set

- [Genome, Minimal](#)

Minimal Metabolism

- [Metabolism](#)

Mini-Neptunes

Nader Haghighipour¹ and Lisa Kaltenegger²

¹Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

²Cornell University, Ithaca, NY, USA

Definition

Mini-Neptune is the suggested term for a diverse class of exoplanets with masses in the upper range of ► [Super-Earths](#) (e.g., 7–10 Earth-masses, see the entry on ► [Super-Earths](#)). Unlike low-mass super-Earths, mini-Neptunes can have more massive and thicker atmospheres, and as a result, a small mean density. An example of a mini-Neptune could be Kepler-11f. With a radius of ~ 2.5 Earth-radii and mass of ~ 2 Earth-masses, this planet has a density of ~ 0.7 g/cc, similar to that of the gas-giant planet, Saturn.

Cross-References

- [Atmosphere, Structure](#)
- [Habitable Planet, Characterization](#)
- [Scale Height](#)
- [Super-Earths](#)

Minor Planet

- ▶ [Asteroid](#)
- ▶ [Small Solar System Body](#)

Miranda

Therese Encrenaz

XLESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Miranda, discovered by Gerard Kuiper in 1948, is the innermost of ▶ [Uranus](#)' five major satellites; it is also the smallest one, with a diameter of 470 km. Its surface mainly consists of water ice. Miranda was explored in 1986 by the Voyager 2 spacecraft whose images revealed a great variety of structures, with heavily cratered terrains but also rift-like canyons, faults, and valleys, showing evidence for an intense tectonic activity in the past history of the satellite. Some features could also result from ▶ [cryovolcanism](#) driven by tidal heating. In the 1980s it was proposed that these structures could have formed due to an early disruption of the object by a collision, followed by an accretion of the fragments in Uranus' orbit.

Cross-References

- ▶ [Cryovolcanism](#)
- ▶ [Giant Planets](#)
- ▶ [Uranus](#)
- ▶ [Voyager, Spacecraft](#)

Mirror Symmetric

- ▶ [Achiral](#)

Mitochondrion

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Mitochondrion is a semi-autonomous organelle occurring in eukaryotic cells. Structurally, it consists of two closed membranous sacs (outer and inner membranes) and a matrix, containing a set of enzymes and a genetic apparatus for the expression of its own mitochondrial genome (mtDNA). The metabolic functions of mitochondria include oxygen ▶ [respiration](#) (at the inner membrane) and the TCA cycle (at the matrix). The mitochondrion is descendant of an ancient alpha-proteobacterium, as showed by extensive phylogenetic analysis of the mtDNA. During eukaryotic evolution, and as a consequence of anaerobic adaptations, mitochondria have originated different organelles as hydrogenosomes and mitosomes.

Cross-References

- ▶ [Citric Acid Cycle](#)
- ▶ [Endosymbiosis](#)
- ▶ [Respiration](#)

Mixed Breccia

- ▶ [Suevite](#)

Mixtite

- ▶ [Diamictite/Diamicton](#)

MKS (Russian Acronym)

- [International Space Station](#)

MMX

- [Martian Moon Exploration](#)

MOA

- [Microlensing Observations in Astrophysics](#)

Modelling Terrestrial Planetary Atmospheres

Robin Wordsworth

School of Engineering and Applied Sciences,
Department of Earth and Planetary Sciences,
Harvard University, Cambridge, MA, USA

Keywords

Fluid dynamics · Radiative transfer · Convection · Clouds · Atmospheric chemistry · Planetary boundary layer · Hydrology · Biosphere · Ocean-atmosphere coupling · Albedo · General circulation model

Definition

Terrestrial planet atmospheric modelling is the process of quantitatively describing the physical and chemical behavior of the atmospheres of planets that are predominantly rocky in composition. It is performed to interpret *in situ*, satellite and telescope observations of Earth, other solar system planets and exoplanets. Model results influence multiple fields of research including geology, biology, and environmental science, as well as spacecraft mission planning.

History

Qualitative attempts to model terrestrial planet atmospheres goes back as least as far as the seventeenth century, when natural philosophers such as Edmund Halley began to build physical theories of the circulation of air in Earth's tropics. Halley's ideas were built upon by George Hadley in the eighteenth century, who first proposed the theory of Earth's trade winds based on conservation of angular momentum that now bears his name. Progress on understanding the atmospheric *greenhouse effect* (the trapping of infrared radiation that maintains Earth's habitability) occurred more slowly, with the first major steps forward made by Joseph Fourier in the nineteenth century.

A modern quantitative understanding of planetary climate and atmospheric chemistry only became possible after the development of quantum mechanics in the late nineteenth and early twentieth century. Experiments by John Tyndall and others demonstrated the infrared absorption features of water, carbon dioxide, and other molecules, but the development of Planck's Law for blackbody radiation and an understanding of quantum spectroscopy made rigorous climate science possible by the early twentieth century. The mid-twentieth century also saw several important developments in atmospheric fluid dynamics that laid the foundation for much modern understanding, including the concepts of potential vorticity, baroclinic and barotropic instability, and Rossby wave propagation. In atmospheric chemistry, early twentieth century experiments by Fabry, Buisson, Dobson, and others indicated the presence of an ozone layer in Earth's atmosphere, and models of its chemistry began to be developed from the 1930s onwards.

Investigation of the atmospheres of terrestrial-type planets beyond Earth started centuries ago, but did not make substantial progress until the advent of the space race in the middle of the twentieth century. Mars' atmospheric properties were studied by astronomers such as Herschel as long ago as the eighteenth century, but quantitative analysis and modelling of its atmosphere began in the 1960s, when the first global circulation models (GCMs) were developed and

photochemical analyses were performed. Venus' high surface temperatures were deduced from a combination of microwave observations by Earth-based telescopes and simplified atmospheric modelling in the early 1960s. Our understanding of Titan's atmosphere grew more slowly, with detailed models of its chemistry and climate emerging in the 1980s following flybys by Pioneer 11 and Voyager 1. Over the last few decades, a combination of data from new missions and advances in numerical techniques have led to numerous advances in modelling. The emergence of the field of exoplanet research has led to huge growth in the area of comparative planetology, and a growing number of modelling studies now focus on understanding terrestrial planets in a generalized way, rather than on simulating individual objects.

Overview

Modeling terrestrial planetary atmospheres requires a diverse array of tools, ranging from very simple to very complex. Because the composition and physical state of atmospheres depends on a host of different processes, incorporation of a wide range of physical, chemical, and biological effects is required in models depending on the problem of interest. Atmospheric modelling informs our understanding of a range of vital problems in planetary science, including anthropogenic global warming on Earth, the CO₂ cycle and atmospheric stability on Mars, the behavior of organic hazes on Titan, and the nature of ancient climates on Earth, Mars, and Venus. Observational constraints remain scarce for terrestrial-type exoplanets, but a combination of modelling and observations is going to vastly increase our knowledge of these objects in the coming decades.

Basic Methodology

The methodologies involved in modelling terrestrial planet atmospheres are highly diverse. The simplest modelling approaches can be purely

analytical, such as when equilibrium temperature is estimated for newly discovered exoplanets. On the other end of the scale, the most complex and numerically intensive approaches involve high-resolution simulations of entire planetary atmospheres in three dimensions (Fig. 1) including fluid dynamics, radiative transfer, atmosphere-ocean coupling, biosphere interactions, and other complex effects. Generally speaking, there is no right or wrong level of model complexity: the choice depends on the problem at hand and the nature of the observational constraints. *Hierarchical* modelling approaches are increasingly common, particularly for problems involving atmospheric fluid dynamics. In a typical hierarchical approach, an observed phenomenon is first investigated using a complex numerical model, and then a range of simpler models is used to replicate the key results as a way to test understanding of the underlying mechanism. Atmospheric modelling methodologies can be conveniently divided up into several categories based on the physics and/or chemistry they incorporate, as described in more detail below.

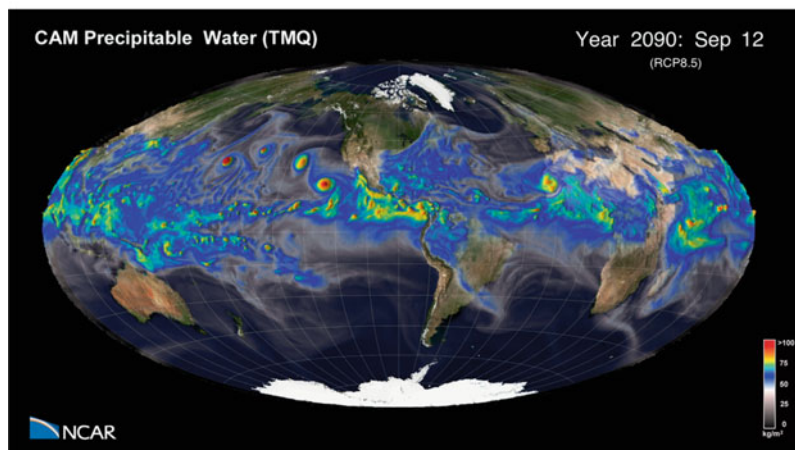
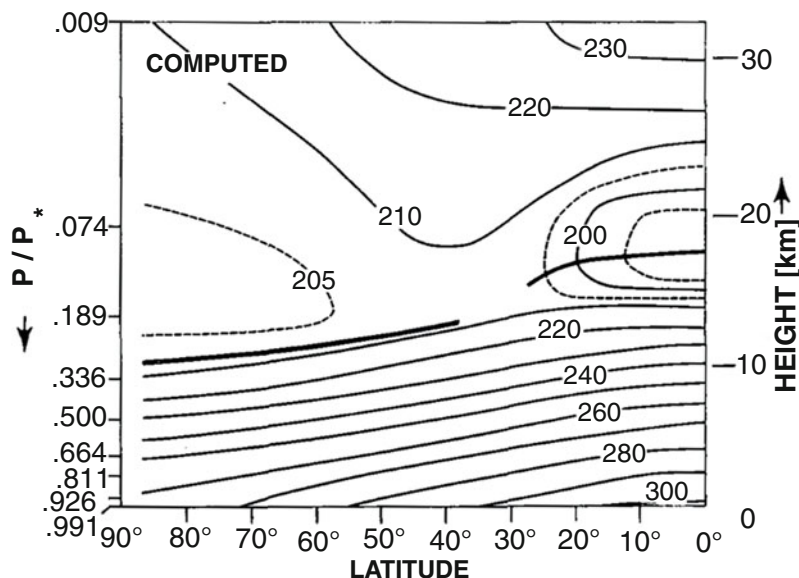
Radiative Transfer

Any planet's atmosphere interacts with electromagnetic radiation from its host star and from internal sources. The shortest wavelength stellar radiation dissociates and ionizes molecules in the upper atmosphere, driving atmospheric chemistry and causing escape of some chemical species to space. Longer wavelength radiation penetrates deeper into the atmosphere, causing warming when it is absorbed. In atmospheres like Earth's that are relatively transparent at visible wavelengths but opaque at longer infrared wavelengths, the trapping of upwelling infrared radiation and reemission higher in the atmosphere gives rise to the greenhouse effect. In some other cases, such as Titan, absorption of solar radiation higher in the atmosphere and subsequent cooling of the surface relative to the clear-sky case causes a so-called *anti-greenhouse effect*.

The most comprehensive and accurate approach to modelling radiative transfer in planetary atmospheres randomly selects individual photons and tracks their motion. This *Monte*

Modelling Terrestrial Planetary Atmospheres,

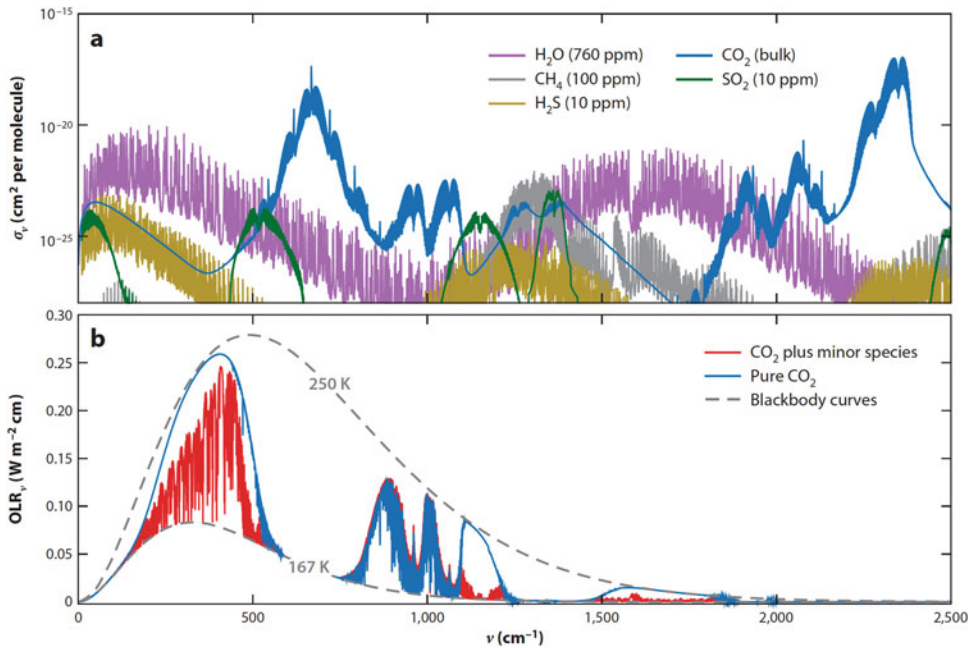
Fig. 1 Left: Output from an early general circulation model (specifically, zonally averaged temperature as a function of latitude and pressure/altitude; Manabe et al. 1965). Right: Output from a modern general circulation model (specifically, precipitable water on a single day in 2090 predicted by the Community Atmosphere Model, from the NASA Visible Earth Project)



Carlo method is reliable and in principle highly accurate, but it is too computationally costly to be used in climate simulations or in most retrievals of observational data. More commonly, the full radiative transfer equations are approximated to allow propagation in a limited number of directions only. In climate studies, the most common approach of all is a two-stream calculation, where the only permitted radiation directions are upward and downward.

The infrared absorption spectra of typical greenhouse gases such as CO_2 and H_2O are extremely complex, with large numbers of overlapping spectral lines due to coupled vibrational and rotational quantum transitions. Large spectral

databases such as HITRAN exist to permit the calculation of atmospheric absorption spectra (Fig. 2) at high resolution as a function of composition, pressure, and temperature. Once these spectra have been calculated, they can either be used directly in radiative transfer calculations (the “line-by-line” approach) or to calculate heating rates indirectly via approximations such as the correlated- k approach. An even simpler approach that is particularly useful for idealized simulations is to assume uniform atmospheric absorption at all thermal wavelengths (the “gray gas” model). Whatever the approximation, any radiative calculation is only as good as the absorption data it uses, and in recent years, much effort has been



Modelling Terrestrial Planetary Atmospheres, Fig. 2 Top: Infrared absorption cross-sections for a range of plausible greenhouse gases in an early martian atmosphere with an assumed 1-bar CO₂ atmosphere.

Bottom: Outgoing longwave radiation for a pure CO₂ atmosphere and for the same atmospheric composition as above, as simulated by a high spectral resolution radiative-convective climate model. (From Wordsworth (2016))

M

expended to improve the quality of absorption data for a large number of species over wide ranges of pressure and temperature appropriate to both solar system objects and exoplanets.

Atmospheric aerosols (e.g., condensate clouds, dust, and hazes) can have a profound effect on atmospheric radiative transfer and must also be taken into account in modelling calculations. Aerosols are particularly problematic for exoplanets, where frequently even their composition is unknown. For liquid aerosol particles of uniform composition and known refractive index, Mie theory can be used to calculate scattering and absorption properties. For more complex non-spherical and/or heterogeneous composition particles (e.g., water ice crystals on Earth or fractal tholin hazes on Titan), more complex modelling techniques are needed and the uncertainty in aerosol properties remains a challenge.

Planetary-Scale Fluid Dynamics

The large-scale motion of a terrestrial planet's atmosphere is ultimately driven by heating from

stellar radiation absorbed either at the surface or sometimes in the atmosphere itself. Aspects of this motion are usually highly nonlinear and chaotic, leading to sensitive dependence on initial conditions (the “butterfly effect”) that renders accurate long-term prediction of detailed behavior impossible. Nonetheless, large-scale flow features such as the Hadley circulation are generally much more robust and predictable. Often, planetary circulation modelling is performed in three dimensions using a computer program that solves an appropriate set of equations for conservation of fluid mass, momentum, and energy subject to source and sink terms and boundary conditions at the planet's surface and “top of the atmosphere,” which is usually defined as a fixed minimum pressure level. A wide variety of numerical techniques are used solve these equations, including finite difference, finite volume, and spectral approaches. Most modern codes are now adapted for parallelized computation, allowing much higher model spatial resolution than was possible in the past.

Simplified models that solve fluid equations in a few shallow layers only or for some restricted portion of the flow (e.g., the longitudinally averaged winds) also exist and are frequently used when deep understanding of the driving processes is sought after. Various diagnostic techniques such as eddy-mean flow decomposition, instability analysis, and spectral decomposition are also commonly used to analyze the nature of the flow in different regimes. Because terrestrial planetary atmospheres usually obey the ideal gas law fairly closely, treatment of dry thermodynamics is generally simpler than in gas giant simulations or planetary interiors (although exceptions exist, such as in the deepest portions of the Venusian atmosphere).

Volatile Cycles

The inclusion of radiative transfer and fluid dynamics processes in atmospheric models allows predictions of seasonal and regional changes in climate once a planet's orbit, rotation rate, and key surface properties (e.g., topography, visible reflectivity, thermal inertia) are taken into account. For a planet like Earth, however, these predictions will not be accurate unless another major set of processes is taken into account: the water cycle. More broadly, other solar system bodies have different condensable substances that undergo volatile cycling, such as CO₂ and H₂O on Mars, CH₄ on Titan, H₂SO₄ on Venus, and N₂ on Pluto. In all cases, the presence of a condensable species adds considerable complexity to atmospheric behavior.

Modern general circulation models treat condensables as tracer species that are actively tracked in time and space and allowed to evolve according to advective transport processes, turbulent sub-grid-scale “diffusion” and thermodynamic phase changes. Moist convection, the process by which condensables like H₂O are transported vertically in a planet's atmosphere, is a notoriously complex process that remains a significant source of uncertainty in climate models. Typically, the spatial resolution of global climate models is too low to resolve moist convection directly, so parameterizations must be used, although so-called “super-parameterized” models that replace the standard parameterizations with sub-

grid-scale 2D cloud-resolving models are becoming more widely used (e.g., Khairoutdinov and Randall 2001).

Beyond the complexity of moist convection itself, another major source of uncertainty arises from the *microphysics* of volatile condensation and evaporation processes (i.e., physics which occurs <1 mm scale). The size distribution of particles in a cloud is of fundamental importance for evaluating its lifetime, its radiative properties (which impacts climate), and the rate at which it produces precipitation (rain or snow). However, the way in which cloud particle size distributions vary with planet type, atmospheric composition, and other factors is still poorly understood. It is still common for general circulation models to assume a single fixed average cloud particle size, even in exoplanet and solar system paleoclimate simulations. On present-day Earth, much of the uncertainty in future climate change predictions comes from cloud behavior (Boucher et al. 2013).

Planetary Boundary Layer Modeling and Mesoscale Simulations

As was previously noted, planetary atmospheres are typically highly turbulent, and global models of the atmospheric circulation are never capable of resolving this turbulence down to the smallest scales. This is particularly important in the lowest portions of the atmosphere, the *planetary boundary layer* (PBL), where mechanical drag, convection and fluxes of volatiles, trace chemical species, and aerosols like dust connect the surface to the atmosphere. Planetary boundary layers are complicated but the theory of how they behave over a wide range of conditions is now well established. The behavior of Earth's planetary boundary layer is particularly well-constrained by observations, but PBL data also exists for other planets, such as Mars. Planetary boundary layer parameterizations in global climate models are based on turbulence similarity theories and closure schemes of varying complexity (e.g., Mellor and Yamada 1982). They are generally regarded as fairly reliable, although under certain conditions, such as the strong thermal inversions that occur in polar night or on the dark side of

tidally locked exoplanets, difficulties still occur (Joshi et al. 2020).

Mesoscale models, as the name implies, are models of the atmosphere that are localized to a domain that is intermediate in scale between the entire planet and the smallest scales. The definition varies, but a typical mesoscale model for Earth might cover a domain of 500×500 km in the horizontal and 15 km in the vertical. Mesoscale models sacrifice the ability to provide a global view on annual to decadal timescales, but in return they provide a wealth of information on turbulent and convective processes, which they are able to resolve to a far greater extent than global models. Mesoscale climate models are frequently used on Earth for weather prediction and fundamental research, and have also been applied to Mars and Titan (e.g., Spiga and Forget 2009). Their use as unique tools to enable insights into atmospheric processes that cannot be captured by global models is likely to grow considerably in the future.

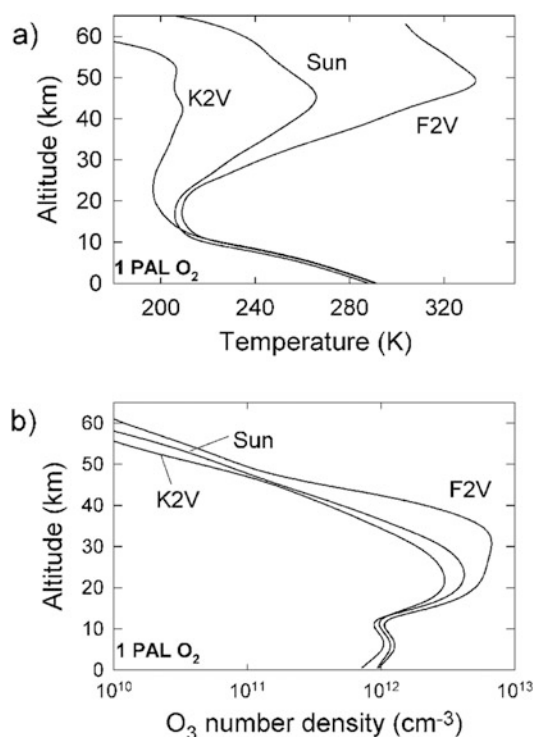
Atmospheric Chemistry

The chemistry of terrestrial planet atmospheres is both fascinating in its own right and of immense importance to astrobiology, because it determines the robustness of atmospheric *biosignatures*. For most terrestrial planets, atmospheric chemistry is heavily influenced or dominated by photochemical processes, i.e., the photodissociation of molecules in the upper atmosphere by ultraviolet stellar photons. Classic examples of photochemical processes include the production of ozone on the modern Earth, the CO_2 photodissociation cycle on Mars, and the formation and evolution of organic hazes in the atmosphere of Titan. Modeling these processes requires accurate data on the ultraviolet cross-sections of all key molecules present in the upper atmosphere and kinetic data on the most important reactions between chemical species and radicals. Obtaining and validating this data is a continuing challenge, particularly in an exoplanet context, and species as well-known as H_2O continue to produce surprises (Ranjan et al. 2020).

The governing equations for atmospheric chemistry are frequently stiff in the numerical

sense, which means that solvers for these systems must be chosen carefully. The simplest atmospheric chemistry models are zero-dimensional (the box model approach), although one-dimensional models that allow for vertical transport of species are more common (Fig. 3; Nair et al. 1994; Segura et al. 2003). While computationally expensive, three-dimensional atmospheric chemistry modeling can also be very informative when the fidelity of observations justifies it. In this case, every long-lived chemical species must be treated as a tracer in the model, subject to advection by winds and chemical reactions at every grid point and time step.

Additional challenges arise when heterogeneous chemical processes are important, i.e., processes that couple aerosol phase (liquid or solid) chemistry with the gas phase. Such processes have been studied fairly intensively on Earth, but



Modelling Terrestrial Planetary Atmospheres, Fig. 3 Simulated atmospheric temperature (top) and ozone number density (bottom) as a function of star type for an Earth-like exoplanet, as simulated by a coupled radiative-convective/photochemical model. (Reproduced from Segura et al. (2003))

our understanding of their importance is much less well developed for other solar system planets (not to mention for exoplanets). Laboratory experiments play a particularly important role in determining production pathways and mechanisms in this context, although many uncertainties remain, particularly for the complex organic haze formation in Titan's atmosphere (Trainer et al. 2006; Hörst et al. 2012).

Upper Atmospheres

The highest regions of planetary atmospheres are of inherent interest because of the unique physics and chemistry that occurs there. They are also particularly important to long-term atmospheric evolution, because their behavior determines the rate at which the atmosphere escapes to space. Upper atmosphere models present special challenges because radiative transfer at these altitudes is often far from local thermal equilibrium, which necessitates more complex or more approximate methods to calculate heating rates. Other effects such as thermal conduction, gravity wave propagation and breaking, and ionization of the gas and interaction with the planet's magnetic field (if it has one) are also frequently important. Finally, rapidly escaping atmospheres may cease to be in hydrostatic equilibrium, which requires fluid dynamical solvers that are quite different from the type typically used to simulate the lower atmosphere. Upper atmosphere models of varying complexity have now been developed for most solar system planets and moons. Upper atmosphere modeling is also frequently performed for exoplanets to assess long-term evolution, although the scarcity of direct observational constraints for exoplanet upper-atmosphere models remains a major issue.

Biosphere-Atmosphere Couplings

A particularly interesting complication in modeling Earth's atmosphere occurs due to interactions with the biosphere. Many types of biosphere-atmosphere couplings exist, but on human timescales (years to centuries), links between vegetation and hydrology, the carbon cycle and human activities are particularly important. On geological timescales, the biosphere

strongly influences atmospheric composition via the role of photosynthesis in O₂ release and carbon burial, the carbon and nitrogen cycles, and other effects. The final and most vexing example of biosphere-atmosphere coupling is the recent influence of human industrial activity on the atmosphere, via emission of localized air pollution in cities, trace species like CFCs that alter stratospheric chemistry, and of course the long-term emissions of carbon dioxide that are currently dramatically changing our planet's climate.

Modeling of Formation, Long-Term Evolution, and Extreme Events

Techniques for modeling the formation of planetary atmospheres and their long-term evolution are usually quite distinct from the methods used to simulate present-day atmospheres. Models that span millions to billions of years of evolution generally do not have the luxury of resolving atmospheric circulation in three dimensions, so it is typical to describe the atmosphere as a vertical column or even a zero-dimensional box. Much of the challenge in producing accurate long-term atmospheric evolution models lies in accurately characterizing source and sink terms for atmospheric gases. A key source for atmospheric gases throughout a planet's history is volcanic eruptions, while a key sink is escape of the atmosphere to space. Two other processes, crustal alteration and bolide impacts, are also extremely important but can act as either sources or sinks depending on the context and gas species of interest. Data to constrain these processes comes from a variety of sources, with laboratory experiments, field observations, and geodynamic models all playing important roles. Extrapolation of processes outside of the regimes in which they are observed is frequently necessary. Stochastic (i.e., nondeterministic) modeling of atmospheric evolution is still relatively undeveloped, particularly for planets other than Earth, but is likely to grow in importance in the future.

Finally, in terms of their effect on climate and ecology, some of the most important events in atmospheric evolution are extremely short in duration and involve abrupt deviations from the mean state. Two major examples of this are

meteorite impacts and large volcanic eruptions. Both classes of event are believed to cause major short-term perturbations to the state of the atmosphere, which can have geological effects or (on inhabited planets) significantly disrupt ecosystems, giving rise to mass extinction events. Classic examples include the Chicxulub impact that triggered the demise of the non-avian dinosaurs 66 Mya, the Siberian Traps eruptions 252 Mya believed to have caused the end-Permian mass extinction, and the meteorite impacts on early Mars that have been linked to surface aqueous activity. Modeling atmosphere and climate during such events presents a challenge because of the range of physical processes involved, but some studies have tackled this difficult problem (e.g., Pierazzo et al. 2003; Steakley et al. 2019).

Key Research Findings

Terrestrial planet atmospheric modelling is such a wide research area that a comprehensive summary of findings is not possible in a single encyclopedia entry. Here, a non-exhaustive selection of some research highlights from this field is presented.

Anthropogenic Climate Change

Without any doubt, the most fundamental contribution of planetary atmosphere modelling so far in terms of societal importance has been the revelation that human emission of carbon dioxide to the atmosphere from fossil fuel burning will cause dangerous increases in Earth's global mean temperature in the future. Research since the 1900s into anthropogenic climate change has revealed with ever-increasing confidence that increases in the CO₂ abundance in Earth's atmosphere from the preindustrial level of around 280 ppmv are leading to substantial increases in surface temperature. Based on the latest ensemble results from global climate models, increases of between about 1.8 and 4 K by the end of the twenty-first century are currently predicted. The impacts of such a change on the biosphere and on human society are likely to be severe. Besides predicting changes in global mean temperature, modern climate models predict changes in climate and weather

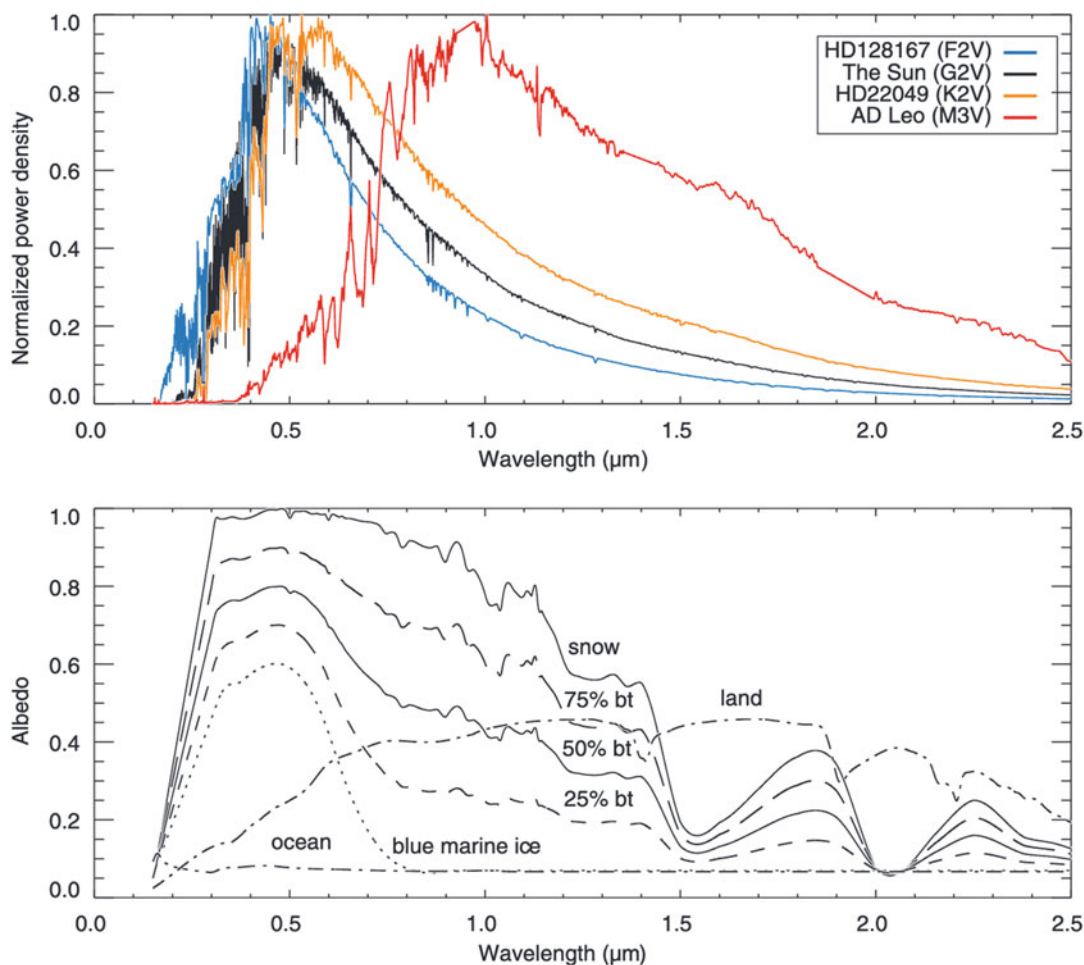
extremes, precipitation patterns, and increasingly, the coupled effects of climate change on atmospheric chemistry, hydrology, ecosystems, and other aspects of the Earth system. Much of the remaining uncertainty in Earth climate modelling projections derives from our poor understanding of cloud feedbacks (Boucher et al. 2013).

Earth Climate History

The field of planetary climate modelling has been strongly influenced by the study of Earth's history and in some senses has grown up in parallel to it. An excellent example of this interaction is the Snowball Earth phenomenon. First hypothesized as a transition that could occur due to the ice-albedo feedback by Mikhail Budyko in 1969, Snowball Earth was initially considered to be of theoretical interest only, on the basis that if it had ever occurred, Earth would have remained forever trapped in a Snowball state. This view changed starting in 1981, when it was hypothesized that arrest of the carbonate-silicate weathering feedback in a Snowball event would lead to buildup of CO₂ in the atmosphere until the ice melted, providing an exit mechanism (Walker et al. 1981). Then, in the 1990s, mounting evidence convinced researchers that Snowball Earth episodes had in fact happened in Earth's history at least twice, in the Neoproterozoic era between 717 and 634 Ma (Kirschvink 1992; Hoffman et al. 1998). Since this time, our understanding of Snowball Earth conditions has been greatly enhanced by climate theory and modelling (Pierrehumbert et al. 2011). Snowball Earth modelling has been applied to exoplanets, where effects such as differing stellar spectrum have been investigated (Fig. 4; Joshi and Haberle 2012; Shields et al. 2013). Climate and atmospheric modelling have also been employed to elucidate many other events in Earth history, such as the Pleistocene ice ages, the rise of oxygen in the Proterozoic, and even the origin of life itself in the Hadean.

Mars Volatile Cycling, CO₂ Chemistry, and Early Evolution

One of the early successes of planetary atmospheric modelling in the space age was the deduction of the processes that govern Mars'



Modelling Terrestrial Planetary Atmospheres,
Fig. 4 Plot of the spectral energy distributions for a range of star types (top) and albedos of various surface materials for Earth-like exoplanets. Total integrated planetary albedo is a function of both the surface properties and

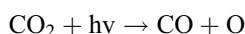
the star type, which leads to predicted differences in ice-albedo feedbacks and other effects for planets orbiting M-class (red dwarf) stars. (Reproduced from Shields et al. (2013))

atmospheric stability. Mars has a ~ 600 Pa atmosphere that is in quasi-steady equilibrium with surface deposits of CO_2 at the poles. Seasonal changes in insolation cause sublimation and recondensation of CO_2 ice, which leads to strong variations in atmospheric pressure. The basic features of this process were worked out in the 1960s via a combination of observations and numerical models. In the modern era, Mars climate research has focused on understanding the dust cycle on a range of spatial and temporal scales, and the water cycle, including the effect of water ice clouds on climate. Most recently, a combination of

modelling and observations has revealed strong links between the dust cycle and H_2O lofting to the high atmosphere, which enhances hydrogen escape and hence oxidation of the planet over geologic timescales (Heavens et al. 2018). Mars' early climate is also a subject of intense study because of the abundant geological evidence for liquid water in the past. Much progress has been made recently in one- and three-dimensional modelling of the early climate, although challenges remain (Wordsworth 2016).

Many insights into the photochemistry of the martian atmosphere have also been gained from

modelling. Indeed, breakthroughs in understanding of martian photochemistry preceded many developments in atmospheric chemistry on Earth. A key early question in martian photochemistry was why the atmosphere is CO₂-dominated when the photoreaction



efficiently destroys carbon dioxide, and recombination of CO and O (or O₂) is kinetically inhibited. The answer, which involves the catalytic effect of the OH radical, was first proposed in the early 1970s (McElroy and Donahue 1972). Modern models of Mars photochemistry are now able to accurately determine both bulk composition and spatial and temporal variations in key species. Challenges remain in reconciling models with observations of gases such as methane, although recent orbital observations suggest the disagreement between models and observations may be less significant than believed previously (Korablev et al. 2019).

Venus Climate and Sulfur Cycle

Early attempts to understand Venus' atmosphere and surface conditions struggled with the permanent haze layer present in the planet's upper atmosphere (a problem that is now recurring with exoplanet observations in the modern era). The surface conditions on Venus were first resolved by ground-based microwave observations, which when combined with basic reasoning and simple atmospheric models were shown to indicate high temperatures incompatible with surface liquid water (Sagan, 1961). Modern climate models are able to explain Venusian surface temperatures with fairly high accuracy, although uncertainties regarding the collision-induced absorption effect of CO₂ and the radiative role of sulfate hazes remain.

In terms of atmospheric chemistry, Venus represents a striking example of how differently a relatively familiar process on Earth (sulfate aerosol formation) can behave on a planet with similar mass but different atmospheric composition. On Earth, optically thick stratospheric H₂SO₄ hazes appear transiently in the aftermath of large

volcanic eruptions, but are not observed to last longer than a few months to a year. On Venus, in contrast, the haze layer is permanent because haze particles undergo thermolysis as they descend into the lower portions of the atmosphere. Atmospheric chemical models can now reproduce many aspects of Venusian chemistry, although several important uncertainties remain. Insights into the extreme differences in the sulfur cycle on Earth and Venus are now being used to make theoretical predictions for terrestrial exoplanets on the basis of their surface liquid water inventories (Fig. 5; Loftus et al. 2019).

Titan and the Outer Solar System

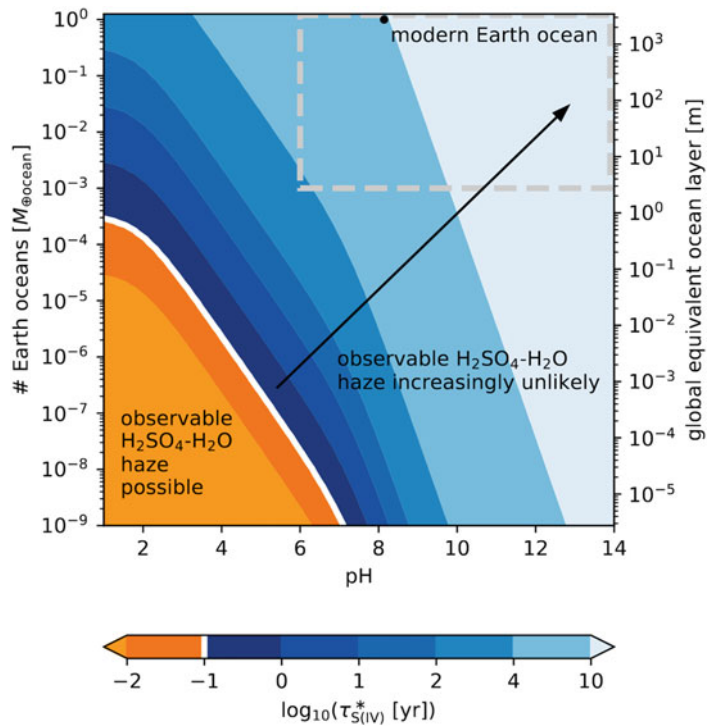
Titan is one of the great case studies for comparative planetology in our solar system. With its methane-dominated volatile cycle, low gravity, and thick atmosphere, it exhibits strangely Earth-like behavior in some respects, but is in other ways a radically different world. As is so often the case in planetary science, our understanding of Titan's atmosphere has been driven by spacecraft observations, of which the Voyager 1 and Cassini-Huygens missions were particularly important. Notable modelling advances enabled by these observations include a theoretical explanation of the *anti-greenhouse* nature of Titan's tholin haze (McKay et al. 1989), development of vertically resolved photochemical models of the planet's atmosphere (Yung and DeMore 1998), and a greater understanding of the unusual properties of methane rain microphysics (Lorenz 1993). Although our understanding of Titan has grown immensely over the last few decades, many uncertainties about its atmospheric processes and long-term evolution remain. Finally, atmospheric modelling of other outer solar system objects, such as Pluto, is still in the early stages of development but has nonetheless already shown success in explaining key observations by spacecraft such as New Horizons (Fig. 6; Bertrand and Forget 2016).

Terrestrial Exoplanets

Given the scarcity of observations of terrestrial exoplanet atmospheres in 2020, it would be premature to claim that atmospheric modelling

Modelling Terrestrial Planetary Atmospheres, Fig. 5

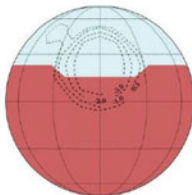
Simulated likelihood of the buildup of a permanent sulfate aerosol haze layer on Earth-like exoplanets with variable ocean volumes and pH levels, based on the results of an idealized sulfur cycle model. Results show that upper atmospheric observations of an exoplanet may be used to constrain the presence/absence of surface liquid water indirectly. (Reproduced from Loftus et al. (2019))



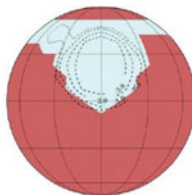
Initial distribution



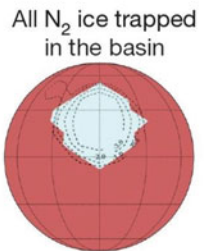
After 250 years



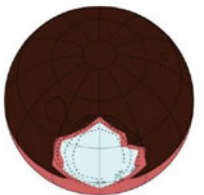
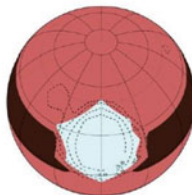
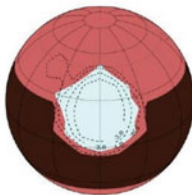
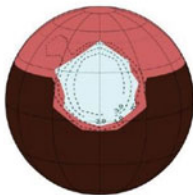
After 4,000 years



After 10,000 years



After about 50,000 years



1994
 $L_s = 15^\circ$

2002
 $L_s = 34^\circ$

2015
 $L_s = 63^\circ$

2030
 $L_s = 91^\circ$

■ Pure CH₄
□ N₂ + CH₄ + CO
■ Ice-free

Modelling Terrestrial Planetary Atmospheres, Fig. 6 Maps of the long-term evolution of surface volatiles (CH₄, N₂, and CO) on Pluto, as modelled by a three-

dimensional general circulation climate model. (Reproduced from Bertrand and Forget (2016)).

(or more accurately, the combination of observations and modelling) has yet led to major advances. Nonetheless, initial steps have already been made in this exciting new direction. For most discovered exoplanets in the terrestrial mass regime, the information we have available is radius, orbital distance, and in some cases, planet mass. A small subset of these planets are amenable to follow-up observations via transit spectroscopy, and for a few of them, constraints on atmospheric properties are now emerging (Diamond-Lowe et al. 2018; Kreidberg et al. 2019).

Considerable attention has been paid recently to the physical processes that drive the loss of molecular hydrogen from terrestrial-type planetary atmospheres. It is now clear that the division between gas/ice giants and rocky planets in the solar system is unusually distinct, and an emerging class of “enveloped terrestrial planets” appear to have both predominately rocky composition and hydrogen-dominated atmospheres. How the transition from enveloped terrestrial planets to rocky worlds like those in our solar system occurs is still a subject of investigation, with photo-evaporative and “core-powered” hydrogen loss to space currently among the leading hypotheses.

Most terrestrial planets with observable atmospheres will be around M-class (red dwarf) stars, rather than Sun-like stars, for the near to medium term future. As a result, much modelling work has focused on the differences in evolution that should occur for planets in M-class systems. Early work noted that planets that receive Earth-like levels of stellar irradiation will have close orbits around M-stars and hence may be tidally resonant or completely locked, with permanent day and night sides. General circulation modelling work has established that thin atmospheres may freeze out on the night side in this case, but thicker (i.e., greater than about 0.1 bar) atmospheres can remain stable. Notably, analytical formulae can successfully predict the day-night temperature differences on such planets obtained in far more complicated general circulation models, which is interesting given how difficult it is to create quantitative models of heat redistribution on planets like Earth. Other recent theoretical results of note

for M-dwarf terrestrial planets include predictions of enhanced cooling due to higher reflectivity from thicker clouds on the planet’s permanent dayside (Yang et al. 2013), predictions of water loss and abiotic O₂ buildup as a result of the long pre-main sequence phase that M-stars undergo (Luger and Barnes 2015; Schaefer et al. 2016), and predictions of high rates of atmospheric erosion generally due to enhanced stellar activity. All of these predictions are going to be testable in the coming decades when next ground and space-based observing facilities come online, but for the moment they remain unproven by observational data.

Applications

The applications of terrestrial planet atmosphere models are as diverse as the planets themselves. On Earth, atmosphere modelling contributes in a fundamental way to environmental science, operational meteorology, and to predictions of the impacts of climate change on global to regional scales. On longer timescales, atmospheric modelling informs us of paleoclimate conditions in the recent and distant past, with implications for archaeology, geochemistry, paleontology, and geobiology, to name just a few disciplines.

On solar system planets, there are already some operational applications for atmospheric modelling, most notably on Mars where global circulation model predictions are used to assess landing site risks for rover missions. As exploration of the solar system continues, these applications will grow accordingly. More broadly, atmospheric models of solar system planets allow big picture questions in planetary science to be addressed. For example, on Titan, the puzzle of the high atmospheric methane content requires coupling of atmospheric models to models of the deep interior. On Mars, climate modelling is needed to provide context to geological observations, and the search for life is strongly influenced by our evolving understanding of the planet’s early climate. On Venus, questions about the long-term stability of the atmosphere drive improvements in our understanding of processes like high-

temperature mineralogy at the surface and volcanism at high temperature and pressure. For early Venus, climate modelling is also needed to identify whether a *runaway greenhouse* phenomenon ever occurred (and if so at what point in the planet's history).

Finally, for exoplanets, atmospheric science is particularly critical because for the majority of cases, the atmosphere is the only part of the planet we are ever able to view directly. For the planets with atmospheres that can be observed today (which are not capable of supporting Earth-like life), atmospheric modelling allows competing theories of evolution to be tested and the maximum information to be gained from sparse observations. For potentially inhabited exoplanets, the importance of atmospheric modelling is even greater. Life detection relies on the concept of an atmospheric "biosignature," which is meant to be an observation that is a unique determinant of life. Identifying biosignature gases is an ongoing challenge that is addressed through a combination of atmospheric evolution and chemical modelling. This work is important for identifying *false positive* biosignature gases (or gas combinations), such as O_2 in cases where photochemical dissociation of H_2O and subsequent loss to space of hydrogen is effective.

Future Directions

Advances in terrestrial planet atmosphere modelling in the future are likely to occur primarily through close intercomparison between model results and observations. Despite decades of improvements to models and many demonstrations of their descriptive and predictive power on Earth and other planets, clear challenges remain. From a climate perspective, clouds remain a major source of uncertainty in predictions of anthropogenic climate change, of paleoclimate on Earth and Mars, and of the habitability of exoplanets. Reduction in model uncertainty will require a combination of more physically grounded models of convection and cloud microphysics, a better understanding of cloud radiative transfer, and in some cases further increases in model resolution and complexity. Finally, for many areas of atmospheric modelling,

better constraints on basic processes from either laboratory experiments or fundamental physics/chemistry calculations are still required.

Major outstanding questions remain regarding the long-term evolution of Venus, Mars, and Titan. For Venus, it is still unclear whether surface liquid water was ever present, and if so for how long. For Mars, the evidence for ancient surface liquid water is incontrovertible, but explaining how it occurred is still a major climate modelling problem. For Titan, the apparent instability of its current atmosphere to methane photodissociation and hydrogen loss to space raises major questions about the evolution of its atmosphere through time and effect of interior processes on a world that has no analogue in the inner solar system. For all solar system objects, more data from spacecraft missions is required to continue providing vital constraints that allow models to be tested.

The emerging field of exoplanets provides both challenges and immense opportunities. Exoplanet observations will provide data on a huge range of targets. Although this data will be very limited compared to what we have available in the solar system, the fact that it will cover such a wide range of planets means that it will revolutionize our understanding of many planetary processes. Within the next decade, it is likely that long-standing questions from solar system planetary science will be elucidated by exoplanet observations and modelling. For terrestrial-type targets, the best information will initially come from planets too hot to support life. Ultimately, however, high quality observations of potentially habitable exoplanets will become possible, and modelling of terrestrial-type atmospheres will be able to contribute to the grand challenge of searching for life in other star systems.

Cross-References

- [Atmospheric Modeling: 1D Model](#)
- [Climates, Diversity in the Solar System](#)
- [Earth-Like Atmosphere](#)
- [Faint Young Sun Paradox](#)
- [Greenhouse Effect](#)
- [Habitability, Role of the Atmosphere](#)

- [Habitable Zone](#)
- [Planet Characterization: Emitted and Reflected Light](#)
- [Planet Characterization: High-Resolution Spectroscopy](#)
- [Planet Characterization: Transmitted](#)
- [Radiative Transfer \(Atmospheres\)](#)
- [Snowball Earth](#)
- [Stratosphere](#)
- [Terrestrial Planet](#)
- [Troposphere](#)
- [Venus Clouds](#)
- [Water in the Solar System](#)

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Modern Stromatolites

- [Microbial Mats](#)
- [Stromatolites](#)

Moho

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Synonyms

[Mohorovicic discontinuity](#)

Definition

The *Moho*, an abbreviation of the term *Mohorovicic discontinuity*, is the boundary

between the Earth's crust and the ► [mantle](#). Identified first as a seismic reflector, where a marked change in the velocity of seismic waves reflects a change in rock type from low-density rocks of the crust (► [basalt](#) or ► [granite](#)) to high-density rocks of the mantle (► [peridotite](#)). The Moho lies in 6–9 km depth beneath oceanic crust, where it also separates the oceanic ► [lithosphere](#) to the mantle ► [asthenosphere](#), and at an average depth of about 30 km below continents where it lies entirely within the continental lithosphere. It is shallower (0–10 km) in rift environments where ► [continental crust](#) is stretched and thinned, and is deeper (80–100 km) in orogens where crustal segments have been thrust on top of each other.

Cross-References

- [Asthenosphere](#)
- [Continental Crust](#)
- [Craton](#)
- [Crust](#)
- [Lithosphere, Planetary](#)
- [Mantle](#)
- [Plate Tectonics](#)

Mohorovicic Discontinuity

- [Moho](#)

Moiety

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In organic chemistry, the term moiety is used to denote a portion of a molecule, which may be a

functional group, or to describe a portion of a molecule with multiple functional groups which share common structural aspects. For example, the molecule NAD^+ (nicotinamide adenine dinucleotide) contains nicotinamide, which includes an amide functional group, in which the amide functional group can be described as containing both amine and carboxylic moieties, in this case ammonia and nicotinic acid, respectively. The two terms (moiety and functional group) are often used synonymously; however, the International Union of Pure and Applied Chemistry (IUPAC) makes a distinction between the two, although in common practice this distinction can be ambiguous. Nevertheless, “functional group” is generally reserved for a portion of a molecule with some common chemical behavior, while “moiety” is more often used as a structural description.

Mole

John H. Chalmers
Scripps Institute of Oceanography Geosciences
Research Division, University of California, San
Diego, CA, USA

Definition

A mole is the amount of matter consisting of one Avogadro's number ($\sim 6.022 \times 10^{23}$) of atoms, molecules, or elementary particles. Operationally, a mole is the atomic, molecular, or formula weight expressed in grams, but this usage is obsolete, and one should use relative atomic mass or relative molecular mass in kilograms multiplied by 10^{-3} according to rules of the International System of Units (SI).

Cross-References

► [Molecular Weight](#)

Molecular Beacon

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Molecular beacon probe](#)

Definition

In molecular biology, molecular beacons are ► [oligonucleotide](#) ► [hybridization](#) probes used to report the presence of specific nucleic acids in heterogeneous solutions. They are hairpin-shaped molecules with an internally quenched ► [fluorophore](#) whose ► [fluorescence](#) is restored when they bind to a target nucleic acid sequence. This is a method of detecting specific nucleic acid sequences. They are useful when it is either not possible or desirable to isolate the target nucleic acid sequence from an excess of the hybridization probes. They are typically ~ 25 nucleotides long. The middle 15–30 nucleotides are complementary to the target sequence, and the five nucleotides at each end are complementary to each other and not to the target DNA. At the 5' end of the beacon a fluorophore is attached, and at the 3' end a quencher is attached. When the molecule is not hybridized to the target sequence, fluorescence quenching occurs. After hybridization quenching is stopped, the fluorophore is able to emit light.

Cross-References

► [Fluorophore](#)
► [Nucleic Acids](#)
► [Oligomer](#)

Molecular Beacon Probe

► [Molecular Beacon](#)

Molecular Beams

Nadia Balucani

Dipartimento di Chimica, Biologia e
Biotecnologie, Università degli Studi di Perugia,
Perugia, Italy

Acronyms

[MB]

Definition

Molecular beams are streams of molecules (or, in a broader sense, other particles such as atoms, free radicals, ions) that move in the same direction and with a defined speed range. They are produced by expanding a gas from a high-pressure region to a low-pressure region through an orifice. According to the way in which the expansion is obtained, they can be distinguished into effusive or supersonic beams. Also, they can be continuous or pulsed if a pulsed valve is used instead of an open orifice. Molecular beams can be used to investigate chemical reactions in crossed molecular beam experiments.

History

Since their development, molecular beams have been used in many different research fields. In the context of astrochemistry and astrobiology, the role of molecular beams is related to the study of elementary chemical reactions in the gaseous phase and, in particular, of bimolecular reactions between neutral species (although several studies for ion-molecule reactions are available in the literature). This technique, coupled with

spectroscopic methods or mass spectrometry, allows one to measure reactive cross sections, determine the nature of the reaction products and their yield, study the reaction dynamics and establish the mechanism followed by the process. Reactive processes are studied under single collision conditions, thus reproducing the low number density conditions for the reactions that occur in the interstellar medium, in cometary comae and in the rarefied regions of planetary atmospheres. In this way, the formation route of the organic molecules, with prebiotic potential, that have been identified in those environments can be clarified and their possible role in the origin of life speculated.

Cross-References

- [Bimolecular Reaction](#)
- [Interstellar Chemical Processes](#)
- [Supersonic Jet Expansions](#)

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Molecular Biomarkers

- [Biomarkers](#)
- [Molecular Fossils](#)

Molecular Biosignatures

- [Biomarkers](#)
- [Molecular Fossils](#)

Molecular Clock

Fabia Ursula Battistuzzi
Oakland University, Rochester, MI, USA

Keywords

Neutral theory of evolution · Time ·
Evolutionary rate · Fossil record · Calibration

Definition

The molecular clock is a technique used to estimate divergence times in a phylogeny using calibrations, generally from the fossil record, and evolutionary rates. Its theoretical background is rooted in the neutral theory of evolution which predicts the approximately linear accumulation of neutral substitutions in genes through time. Molecular clocks use sequence alignments of nucleotides or amino acids to estimate the time of speciation events and the evolution of gene families by duplication. They are the basis for the estimation of the time tree of life, which is a chronological depiction of the origin of major taxonomic groups throughout Earth's history.

Overview

Molecular clocks provide a powerful tool used to estimate the chronological dimension of a phylogeny where nodes can represent speciation or duplication events. Their theory rests on the observation that genetically similar sequences (of either nucleotides or amino acids) share a more recent common ancestor compared to sequences that are more different. In other words, neutral substitutions (i.e., neutral

mutations in nucleotide or amino acid states between pairs of sequences) stochastically accumulate through time in an approximately linear fashion (Zuckerandl and Pauling 1962; Kimura 1968).

According to this hypothesis, the divergence time of a node can be obtained by the relation $t = d/r$, where t is time, d is the genetic distance for a pair of sequences, and r is the rate of accumulation of substitutions. Because the rate parameter is expressed in time units (e.g., number of nucleotide/amino acid substitutions per million years), it is necessary to provide time information for at least one node in the phylogeny in the form of a calibration point. This node generally marks a speciation event recorded in the fossil record which can be used to estimate an approximate rate of substitution. Such a rate can then be used to extrapolate the time of divergence of other nodes in the phylogeny which will all be scaled to the same time unit provided by the calibration (e.g., millions of years).

Basic Methodology

Molecular clocks fall into one of two main categories based on their treatment of substitution rates. Initial methods, called global clocks, assumed a single substitution rate for all branches in the tree, a condition that seemed plausible given the initially small datasets available. However, the availability of larger numbers of molecular sequences, in terms of species and genes, showed the fallacy of this assumption: genes evolve at different substitution rates, and some lineages evolve faster than others. Corrective measures to address the issue of rate variation led to the development of molecular clock approaches that take into consideration rate variation among branches. The linearized tree method (Takezaki et al. 1995) takes advantage of relative rate tests to identify those genes and lineages violating the rate constancy assumption and removes them from the dataset. This method reduces the size of the dataset in order to preserve the validity of the rate constancy assumption of global clocks. Alternative methods, such as local and relaxed clocks,

allow for various degrees of flexibility in rate variation among branches permitting the analysis of larger datasets irrespective of their evolutionary complexity. While the local clocks require an *a priori* identification of groups of branches evolving at different rates, relaxed clocks, which are the most commonly used methods, estimate substitution rates specific to each branch in the phylogeny (Kumar 2005).

The correct modeling of rates is also highly dependent on the calibration point(s) used to scale the genetic distances to time units. These points are nodes in the tree for which independent information regarding their time is available from nonmolecular data. For example, in a phylogeny of multiple species, the fossil record can often be used to anchor some of the nodes to the time of the geologic stratum in which the fossils for a given lineage are found. Unfortunately, few well-constrained calibration nodes are available to time large phylogenies and, in most cases, are constrained to the Phanerozoic. The limitation of the fossil record results in higher uncertainties for more ancient divergence times because the estimated nodes are farther removed from the available calibrations.

In relaxed clock methods, the final step of time estimation for each node in the phylogeny is the result of a maximum-likelihood (ML) or Bayesian approach that uses the calculated genetic distances and evolutionary rates to provide an optimized timeline of the phylogeny under study. The use of these heuristic methods is necessary for the estimation of divergence times in large phylogenies that present a parameter space that is too large to be exhaustively explored. In order to restrict the plausible parameter space, ML and Bayesian methods require the specification of a set of *a priori* parameters that provide a plausible starting point for the search algorithm. In most cases, these priors are unknown, and default values are used without a clear understanding of the effects on the accuracy of estimations. For this reason, recent efforts have been directed toward the development of molecular clocks that require only few prior parameters (Tamura et al. 2012).

The accuracy of molecular clock analyses can be affected by a number of methodological

problems that are being actively investigated. Among these, two are prominent: the model of rate variation and the use of calibration points. Although relaxed clocks allow for rate changes to happen on each branch, most methods (e.g., BEAST, MCMCTree, Phylobayes) require a model of rate changes among branches that will be used as a basis to estimate the actual branch-specific substitution rate (Drummond and Rambaut 2007; Dos Reis and Yang 2011; Lartillot et al. 2009). Currently, two models are being used: the autocorrelated and the uncorrelated models. The first assumes small rate changes between ancestor and descendant lineages and is justified by biological similarities of closely related species. The second, instead, does not constrain the amount of rate variation change between branches, based on the assumption that missing lineages in a phylogeny may be hiding the gradual nature of the process of substitution accumulation, especially for distantly related lineages. Simulation studies have shown that time estimates based on these two models can be different, thus raising the issue of how to choose the most appropriate model when *a priori* information is not available.

The other issue known to affect the accuracy of the estimated times is the use of calibration points. This issue is twofold: first, the number of calibration points is usually small compared to the total number of nodes in a phylogeny. This means that many of the nodes to be estimated will be phylogenetically distant from the calibration used. Extrapolation of rates and correlated divergence times becomes increasingly uncertain with larger distance from the calibration because of error propagation in estimates from branch to branch. There is therefore great interest in increasing the number of calibrations. Unfortunately, this is difficult to achieve because of the incompleteness of the fossil record and the uncertainty surrounding many potential calibration points. Simulation and empirical studies have shown that the use of few well-constrained calibration points produces time estimates that are more accurate than those obtained using more numerous but less accurate calibrations (Hedges and Kumar 2004; Graur and Martin 2004).

Second, the boundaries used to define the calibrations are often uncertain. Calibration points can be defined using three types of boundaries: (i) a minimum-only boundary that allows the node to be potentially older, but not younger, than the given value; (ii) a maximum-only boundary which is the opposite of the minimum boundary; and (iii) a combination of minimum-maximum boundaries that constrains the node in both temporal directions. Furthermore, each of these types can be associated with a different probability distribution that is a measure of the confidence in the value provided. For example, a lognormal distribution on a minimum-only boundary can have a very long left tail (extending toward deeper times) in those cases in which we suspect the node in question to be much older than its fossil record. Unfortunately, boundaries and probability distribution are, in many cases, subjective, and their different use can lead to discrepancies in molecular clock analyses.

Key Research Findings

For centuries, the fossil record was the only source of information on the past evolution of species. However, this record is applicable, almost exclusively, to macroscopic species and, even for many of these, is incomplete. Moreover, the majority of the tree of life is composed of microbes (prokaryotes and unicellular eukaryotes) for which little or no chronological information can be obtained from nonmolecular data. One of the major findings of molecular clocks has been a timeline of life from the first prokaryote divergences in the Archean eon to the recent evolution of pathogenic strains of bacteria and viruses (Hedges and Kumar 2009). The time tree of life provides insights into the evolution of Earth as a habitable planet highlighting the correlation between the coevolution of major metabolisms and the changes in Earth's geosphere. The most classic example of this is the connection between the evolution of cyanobacteria, their oxygenic photosynthesizing metabolism, and the rise in atmospheric oxygen levels ~2.4 billion years ago (Holland 2002). In addition to producing a

time tree of species, molecular clocks are the only approach able to estimate the time of evolution of genes and gene families. This approach is fundamental to uncover the connections between genetic innovations, phenotypic variability, and environmental effects.

Applications

Applications of molecular clocks span many fields in evolutionary biology, from the chronology of species divergences to the origin of genes and gene families. The most recent application is within the field of evolutionary medicine in which molecular clocks are being used to identify the genetic origins of diseases in humans.

Future Directions

The application of molecular clocks to the evolution of genes and gene families is still in its infancy and requires a systematic evaluation of its accuracy. Nonetheless, this approach holds great potential in uncovering coevolutionary mechanisms between genotypes and environmental changes. Knowledge of such mechanisms will be necessary to understand not only the evolution of life in the history of Earth but also life's potential response to future planetary-scale environmental changes and its eventual interactions with extraterrestrial environments.

Cross-References

- ▶ [Chronological History of Life on Earth](#)
- ▶ [Common Ancestor](#)
- ▶ [Evolution, Biological](#)
- ▶ [Evolution, Molecular](#)
- ▶ [Fossil](#)
- ▶ [Genetics](#)
- ▶ [Great Oxidation Event](#)
- ▶ [Mutation](#)
- ▶ [Phylogenetic Tree](#)
- ▶ [Phylogeny](#)

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Molecular Cloud

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A molecular cloud is a concentration of interstellar gas and dust in which the gas phase is primarily molecular, with the dominant constituent being molecular hydrogen (H₂). It is in molecular clouds that new stars and planetary systems are born. Because molecular hydrogen lacks pure rotational transitions, molecular clouds are normally traced

by radio astronomers by observing the millimeter-wavelength transitions of the next most abundant constituent, carbon monoxide (CO). There are in addition more than 150 other molecular species that have been detected in molecular clouds, most of these species being organic (see ► [Molecules in Space](#)). Although molecular clouds occupy only a small fraction of the volume of the Milky Way and other galaxies, they contain a significant fraction of the total gas mass. The largest such clouds are called giant molecular clouds, or GMCs, and can contain more than a million times the mass of the Sun. For a comprehensive description of the ► [Interstellar Medium](#), see the entry in this Encyclopedia.

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Star Formation, Observations](#)

Molecular Depletion

Steven B. Charnley

Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Molecular depletion from the gas phase occurs when gaseous molecules in interstellar clouds collide and stick onto dust grains. In cold ► [molecular clouds](#), this leads to the formation of icy grain mantles.

Cross-References

- [Dust Cloud, Interstellar](#)
- [Interstellar Dust](#)

- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)

Molecular Fossils

Ross H. Williams

CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology/
University of Maryland, College Park, MD, USA
NASA Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, MD, USA

Keywords

Biomarkers · Gas chromatography ·
Hydrocarbons · Lipids · Mass spectrometry ·
Organic biosignatures

Synonyms

[Geolipids](#); [Molecular biomarkers](#); [Molecular biosignatures](#)

Definition

Molecular fossils are organic molecules derived from once living organisms. They fall within the category of biomarkers (or biosignatures), which are substances or characteristics that indicate a modern or past biological presence, state, or process. Molecular fossils are definitive biosignatures, and most of them are unambiguously derived cell ► [membrane](#) lipids and other aliphatic ► [hydrocarbons](#). Structures and abundances of molecular fossils and their precursor biomarkers show varying degrees of biological and environmental specificity, which reflect genetic, enzymatic, and environmentally controlled lipid production by source organisms (Gaines et al. 2009; Eglinton and Pancost 2004). Molecular fossil structures also record the nature and extent of some diagenetic and postdepositional geological conditions, and

their isotopic compositions record metabolic and environmental information.

History

The first molecular fossils were discovered in the 1930s by Alfred Treibs who observed porphyrins (compounds derived from chlorophylls a or b) in ancient oil, shale, and coal (Kvenvolden 2002). In the 1960s Geoffrey Eglinton and colleagues proposed the concept of molecular fossils as recorders to ancient microbial life. By the early 1970s it was well established that petroleum was composed of molecules of ancient biological origin and contained molecular fossils. Subsequent petroleum and paleoenvironmental research provided a foundation for understanding the occurrences, modifications, and environmental relationships of molecular fossils in the geological record. By the 1990s, organic biogeochemical studies (structural and isotopic) of recent sediments and modern environments provided the crucial observations required to ground the molecular fossil approach to the geobiological record (e.g., Freeman et al. 1990; Hayes et al. 1990; Logan et al. 1995; Summons and Jahnke 1992; Summons et al. 1987).

Overview

When organisms die, their cells decompose. Most biomolecules released to the ambient environment are oxidized or reworked by living microbes and geochemicals. However, in some aqueous environments, biomolecules are preserved by reaction, sorption, and encapsulation by minerals or more refractory organic carbon. Under anoxic conditions, they may also react with sulfur to produce sulfurized molecules or may form kerogen-like macromolecules that aid their preservation. Most biomolecules are highly functional and thus quite labile in oxidizing or nutrient-limited environments. In contrast, membrane lipids are mostly composed of a hydrocarbon skeleton, which makes them more refractory. Over geological time scales (10^4 – 10^6 years), lipids lose any weakly bound head groups and are defunctionalized

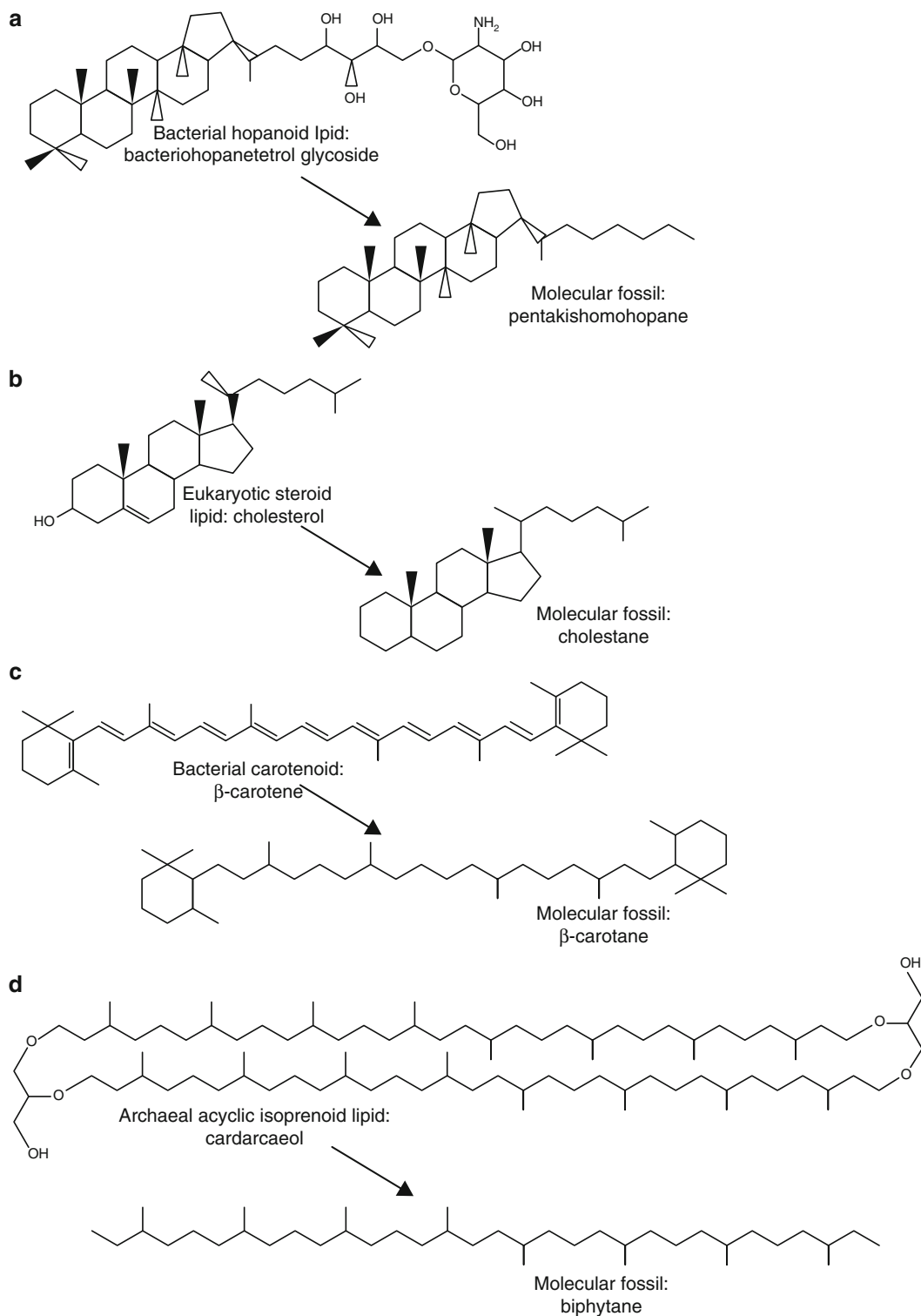
(e.g., loss of double bonds or carboxyl, hydroxyl, and amino groups) and reduced. This leaves the hydrocarbon skeleton relatively unaltered for preservation in rocks as constituents of ► **kerogen**, bitumen, oil, resins, or coal. For example, fatty acid lipids may preserve as esters or alkanes, β -carotene as carotane, cholesterol as cholestane, and bacteriohopanepolyol lipids as hopanes (Fig. 1). Importantly, lipids are released to the environment in high abundance, especially by microorganisms, but only a small amount is actually preserved. What is more, lipids have varying functionality, three-dimensional shapes, and biomineral associations that may lead to preferential preservation under certain circumstances. It is during early diagenesis that the fate of most biomolecules in sediments is determined. In general, the faster biomolecules are buried and removed from oxidizing conditions, the greater their potential is for preservation as molecular fossils in the geological record (see Eigenbrode 2007 for review).

A variety of molecular fossils in geological records are observed, and they have identifiable lipid precursors in living organisms. The organic geochemical record reflects a dominance of microbial molecular fossils, which is extremely valuable since unambiguous macrofossil of microorganisms is rare and microorganisms have played a key role in biogeochemical cycling over 3.5 billion years of Earth's history. These fossils include, but are not limited to, acyclic ► **isoprenoids**; aryl isoprenoids; bi-, tri-, and tetracyclic terpenoids; and pentacyclic terpenoids including hopanoids, oleanoids, and steroids. Other hydrocarbon structures (e.g., *n*-alkanes, alkyl-alkanes, organic acids, and polyaromatic hydrocarbons) may be regarded as potential biosignatures and hence not necessarily molecular fossils, since they may form from abiogenic processes. Molecular patterns in their structures and isotopic composition may help ascertain whether these compounds are indeed molecular fossils.

As membrane biomolecules, the evolution of lipids is highly conserved due to their key role in providing the necessary membrane rigidity and selective permeability required by organisms that need to separate cellular chemistry from the ambient environment while still passing selective

substrates and waste product through membranes. Cell membranes are similar to nonbiologically formed liposomes, where, in the presence of water, polar head groups of molecules having hydrocarbon tails, such as carboxylic acids with carbon chains, line up to form a polar (or hydrophilic) surface facing the water. The hydrocarbon tails make up a hydrophobic region that repels water, thus creating a structural boundary for isolating different chemical environments. Most biological cell membranes are composed of two layers with hydrocarbon tails facing the center of the bilayer. Life has evolved hydrocarbon structures that are much more complex than simple straight chains of carbon. Branches, cyclic rings, double bonds, and, sometimes, alcohol groups are included in the hydrocarbon tail and consequently change the functionality of the lipid and the characteristics of the membrane. In addition, the hydrocarbon tail may be linked to a wide diversity of polar head groups by ester bonds or ether bonds, as is diagnostic of the domain ► **Archaea** membranes. The fundamental need for all cellular life to maintain membranes limits the structural possibilities for lipids, thus explaining the occurrence of common molecular fossil groups throughout the geological record.

The provenance of different molecular fossils and their lipid precursors has largely been established through a combination of studies including lipid compositions associated with particular modern organisms or environmental conditions, molecular fossils associated with past environmental settings or diagenetic conditions, an understanding of the biochemical pathway for synthesizing lipids, and, more recently, phylogenetic analyses targeting the presence or absence of genes required for making the key enzymes of these pathways. These efforts are being pushed further by the application of molecular clock approaches to elucidate when in Earth's history different groups and biosynthetic pathways have evolved. Establishing biological provenance of lipid structures and their molecular fossils is a very active research field. However, there is consensus on the conservation of key lipid assemblages along major evolutionary lines. These key assemblages include hopanoids, acyclic



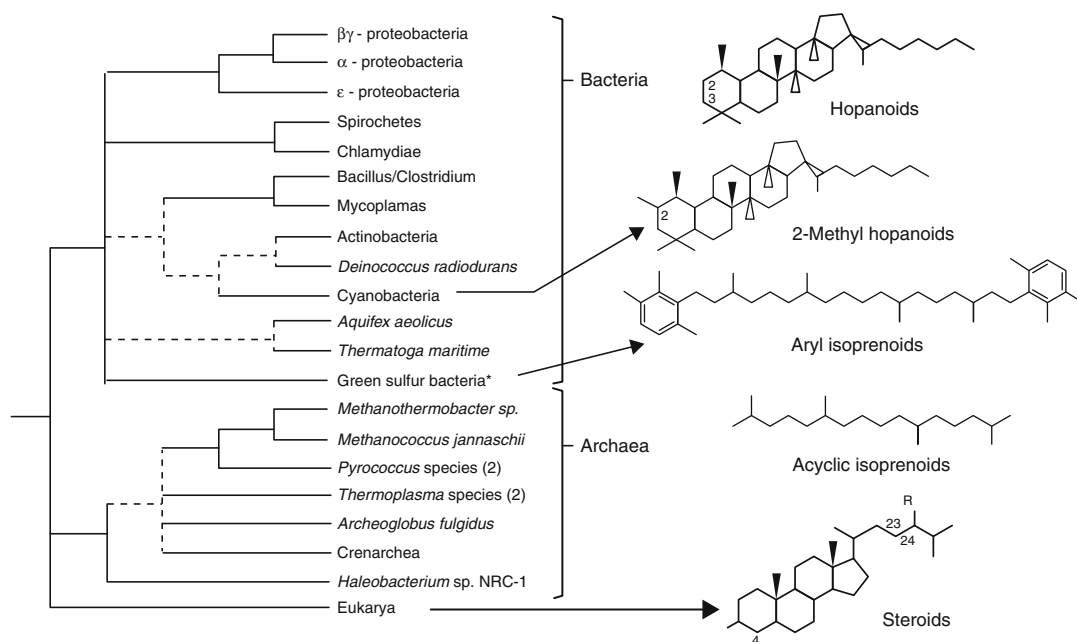
Molecular Fossils, Fig. 1 Geological alteration of cellular membrane lipids to molecular fossils: (a) bacteriohopanetetrol glycoside to pentakishomohopane, (b) cholesterol

to cholestane, (c) β -carotene to β -carotane, and (d) cardarchaeol to biphytane

isoprenoid alcohols and ethers, and steroids (particularly those having an alkyl group at the C24 position) that are diagnostic of the ► *Bacteria*, Archaea, and ► *Eukarya* domains (Fig. 2). Other lipids and their molecular fossils show varying degrees of taxonomic and environmental specificity. Examples of strong taxonomic associations include certain aryl isoprenoids diagnostic energy-harvesting biomolecules (carotenoids) of green sulfur bacteria, 2-methyl hopanoids common of cyanobacteria and some α -proteobacteria (Welander et al. 2010), and 3-methyl hopanoids diagnostic of type I aerobic methylotrophic bacteria. Examples of environmental associations are aryl isoprenoids diagnostic of euxinic photic zones and 2-methyl hopanoids of marine carbonate environments. Often, where individual compound specificity falls short, assemblage analyses may be utilized to elucidate biologic origin. Taxonomic and/or environmental provenances can be used to infer past depositional or diagenetic conditions and biological community composition;

thus, molecular fossils can be extremely useful in furthering our understanding of the evolution Earth's biosphere.

Applications of molecular fossils can be hampered by poor preservation, loss (destruction or migration out of the rock), and overprinting by later processes. Factors that influence establishment and detection of a molecular fossil record may impact the initial preservation, long-term preservation, or sampling and analysis. Even though lipids are more recalcitrant to biological and geochemical oxidation, they are still susceptible to this form of destruction, particularly if they are exposed to water, gas, and chemical exchange or geothermal heat over geological time. For this reason, sediments of high permeability (e.g., sandstones) are not likely to preserve indigenous molecular fossils. In contrast, low-permeability sediments, such as mudstone and shale, boost the likelihood of preservation. Anoxic environments are more favorable for initial preservation. Sediment compositions that help



Molecular Fossils, Fig. 2 The genomic tree of life annotated with diagnostic molecular fossil structures for the three domains of life (black) and select taxonomic groups (gray) (Genomic tree modified from Wolf et al. (2002) according to House et al. (2003) by the addition of green

sulfur bacteria (*). R indicates additional methylation at the C24 position on the sterane structure. Other common methylation occurs at C2 and C3 positions of hopanoids and C4 and C23 of steroids

to stabilize the redox conditions during burial, even if in microcavities of pores or mineral inclusions, will improve the preservation potential. Furthermore, it is a natural consequence of burial and geological activities for sedimentary organic matter containing molecular fossils to undergo thermal maturation. As part of early diagenesis, many biomolecules chemically react with each other, minerals, and solutes (e.g., phyllosilicates or sulfides) to form sedimentary macromolecules, while some biomolecules maintain their original macromolecular form. In rocks, this macromolecular material is called kerogen. Formation of macromolecules aids the preservation of molecular fossil constituents contained within them. Following diagenesis, heat thermally matures organic matter through a process known as catagenesis. The weaker bonds holding the macromolecules together are thermally broken resulting in the release of molecular fossils and overall loss of O, S, N, and eventually H. The molecules freed from the kerogen may be retained by the host rock as bitumen or migrate to other rocks as oil. Decades of petroleum research have demonstrated that bulk characteristics of bitumen and oil, as well as composition of the thermally matured molecular fossil record aspects of these alteration processes often without complete loss of structural information diagnostic of biological and environmental provenance. Moreover, owing to a ubiquitous biosphere, the molecular fossil record is continually susceptible to alteration by biology in the subsurface (particularly carried by groundwater) and surface once rocks are reexposed. The extent that the original syngenetic record of the host rocks is lost or overprinted by lipids from newly introduced biology will largely depend on the level of metabolic activity, biomass turnover, and time. As with thermal maturation, there are chemical signatures that record the biological alteration. Lastly, the same factors that influence preservation in the rock record apply to sampling, storage, and analysis. Once a sample is removed from its *in situ* conditions, it is susceptible to oxidation, contamination, and other degradations. These factors become increasingly important for the recovery of trace quantities (sub-ppb concentrations) of indigenous molecular fossils.

Thus, under favorable conditions, carbon skeletons of lipids have the potential to be preserved as molecular fossils for billions of years, but their detection and recognition as indigenous and syngenetic signatures of host rocks may be dependent on resolving the complex record of alteration occurring since deposition.

Basic Methodology

Molecular biomarkers and their fossils are typically recovered from biological materials, sediments, oil, bitumen in rocks, or coal using organic solvents. The molecular composition (structures, molecular abundances, and compound-specific isotopic compositions) is then determined using highly sensitive analytical tools such as gas or liquid chromatographs and mass spectrometers. Alternative extraction approaches involve laser desorption ionization (e.g., LDI and MALDI), extraction by heat instead of solvents (e.g., thermal desorption and pyrolysis) or some combination of heat, chemical reactants, and solvents (e.g., thermochemolysis).

Key Research Findings

The field of molecular fossil research has been evolving for over 50 years. Some of the more recent key research findings include, but are not limited to, the following:

1. The finding that preservation of molecular fossil record occurs largely through abiotic reductive transformation by the early diagenetic incorporation of sulfur into sedimentary lipids and other biomolecules (Hebting et al. 2006; Adam et al. 1993; Sinninghe Damsté et al. 1989).
2. The analytical advancement of compound-specific isotope analysis (CSIA) via gas chromatography–isotope ratio mass spectrometry (GC-IRMS) and the recognition that molecular fossils (and their lipid precursors) retain isotopic signatures diagnostic of carbon sources and metabolisms (Freeman et al. 1990; Hayes et al. 1990; Pancost and Sinninghe Damsté 2003). This finding opened a new door to

- understanding the activities of community organisms in past environments and has expanded to include CSIA of nitrogen, hydrogen, and sulfur. More recently, this has been expanded to site-specific isotopic measurements as well as analysis of clumped isotopes.
3. Taxonomic, metabolic, and environmental interpretations of molecular fossils are largely dependent on their observed occurrence in the sedimentary rocks and modern biota. More recently, however, new insights in the molecular fossil sources are coming from the application of genomic techniques to evaluate lipid biosynthetic capabilities (Welander et al. 2010; Fischer et al. 2005; Pearson et al. 2003) and lipid function (Welander et al. 2009).
 4. Observations and subsequent critical analyses of a suite of originally proposed indigenous and syngenetic molecular fossils of Neoproterozoic sediments that are indicative of ancient microbial diversity (Brocks et al. 1999; Waldbauer et al. 2009; French et al. 2015) and changes in biological oxygen and methane use (Eigenbrode et al. 2008) beginning >200 million years before the first significant rise in atmospheric oxygen concentrations at 2.5 Ga. However, the antiquity of these biomarkers is subject to debate and contamination suspected for most of the Archean record (Rasmussen et al. 2008; French et al. 2013).
 5. The discovery of the steroid, 24-isopropylcholestane, a molecular fossil of demosponges, Neoproterozoic Maronian glacial cap carbonate rocks, pushes back the record of animals on Earth to 635 Ma, making it the oldest evidence for animals (Love et al. 2009), though this also has undergone additional scrutiny recently as the diagnostic compound has also been reported from an alternative source (Nettersheim et al. 2019).
- community composition, and ecologies – all of which are useful in paleoclimate studies (e.g., Zachos et al. 2006), constraining biological evolution (e.g., Brocks et al. 1999; Love et al. 2009), understanding catastrophic and global events (e.g., Grice et al. 2005; Eigenbrode et al. 2008), and correlating oil source rocks with petroleum reservoirs (cf. Peters et al. 2007). Molecular fossils are particularly useful as markers for microbial contributions to sediments (cf. Brocks and Summons 2003), and their isotopic compositions can reveal associated metabolisms and biogeochemical cycling (e.g., Freeman et al. 1990; Pancost and Sinningh-Damsté 2003).
- In extraterrestrial studies, the identification of molecular fossils as definitive biosignatures will be a particularly difficult challenge in the absence of a broad understanding of the biochemistry, physiology, and ecology of modern extraterrestrial life. However, molecular biomarker and molecular fossil studies on Earth reveal generic traits of life (Summons et al. 2007) and ecology (Eigenbrode 2007) that will be essential in evaluating the biosignature potential of extraterrestrial organic molecules. Moreover, organic geochemical studies provide the foundation for understanding sources (biogenic or abiogenic) as well as surface and subsurface alteration processes. A caveat to extraterrestrial studies will be confirmation that the molecules detected are indigenous and were not transported from Earth.

Future Directions

Contemporary interdisciplinary studies that integrate lipid biomarkers, isotopic compositions, microbial physiology and ecology, and microbial genomics are advancing our understanding of molecular biomarker specificity for phylogenetic groups and environmental conditions. Concurrent research efforts that focus on the fate of molecular biomarkers from origin to deposition and preservation in the geological record are providing essential insight for detecting and improving the recovery of molecular fossil records. Both lines of study aim to revolutionize our understanding of

Applications

On Earth, molecular fossils are used to understand a variety of aspects about ancient life (cf. Gaines et al. 2009). They are particularly valuable in reconstructing ancient environmental conditions,

evolution of the biosphere on Earth and will aid in the exploration, detection, and establishment of biogenetic confirmation criteria for molecular biomarkers and their fossils in extraterrestrial sediments should they exist.

Cross-References

- [Archaeal Traces of Life](#)
- [Aromatic Hydrocarbon](#)
- [Bacteria](#)
- [Biomarkers](#)
- [Cyanobacteria, Diversity and Evolution Of](#)
- [Ecosystem](#)
- [Eukarya](#)
- [Eukaryotes, Appearance and Early Evolution Of](#)
- [Fortescue Group](#)
- [Geological Timescale](#)
- [Hopanes, Geological Record Of](#)
- [Hydrocarbons](#)
- [Isoprenoids](#)
- [Kerogen](#)
- [Membrane](#)
- [Microbial Mats](#)
- [Photosynthesis](#)
- [Photosynthetic Pigments](#)
- [Phototroph](#)
- [Porphyrin](#)
- [Steranes, Rock Record](#)
- [Syngenicity](#)
- [Tumbiana Formation \(Pilbara, Western Australia\)](#)

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Molecular Interactions

► Van der Waals Forces

Molecular Line Cooling

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Interstellar medium · Molecules

Definition

Molecular line cooling is the physical process whereby de-excitation of collisionally or radiatively excited molecules leads to the emission of a photon, followed by the photon's escape from the local cloud volume, thus cooling the local gas.

Overview

In astronomical environments where most of the gas is molecular, the gas can cool through emission of the photons associated with transitions from higher to lower rotational and vibrational levels in molecules. In cold ► [molecular clouds](#), the major molecular coolant is CO, since the most abundant constituent (H₂) lacks radiative transitions at low temperatures. In shock waves, H₂, H₂O, and CO dominate the molecular cooling. Other molecules that can act as relatively minor coolants are OH, HD, and CH. In ► [photodissociation regions](#), atomic fine structure lines can also be important coolants.

Cross-References

- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Shock, Interstellar](#)

References and Further Reading

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Molecular Line Map

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

A molecular line map is a spatial representation of molecular line emission from an extended astronomical source. Such maps are normally represented in the astronomical coordinates ► [Right Ascension](#) and ► [Declination](#) or in off-sets from a defined position on the sky. Molecular lines are observed either on a predefined set of grid points or by continuous scanning (On-The-Fly mapping), and a map is constructed from the emission intensity, either as contours or using gray or color scales.

Cross-References

- [Line Profile](#)
- [Spectral Line](#)

Molecular Line Survey

Brett A. McGuire^{1,2}, Anthony J. Remijan²,
Ci Xue³ and Andrew M. Burkhardt⁴

¹Massachusetts Institute of Technology,
Cambridge, MA, USA

²National Radio Astronomy Observatory,
Charlottesville, VA, USA

³University of Virginia, Charlottesville, VA, USA

⁴Center for Astrophysics | Harvard &
Smithsonian, Cambridge, MA, USA

Keywords

Chemistry · Green Bank Telescope ·
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species · Atacama Large Millimeter Array ·
Herschel Space Observatory · Amino acid

Synonyms

[Band scan](#); [Broadband line survey](#); [Spectral survey](#)

Definition

A molecular line survey is a study of the spectrum of an astronomical source over a wide, approximately continuous, range of wavelengths, in order to determine the chemical composition and physical properties (temperature, density, and internal motion) of such a region. Primarily, the lower energy transitions of molecules of astrophysical interest are excited at the cold temperatures of ► [molecular clouds](#), and these rotational transitions are typically at centimeter and (sub)millimeter wavelengths (~10–1000 GHz), so that molecular line surveys have normally been carried out using the techniques of radio astronomy.

History

Until recently, radio receivers had instantaneous spectral bandwidths that covered only very small

fractions of the wavelength regions of interest. Consequently, searches for and studies of interstellar molecules were traditionally targeted toward the narrow regions around laboratory-measured transition frequencies of specific molecules. In contrast, spectral line surveys were very time-consuming and could only be carried out at those radio observatories that were willing to devote significant observing time to a survey project. The first spectral line survey was made during 1977–1982 toward the giant molecular cloud known as Sagittarius B2 (Sgr B2) near the center of the Milky Way Galaxy (Cummins et al. 1986), using an antenna at the Bell Laboratories, USA.

The first major projects with the new 20-m-diameter radio telescope at the Onsala Space Observatory in Sweden were line surveys of the nearest region of massive star formation to the Sun, Orion-KL, and the envelope expelled by the evolved carbon star, IRC +10,216 (Johansson et al. 1984). This survey found striking chemical heterogeneity within the Orion molecular cloud. These studies were extended to both higher and lower frequencies in subsequent surveys (e.g., Blake et al. 1987; Turner 1991; Nummelin et al. 1998; Cernicharo et al. 2000; Kawaguchi et al. 1995; Ziurys and McGonagle 1993; Lee et al. 2001) and to additional sources in our Galaxy (e.g., Fontani et al. 2017; Kaifu et al. 2004; Pardo et al. 2007; Helmich and van Dishoeck 1997; Macdonald et al. 1996; van Dishoeck et al. 1995).

The Orion molecular cloud has been surveyed at frequencies blocked by the Earth's atmosphere, using the Odin satellite (Olofsson et al. 2007), and spectral line surveys have been extended to external galaxies (Martin et al. 2006). Surveys of the Orion molecular cloud and Sgr B2(N) have been extended to cm wavelengths with the Green Bank Telescope (GBT) (see, e.g., McGuire et al. 2012) and to THz frequencies with the Herschel Space Observatory (HSO) (Neill et al. 2012). Finally, the Atacama Large Millimeter Array (► ALMA) has sufficient spectral bandwidth and resolution to conduct broadband line surveys commensurate with spatial mapping (e.g., Belloche et al. 2016; Pagani et al. 2019).

Overview

There are many specific reasons why deep spectral line surveys are important and timely, and could significantly advance the field of astrobiology. Surveys not only provide probes of physical and chemical conditions, but they also discover new interstellar molecular species. Building up the chemical inventory of astronomical molecules is important to understand how organic matter is produced in the ► [interstellar medium](#) (ISM). Although significant progress has been made in understanding the chemical content and formation mechanisms in interstellar clouds, it is still challenging to predict with certainty which molecular species will be present. A number of species, such as the 3-carbon sugar glyceraldehyde and the simplest amino acid, glycine ($\text{NH}_2\text{CH}_2\text{C}(\text{O})\text{OH}$), have not yet been confirmed in astronomical environments, even though models and the presence of precursor species suggest that these molecules should be present. Most often, a lack of detection can be traced to a combination of the low abundance of a target species and unfavorable physical conditions – namely, source size and temperature. Despite this, a very low-abundance of molecules can be detected by exploiting phenomena such as masing (see, e.g., McGuire et al. 2012).

The following sections focus on recent molecular line surveys of Sagittarius B2(N) near the center of our Galaxy, Orion-KL in the Orion molecular cloud, and TMC-1 in the nearby Taurus molecular cloud. Of the ~200 astronomical molecules detected to date, more than half have been discovered in these regions. The Sagittarius B2 complex contains compact hot molecular cores, molecular ► [maser](#) emitting regions, and ultra-compact sources of continuum radiation surrounded by larger-scale continuum features, as well as more extended molecular material. The Orion-KL molecular cloud includes several distinct molecular sources, with the “hot core,” “compact ridge,” and “low- and high-velocity outflows” the most prominent among them. The TMC-1 dark cloud has a filamentary morphology with diverse clumpy structures, traced by molecular emissions from different dense gas tracers (e.g., H^{13}CO , NH_3 , SO, CCS). These molecular

species peak in abundance at different regions along the TMC-1 filament, the most well-studied of which is the “cyanopolyne peak” (CP) located at the southeastern end of the filament. While chemically simpler than Sgr B2(N), the proximity and narrower line widths of Orion-KL and TMC-1 result in less confused line surveys.

Key Research Findings

The most prolific source of new, astrobiologically relevant molecular detections is the Sgr B2-(N) region. Dedicated searches of Sgr B2(N) using the Green Bank Telescope (GBT), the National Radio Astronomy Observatory (NRAO) 12-m telescope, Herschel, the IRAM 30-m telescope in Spain, the Arizona Radio Observatory (ARO), and the Atacama Large Millimeter/submillimeter Array (ALMA) have resulted in 23 new molecular detections since 2000. These include key prebiotic molecules such as the simplest sugar-related molecule glycolaldehyde (CH_2OHCHO ; Hollis et al. 2004b); a nucleobase precursor, *E*-cyanomethanimine (HNCHCN ; Zaleski et al. 2013); and the molecules with a peptide bond, acetamide (CH_3CONH_2 ; Hollis et al. 2006b) and urea ($(\text{NH}_2)_2\text{CO}$; Remijan et al. 2014, Belloche et al. 2019), among a wealth of other species (see ► [Molecules in Space](#)).

While many of the species detected in Sgr B2(N) have also later been found in the Orion-KL region, only five new molecular detections have been made in Orion-KL since 2000, the most astrobiologically relevant of which is methyl acetate ($\text{CH}_3\text{CO}(\text{O})\text{OCH}_3$; Tercero et al. 2013). More importantly, the different chemical and physical environments of Orion-KL, while still containing many of the same molecular species as Sgr B2(N), provide a comparative testbed for testing the robustness of astrochemical models.

While observations toward the massive star-forming cores Sgr B2(N) and Orion-KL have expanded the interstellar molecular inventory with, predominantly, saturated terrestrial-type molecules, spectral surveys toward the prestellar core TMC-1 have contributed 19 new molecules

to the inventory since 2000, of which the majority is unsaturated carbon-chain molecules (e.g., HC_4NC , HC_{11}N , $\text{CH}_2\text{CHC}_3\text{N}$). Notably, these new molecules include individual aromatic compounds, $\text{C}_6\text{H}_5\text{CN}$, 1- and 2- $\text{C}_{10}\text{H}_7\text{CN}$ (McGuire et al. 2018, 2021). Aromaticity is of particular biological interest as four amino acids out of 20 composing proteins and all the five nucleotides composing generic materials RNA and DNA consist of the functional groups with aromatic structures.

Two other sources, the red hypergiant VY Canis Majoris and the carbon star outflow IRC +10,216, have provided an additional six and 20 new molecular detections since 2000, respectively. These regions have been the primary source of detections of phosphorous-containing species (e.g., HCP, PH_3 , PO, and CCP) as well as a number of metal-containing species (e.g., TiO, TiO_2 , FeCN, AlNC). IRC +10,216 has also been a primary source of molecular anion detections (see, e.g., C_6H^- in McCarthy et al. 2006). Phosphorus is an essential component of life – phosphates (PO_4^{3-}) are ubiquitous in biological systems, from DNA and RNA to phospholipids which are components in cell membranes. Metals, too, play key roles in biological processes (see, e.g., the iron-containing hemoglobin molecules in human blood).

Finally, while the number of new molecular detections resulting from them has been small, the Herschel/HIFI key project “Herschel/HIFI Observations of EXtra Ordinary Sources” (HEXOS) has provided the largest broadband line survey of Sgr B2(N) and Orion-KL to date (Neill et al. 2012; Crockett et al. 2010), extending from ~450 GHz to 1.8 THz. Additionally, as part of its science verification process, an ALMA Band 6 survey of Orion-KL was conducted covering the range from 214 to 246 GHz. The full dataset is publicly available at <https://almascience.nrao.edu/almadata/sciver/OrionKLBand6/>.

Above all else, these detections have shown that a suite of receivers and telescopes working in synergy is necessary to start investigating the questions of the formation, excitation, and distribution of complex organic molecules in astronomical environments.

Basic Methodology

While each survey will be unique due to specific observing and instrumentation considerations, an excellent and detailed overview of general data collection, reduction, and analysis techniques can be found in Neill et al. (2012).

One challenge facing molecular line surveys is the efficient presentation of the data to the community. The survey of the Sagittarius B2(N) region performed with the GBT, the **P**Rebiotic **I**nterstellar **M**olecule Survey (PRIMOS), is changing the way these data are disseminated. The data from the survey is made available quarterly as data is taken and reduced. Dissemination of the fully calibrated data products is available either in simple ASCII text or available through the **S**pectral **L**ine **S**earch **E**ngine (SLiSE), a dedicated data display java-based tool. SLiSE contains functions to overlay possible molecule identifications based on a current line catalog as well as overlaying H and He recombination lines. For a full description of the PRIMOS project and the SLiSE tool, visit: <http://www.cv.nrao.edu/~aremijan/PRIMOS/>.

The SLiSE tool has recently been populated with line survey data from additional sources, primarily legacy data from Barry E. Turner's NRAO 12 m surveys.

Future Directions

Organic materials found in meteorites are considered to be indicative of the chemicals that are present in extraterrestrial sources, such as molecular clouds. A study of the Murchison meteorite by Cooper et al. (2001) finds (in addition to many amino acids and other molecules of potential biological interest) sugars, sugar alcohols (polyols), sugar acids, and other related species with gas chromatography-mass spectroscopy techniques. Some of the sugars take on an important role in the biochemistry of Earth. In space, the simplest sugar-related molecule, glycolaldehyde (CH_2OHCHO), was detected in the Sagittarius B2(N) molecular cloud, but the simplest sugar,

glyceraldehyde ($\text{CH}(\text{O})\text{CH}(\text{OH})\text{CH}_2\text{OH}$), has been sought but not thus far detected. Nonetheless, given the importance of sugars to both terrestrial and interstellar chemistry, the search for more complex sugars, including the base of RNA, will continue into the next generation of astronomical instruments.

Recent results from NASA's Stardust mission show the presence of the simplest amino acid, glycine, in cometary samples returned from comet Wild 2 (Elsila et al. 2009). Yet, the formation mechanism for this building block of life remains something of a mystery due to a lack of any extrasolar detection of glycine.

Finally, at peak operational capacity, ALMA allows the acquisition of 4+ GHz of instantaneous bandwidth (dependent on required spectral resolution) at extremely high spectral sensitivity commensurate with high-resolution spatial mapping. In essence, each pixel in a map toward a target source (e.g., the ALMA science verification data toward Orion-KL) will contain a complete spectral line survey of the area covered by that pixel. ALMA has enabled unbiased molecular line surveys to become a commonplace. Example ALMA molecular surveys include the **E**xploring **M**olecular **C**omplexity with **ALMA** (EMoCA) – survey of Sgr B2(N) (Belloche et al. 2016), the **P**rotostellar **I**nterferometric **L**ine **S**urvey (PILS) – survey of the low-mass protostar IRAS 16293–2422 (Jørgensen et al. 2016), and the **F**ifty **AU S**Tudy of the chemistry in the disk/envelope system of Solar-like protostars (FAUST) – survey of 13 Class 0/I protostars (Bianchi et al. 2020). ALMA is now one of the most prolific facilities of molecular line surveys.

Cross-References

- [ALMA](#)
- [Herschel Mission](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)

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Molecular Modeling

► Molecular Simulations

Molecular Nitrogen

► Dinitrogen

Molecular Oxygen

► Dioxygen

Molecular Phylogenetics

► Evolution, Molecular

Molecular Recognition

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry and biology, molecular recognition is the specific interaction between two or more molecules through complementary noncovalent bonding, for example, via ► [hydrogen bonding](#); metal coordination; ► [van der Waals forces](#); and $\pi - \pi$, hydrophobic or electrostatic interactions. Molecular recognition plays an important role in biology and mediates interactions between receptors and ligands, antigens and antibodies, ► [nucleic acids](#) and proteins, proteins and proteins, ► [enzymes](#) and ► [substrates](#), and nucleic acids with each other. A number of artificial systems have also been synthesized that depend on molecular recognition, for example, peptide nucleic acid and other antisense ► [oligonucleotides](#).

Cross-References

- [Hydrogen Bond](#)
- [Ligand](#)
- [PNA](#)
- [Van Der Waals Forces](#)
- [Weak Bonds](#)

Molecular Sieves

- [Zeolites](#)

Molecular Simulations

Judit E. Šponer and Jiří Šponer
Institute of Biophysics of the Czech Academy of
Sciences, Brno, Czech Republic

Keywords

Quantum chemical calculations · Molecular
dynamics simulations · Ab initio molecular
dynamics simulations

Synonyms

[Molecular modeling](#)

Definition

Molecular simulations refer to techniques that apply theoretical algorithms to study the atomistic details of various physical or chemical processes. It comprises wide range of techniques with diverse purposes, computational costs, and limitations. Three most common approaches are the following. Standard Quantum Chemical (or mechanical, QC, QM) calculations characterize the potential energy surface of the studied systems by considering their electronic structure via the approximate solution of the Schrödinger equation, with different degrees of rigor. Classical molecular dynamics (MD) simulations describe the molecules using a force-field approximation (molecular mechanics, MM) but aim to characterize the free-energy surfaces by including Boltzmann sampling starting from some initial structure. Often the word simulation is used as a synonym to differentiate MD approaches from mere potential-energy computations. Typical MM descriptions do not allow bond breaking and making. Quantum MD differs from classical MD simulations in that it enables sampling of the free-energy landscape of the studied system using QM treatments rather than the MM

approximation; however, the sampling is limited by orders of magnitude. Some QM MD methods include quantum nature of both electrons and nuclei. QM and MM approaches can be combined into hybrid QM/MM methods where a more interesting part of the system is described by the QM approach and the rest of the system by the MM approach. Efficacy of MD methods to sample the free-energy surface may be boosted by diverse enhanced-sampling methods which, however, may bring significant additional approximations compared to the plain MD simulations, namely, prior chemical information about the studied process. In the last 10 years molecular simulations have matured to serve as a basic technique to supplement experimental investigations of astrobiological relevance.

Overview

Across majority of the disciplines natural sciences use experiments as primary method of acquiring information about the studied system. With the development of computing hardware and software at the end of the twentieth century new computer-based methods appeared on the scene, which enable an atomic-level insight into the structure, energy, electronic properties, and dynamic behavior of the studied systems. Since this information is only indirectly available from experiments it opened new horizons in almost all branches of chemical sciences. In particular, computer simulations became instrumental at unraveling reaction mechanisms, interpreting experimentally measured spectra, or at simulating the time-dependent behavior of various molecular properties. Below, an overview of the most frequently used techniques for this purpose is provided.

Basic Methodology

Properties of small systems (consisting of up to ca. 300 atoms) can be most accurately described using quantum chemical calculations. These methods are based on solving the Schrödinger equation:

$$\mathbf{H}\Psi = E\Psi$$

where $\mathbf{H}$ is the Hamilton operator describing the motion of electrons in the studied system, Ψ is the wavefunction, and E is the electronic energy. The two most frequently applied approaches to solve the Schrödinger equation are the so-called wave-function-based and density functional (DFT) techniques.

Wavefunction-based techniques decompose the total wavefunction to contributions coming from each individual electron (ϕ), while DFT-techniques consider the electronic energy as a function of the electronic density (ρ). Since $\mathbf{H}$, Ψ , E , as well as ϕ and ρ are all dependent on the geometrical parameters describing the configuration of atoms in the studied system, the methods can be used to study structure and energy relationship in a wide range of molecular and supramolecular systems.

Force-field based molecular dynamics methods are dedicated to describe more extended systems (like biomolecules). In this approximation the system is considered as being held together by forces, characterizing the interaction of the constituent atoms, whose motion is described by Newtonian mechanics. This approach offers a convenient way to follow inter- and intramolecular motions on timescales up to milliseconds.

Ab initio molecular dynamics simulations provide an insight into the dynamic behavior of molecules combining the Schrödinger equation for energy estimates and the Newtonian-Lagrangian formalism to describe atomic motions. The advantage of this methodology over quantum chemical calculations is that it gives a time-dependent insight into the development of molecular structures. Thereby it enables an easier prediction of molecular mechanisms which relies less on chemical intuition. Another potential advantage of the methodology is a more accurate description of the solvent environment, which often plays a crucial role at mediating chemical mechanisms. Nonetheless, the descriptions of the electronic structures and thus of the energies in quantum molecular dynamics simulations are generally far less accurate than those obtained from static quantum mechanical approaches, such as mere gradient

optimizations and potential-energy scans. It is because in MD simulations major efforts are invested to include the free-energy surface. Thus, the gains from replacing the potential-energy surface description by free-energy surface description may sometimes be outweighed by reduction of the quality of the method used for energy calculations. In many instances conservative potential energy scans using high-quality QM methods may be more reliable than MD simulations with lower-quality methods.

Modern computational methodologies also include combination of the abovementioned techniques, like the popular QM/MM approach, which combines the more accurate wavefunction (QM) treatment with force-field based molecular mechanics (MM) calculations.

Key Research Findings

One of the main areas where computational studies are highly instrumental is the understanding of chemical mechanisms of elementary reactions that could lead to the complexification of extraterrestrial matter. For example, during the last few years numerous studies have dealt with the synthesis of formamide from simple building blocks like formaldehyde, HCO, NH₂, OH, and CH₂NH radicals (Rimola et al. 2018; Barone et al. 2015b; Vazart et al. 2016). These studies utilized quantum chemical calculations. Further, quantum molecular dynamics simulations were used to follow the atomistic details of the elementary processes acting in the Miller-Urey experiment (Saitta and Saija 2014; Wang et al. 2014). Synthesis of the simplest sugar, glycolaldehyde from two formaldehyde molecules bound to two neighboring Ti³⁺ defect sites of anatase surface has been addressed with DFT calculations (Civiš et al. 2016). The computations have shown that the biradical-character of the defect sites facilitates covalent bond formation between the formaldehyde molecules, which would otherwise be energetically highly unfavored.

Quantum chemical calculations and quantum molecular dynamics simulations are frequently applied to understand the mechanism of synthesis

of biomolecular building blocks from simple organic precursor molecules. These studies enable a unique insight into the main steps of molecular evolution leading to the emergence of terrestrial life. Quantum chemical calculations helped to unravel possible mechanistic scenarios for the synthesis of nucleobases from formamide utilizing thermal chemistry (J. Wang et al. 2013a, b) or radical-assisted pathways (Ferus et al. 2012, 2015). It has been shown that radicals created in extraterrestrial impacts (Ferus et al. 2015) or by irradiation with slow protons (Saladino et al. 2017) may trigger a cascade of highly exergonic processes that could end up with the formation of nucleobases or even nucleosides. Glycosidation reactions between nucleobases and ribose have been described (Šponer et al. 2011; Pérez-Villa et al. 2018). Among them thermodynamics of the reaction between triphosphate-activated ribose and nucleobases has been studied by quantum chemical calculations (Šponer et al. 2011). Subsequent *ab initio* molecular dynamics calculations on the reaction of diphosphate-activated ribose and adenine have provided an overestimation of the reaction free energies most likely because of the inaccuracy of the density functional method used (Pérez-Villa et al. 2018). Quantum chemical calculations have unraveled plausible mechanisms for interstellar glycine formation and have suggested that defects formed in interstellar ices upon irradiation with cosmic rays may trigger various radical reactions of cosmochemical relevance (Rimola et al. 2012).

Formation of biopolymers from monomer precursors is another frequently addressed topic of molecular simulations. Quantum chemical calculations have addressed the mechanism of diglycine formation from glycine in various contexts, like TiO₂ (Pantaleone et al. 2018) and silica (Rimola et al. 2006) surfaces, or in the presence of Cu²⁺ cations in solution (Rimola et al. 2007). The latter study has shown that a synergic effect of Cu²⁺ cations and the surrounding water molecules might catalyze peptide bond formation between two glycine molecules. Oligomerization of imidazole-activated nucleotides on montmorillonite has been studied by force-field based molecular dynamics simulations (Mathew and

Luthey-Schulten 2010). Further insights into the process regarding specific absorption of nucleobases on clay-surfaces were obtained from quantum chemical calculations (Mignon et al. 2009; Mignon et al. 2019). Ring-opening polymerization of cyclic nucleotides has been described using density functional calculations (Šponer et al. 2015). The calculations suggested that the reaction requires formation of a stacked ladder-like supramolecular architecture that provides with optimum steric conditions for the trans-phosphorylation reactions.

Classical force-field based molecular dynamics simulations can be used to describe dynamic behavior of simple biomolecules. For example, transient stabilization of overhang geometries in catalytically active geometries was studied using this methodology (Stadlbauer et al. 2015). The process may be relevant at understanding the emergence of the catalytic activity of short oligonucleotide sequences.

Ab initio molecular dynamics simulations are extensively used to study astrophysical processes relevant to extreme pressures resulted by impact shock-waves. It has been shown that shock-compression of a prototypical astrophysical ice-mixture containing NH_3 , H_2O , CO , CO_2 , and methanol may lead to the formation of glycine (Goldman et al. 2010). Recent model calculations have shown that collision of icy interstellar dust grains containing isocyanic acid may produce a wide plethora of complex organic compounds including formic acid, formamide, carbamic acid, or glycine (Cassone et al. 2018).

In molecular spectroscopy high-level quantum chemical calculations are widely used for interpretation of experimentally measured spectra. For example, computed infrared and rotational spectral signatures may help identification of molecules and molecular complexes in the space based on their observed rotational or vibrational spectra (Barone et al. 2015a).

Future Directions

A recent paper has employed density functional calculations to compare the thermodynamic

stability of a large number of biological and non-biological molecules (Jinich et al. 2020). A detailed statistical analysis performed on a group of selected molecules has shown that metabolites are in general more stable than their non-biological counterparts. This study calls for further investigations of thermodynamic stability in terms of its dependence on environmental effects, which might be a key at understanding the conditions leading to the emergence of life from a lifeless matter.

Combination of various techniques used for molecular simulations represents another promising, so far not sufficiently exploited area which could revolutionize our understanding of chemical mechanisms. For example, combination of quantum chemical calculations and quantum molecular dynamics simulations could bring about a better treatment of solvent environment while achieving highly accurate estimates of energetic data.

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Molecular Spectroscopy

Agúndez Marcelino

Instituto de Física Fundamental, CSIC, Madrid, Spain

Definition

Molecular spectroscopy is the area of science that studies the absorption and emission of

electromagnetic radiation by molecules and its dependence with wavelength, which results in molecular spectra. The spectrum of a molecule is composed of lines that correspond to radiative transitions between discrete energy levels and thus serves as a fingerprint of the molecule. The arrangement of energy levels of a molecule is determined by the molecular structure, i.e., the kinetic and potential energy of electrons (electronic levels), the motion of the nuclei within the molecule (vibrational levels), and the rotation of the molecule (rotational levels). A good introduction to molecular spectroscopy is given by Herzberg (1950). On the other hand, atoms lack vibrational or rotational motions, and thus their energy levels are exclusively associated to electronic states. Atomic spectroscopy studies the radiative transitions between these states, which usually fall in the UV-visible range of the electromagnetic spectrum.

Cross-References

- [Infrared Spectroscopy](#)
- [Spectroscopy](#)
- [Spectroscopy, Electronic \(UV-Vis Astronomy\)](#)
- [Spectroscopy, Rotational](#)
- [Spectroscopy, Vibrational](#)

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Molecular Weight

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Definition

Molecular weight is the sum of the masses of the atoms making up a molecule expressed in atomic

units of mass. One atomic unit of mass, or Dalton (Da), is equal to 1/12th the mass of an atom of the isotope ^{12}C of carbon.

Molecules in Space

Holger S. P. Müller

I. Physikalisches Institut, Universität zu Köln,
Köln, Germany

Keywords

Astrochemistry · Circumstellar envelope ·
Interstellar medium · Ion · Molecule · Radio
astronomy · Rotational spectroscopy

Definition

In this entry, by “molecules” we refer to all types of (generally chemically) bound species consisting of two or more atoms. They may be chemically saturated as well as unsaturated, may contain unpaired electrons (i.e., are radicals), or may be charged positively (cations) or negatively (anions). Space refers here to all regions outside the solar system. On occasion, we restrict the discussion only to the ► [Interstellar Medium](#) and circumstellar envelopes in the Milky Way, thus excluding stellar atmospheres as well as extragalactic sources. Molecules in space usually, but not exclusively, refer to those in the gas phase.

Overview

The spectra produced by molecules in space are used to characterize the physical and chemical properties of certain media in space. For example, certain atomic and molecular absorption lines in the visible region observed in stellar atmospheres are used to classify the stars. Atomic and molecular lines play an important role in star formation, as they help to dissipate the energy of molecular clouds. Lines of specific molecules are used to probe the density, temperature, or ionization degree of the interstellar medium or of

circumstellar envelopes. Complex molecules are of particular interest for astrobiology, as their abundances may provide clues to which extent interstellar chemistry may have played a role in the formation of life on Earth or possibly on other planets.

The Molecules in Space web page (<https://cdms.astro.uni-koeln.de/classic/molecules>) of the Cologne Database for Molecular Spectroscopy (CDMS) (<https://cdms.astro.uni-koeln.de>) (Müller et al. 2001, 2005) features an up-to-date table with about 200 molecular species detected in the interstellar medium or in circumstellar envelopes, as well as an up-to-date table with more than 60 molecules detected in extragalactic sources. Tables 1 and 2 are accurate as of mid-July 2018.

Another useful resource is the web page A Hyper-Bibliography of Known Astromolecules (http://www.astrochymist.org/astrochymist_mole.html) of The Astrochymist (<http://www.astrochymist.org/>) with tables of interstellar and circumstellar molecules, cometary molecules, molecules on planetoids, planetary molecules, and molecules in brown dwarfs and stellar atmospheres.

Basic Methodology

All identified molecules in space have been detected by various spectroscopic means, usually by high-resolution (rotationally resolved) gas phase spectroscopy. Molecules in stellar atmospheres have been identified initially by their electronic spectra in the visible region. Later, the observed spectra were extended to the (vacuum) ultraviolet region and to the near-infrared region. Light hydride species such as H₂O, NH₃, and CH₄ may be detected more favorably by their vibrational spectra in the mid- or near-infrared regions. These relatively short-wavelength spectroscopic methods have also some importance for the detection of molecules in the interstellar medium, circumstellar envelopes, or in extragalactic sources, but the majority of detections and (routine) observations are made by radio astronomy, initially carried out in the radio frequency and microwave region below 40 GHz or with wavelengths longer than 7.5 mm. The millimeter region up to about

300 GHz became accessible approximately in 1970, and around 1985 it was possible to carry out observations at submillimeter or far-infrared wavelengths. Already, the upper millimeter region, and even more so the far-infrared region, are faced with the obstacle that the atmosphere is almost or completely opaque in these frequencies, mainly because of the water vapor. Building observatories at high-altitude sites is a partial remedy; putting them on high-flying airplanes or even on satellites is even better because such observatories are (essentially) not affected by water on the line of sight. On the other hand, such airplane- or satellite-borne observatories are much more expensive to run, and the size of the telescope dish is much more limited.

Key Research Findings

Molecules in Stellar Atmospheres

It is important to keep in mind that the presence or absence of atomic or molecular absorption lines in the visible spectra of stars is used to classify stars. O, B, A, and F stars are too hot and their UV radiation too strong for molecular species to survive. A rather large number of molecular species has been detected in the atmosphere of our sun, a G star, but they were detected mostly in sunspots, which are considerably cooler at the surface than is common. TiO can be observed in late K stars and, more strongly, in M and S stars, which are classified mainly by the strengths of TiO lines and in which other transition metal oxides can be seen, such as VO, ScO, CeO, ZrO, CrO, and FeO. Water can be seen in emission in late K and M giants, while C₂ and SiC₂ have been seen in emission in carbon stars. In still smaller, less luminous, and cooler stars, transition metal hydrides have been identified, such as CrH, FeH, and TiH along with NH₃ and CH₄ and, in at least one case, SH.

On occasion, spectral features of molecules show up in the visible in emission. They are thought to originate from the circumstellar envelope of the star rather than the photosphere. As a consequence, in this entry we separate molecules detected in circumstellar envelopes from those detected in the interstellar medium. The exact

Molecules in Space, Table 2 Molecules in space. Molecules^a detected in extragalactic sources

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	>8 atoms
OH	H ₂ O	H ₂ CO	<i>c</i> -C ₃ H ₂	CH ₃ OH	CH ₃ C ₂ H	<i>l</i> -HC ₆ H*	<i>c</i> -C ₆ H ₆ *
CO	HCN	NH ₃	HC ₃ N	CH ₃ CN	CH ₃ NH ₂		C ₆₀ * (?)
H ₂ *	HCO ⁺	HNCO	CH ₂ NH	<i>l</i> -HC ₄ H*	CH ₃ CHO		
CH	C ₂ H	H ₂ CS?	NH ₂ CN	HC(O)NH ₂			
CS	HNC	HOCO ⁺	<i>l</i> -C ₃ H ₂				
CH ⁺	N ₂ H ⁺	<i>c</i> -C ₃ H	H ₂ CCN				
CN	OCS	H ₃ O ⁺	H ₂ CCO				
SO	HCO	<i>l</i> -C ₃ H	C ₄ H				
SiO	H ₂ S	C ₂ H ₂ *					
CO ⁺	SO ₂						
NO	HOC ⁺						
NS	C ₂ S						
NS	H ₂ O ⁺						
NH	HCS ⁺						
HF	H ₂ Cl ⁺						
SO ⁺	NH ₂						
ArH ⁺							
CF ⁺							
SH ⁺							

^aSee footnote to Table 1

source of emission features in the infrared appears to be more uncertain.

Molecules in the Interstellar Medium and in Circumstellar Envelopes

Around 1935, some diffuse absorption lines, suspected to be of molecular origin, were detected in the visible spectra recorded toward certain stars. The diffuse nature of the lines was interpreted as evidence that the carriers of these lines were not associated with the stellar environment but rather with the interstellar medium on the line of sight. Three lines were assigned to CN, CH, and NaH (McKellar 1940); the latter assignment still remains to be confirmed. It was noted that only transitions originating from the lowest rotational levels could be identified unambiguously, suggesting very low temperatures of the environment. In fact, the second rotational level of the CN radical is at 5.43 K. Shortly thereafter, three additional lines were assigned to CH⁺ (Douglas and Herzberg 1941).

Even though radio telescopes had been available since the early 1930s, the first molecule to be detected by this technique, and the fourth

interstellar molecule altogether, was the OH radical in 1963 (Weinreb et al. 1963). Only diatomic molecules had been detected thus far, and it was even speculated by several astronomers that polyatomic molecules, that is, molecules with more than two atoms, could not be formed in the interstellar medium. Therefore, it came as a big surprise that the next two detected molecules, NH₃ (Cheung et al. 1968) and H₂O (Cheung et al. 1969), were polyatomic molecules. Moreover, the molecular lines were observed in emission toward hot-core sources, the rather warm and dense molecular clouds that enshroud young massive stars. Several further light hydride species, molecules consisting of one heavy atom besides H atoms, have been detected. These include SiH₄, CH₄, H₃⁺, and CH₃, which have been observed by infrared spectroscopy because the molecules do not have a permanent electric dipole moment and thus no radio spectrum.

H₂S, HCl, H₃O⁺, CH₂, NH, NH₂, and HF have been detected or observed employing radio astronomy. However, the strong transitions of these light hydride species occur in the terahertz or far-infrared region, which is partly difficult to

access and in part simply not accessible from the ground, requiring radio telescopes on high terrestrial sites, on board of high-flying airplanes such as the NASA's Kuiper Airborne Observatory (KAO), or on board of satellites such as the ► **Infrared Space Observatory (ISO)**; these two missions were in operation in the 1990s. More recently, the Atacama **Pathfinder EXperiment (APEX)** telescope has been built in the Chilean Andes, and the Atacama Large Millimeter Array (ALMA) has started operations at the same site recently. OH^+ (Wyrowski et al. 2010) and SH^+ (Menten et al. 2011) were detected for the first time with APEX. The Herschel satellite was launched 14 May 2009, and ceased to operate 29 April 2013 because the liquid helium coolant was consumed. Numerous Herschel observations were dedicated to light hydride species, in particular to H_2O . Four cationic hydrides, H_2O^+ (Ossenkopf et al. 2010), H_2Cl^+ (Lis et al. 2010), HCl^+ (De Luca et al. 2012), and most recently ArH^+ (Barlow et al. 2013, see also Schilke et al. 2014), were newly detected. The **Stratospheric Observatory for Infrared Astronomy (SOFIA)** started operating in 2010. The **German REceiver At Terahertz frequencies (GREAT)** permits high-resolution observations, e.g., in a frequency gap of *Herschel*/HIFI around 1.3 THz. The first detection of SH in that gap has been reported (Neufeld et al. 2012).

The first polyatomic molecule with two heavy atoms, formaldehyde, H_2CO , was among the very early detected molecules, and it is rather ubiquitous (Synder et al. 1969). Related molecules H_2CNH , H_2CS , and H_2CCO were detected soon thereafter. The isoelectronic diatomic molecules CO, SiO, CS, and SiS were also among the molecules detected very early in the interstellar medium. CO is particularly important as it is the second most abundant molecule in space after H_2 . Moreover, since H_2 is very difficult to observe, CO transitions are frequently observed in order to trace H_2 , although the H_2/CO ratio is thought to vary somewhat as a function of environment (cf. Pineda et al. 2013). SiO is usually viewed as an indicator of shocks.

It is worthwhile mentioning that many atoms have more than one stable isotope. As a

consequence, several ► **Isotopologs** have been detected for molecules that are abundant in certain regions in space. In the case of CO, for example, all six stable isotopologs involving $^{12,13}\text{C}$ and $^{16,17,18}\text{O}$ have been detected. Eight isotopic species have been observed for SiS in the circumstellar envelope of CW Leonis (IRC +10216), all possible combinations involving $^{28,29,30}\text{Si}$ and $^{32,34}\text{S}$ along with $^{28}\text{Si}^{33}\text{S}$ and $^{28}\text{Si}^{36}\text{S}$, thus providing important information on the nuclear synthesis in this late-type star. PO was the first molecule for which the first detection was described in the circumstellar envelope of an oxygen-rich star, namely, VY Canis Majoris.

HCN and HC_3N are quite abundant in all types of region and were also among the molecules detected earliest. The longer chain molecules HC_5N , HC_7N , and HC_9N have been detected in dark molecular clouds, such as TMC-1 (the Taurus Molecular Cloud No. 1), or in circumstellar envelopes, in particular of the carbon-rich star CW Leonis.

In several cases, more than one isomer of a certain formula has been detected. For example, besides cyanoacetylene, HC_3N , isocyanoacetylene, HCCNC , and iminopropadienylidene, HNC_3 , have been detected. More recently, fulminic acid, HCNO , and cyanic acid, HOCN , were detected, which are isomers of the abundant isocyanic acid, HNCO .

Some molecules were detected by radio-astronomical means prior to their laboratory spectroscopic identification. Formylum, HCO^+ (Buhl and Synder 1970), was the first and most notable example. Others include HNC , CCS , HCS^+ , HOCO^+ , and $c\text{-C}_3\text{H}_2$. Several additional examples will be given below.

Many of the cations observed in the interstellar medium or circumstellar envelopes can be obtained formally by protonation of rather stable, closed-shell species, such as CO, N_2 , CS, CO_2 , HCN, H_2O , HC_3N , H_2 , H_2CO , HCl, and C_3 , thus leading to comparatively stable, closed-shell cations, such as HCO^+ and HOC^+ , N_2H^+ , HCS^+ , HOCO^+ , HCNH^+ , H_3O^+ , HC_3NH^+ , H_3^+ , H_2COH^+ , H_2Cl^+ , $l\text{-C}_3\text{H}^+$, and probably H_2NCO^+ . Doubts on the identification of $l\text{-C}_3\text{H}^+$ have become obsolete with the recent recording of

the laboratory rotational spectrum (Brünken et al. 2014). The remaining known cations are in part radicals, SO^+ , CO^+ , OH^+ , SH^+ , H_2O^+ , and HCl^+ , or also closed-shell species, CH^+ and CF^+ . The latter may seem peculiar to some as it contains the most electronegative element, fluorine, in a cation. However, one should keep in mind that it is isoelectronic with CO.

Only a few cyclic species have been detected unambiguously thus far. Besides $c\text{-C}_3\text{H}_2$, these are $c\text{-SiC}_2$, $c\text{-C}_3\text{H}$, H_3^+ , $c\text{-C}_2\text{H}_4\text{O}$, $c\text{-SiC}_3$, and $c\text{-H}_2\text{C}_3\text{O}$. Aromatic molecules, which play an important role in biochemistry, are mostly too big to be observed. However, benzene was detected in the infrared. In addition, certain infrared features are commonly believed to be due to polycyclic aromatic hydrocarbons (PAHs), but the exact nature of these species is not known.

Fullerenes, large molecules built from carbon only and forming near-spherical cage structures, were thought to be present in space ever since they were detected in the laboratory, and attempts were made to identify them as soon as their IR spectra had been measured. C_{60} was particularly promising because the highly symmetric cage structure gives rise to only four infrared-active vibrations. Moreover, it is usually by far the most abundant fullerene in laboratory experiments. C_{70} is less symmetric and usually less abundant, and this applies even more so to somewhat larger fullerene molecules. C_{60} and C_{70} have been identified unambiguously in space for the first time in the circumstellar envelope of a peculiar planetary nebula Tc 1 (Cami et al. 2010). There have been several later and some earlier reports on the detection of fullerenes in space. However, some of them should be viewed with caution, and some may even be incorrect because first, PAH molecules and fullerenes are not cospatial, and second, some infrared features of C_{60} can be caused by molecules, which contain H atoms and are thus not fullerenes.

Methanol, CH_3OH , is very ubiquitous and was the first complex molecule detected in space (Ball et al. 1970). A complex molecule in radioastronomy may be defined as an asymmetric rotor molecule having at least five atoms and which is usually fully saturated or nearly

saturated. CH_3OH as well as some other complex molecules such as dimethyl ether, vinyl cyanide, ethanol, and methyl formate are so abundant and have such a large number of observable transitions that they have been called interstellar weeds. More complex molecules are usually less abundant, and the intensity of spectral features is distributed over many more lines; both these issues make it harder to detect larger complex molecules unambiguously. Ethyl formate, its isomer methyl acetate, and n -propyl cyanide are the largest complex molecules unambiguously detected thus far, and model calculations are compatible with their formation on grain surfaces.

The purported detection of interstellar glycine shall be mentioned in this context. In 2003, the detection of several transitions of glycine, aminoacetic acid, the simplest amino acid, was claimed in three hot-core sources (Kuan et al. 2003). Such sources are particularly line rich. The detection has been disputed (Snyder et al. 2005) because the derived model required several additional lines to be observable, but they were not detected. It is important to note that emission features assigned to a certain molecule may well be stronger than predicted by a model because of overlap, possibly by an unidentified species, but a line cannot be weaker than predicted if the model is correct. Consequently, only an upper limit is currently known for interstellar glycine. As in similar cases for other molecules, this simply means that the abundance of interstellar glycine in the gas phase is too low to be identified unambiguously at present. This situation may change with Atacama Large Millimeter Array (ALMA), as its much greater sensitivity and its greater spatial resolution may be advantageous for the detection of glycine and other complex molecules. Of course, no statement can be made about glycine residing in the solid phase, for example, in interstellar ices or grains. The detection of molecules with low abundances in the solid phase is generally very difficult, as spectral lines of solids, for example, in the infrared, are quite broad and rarely very distinctive. Nevertheless, a plethora of complex molecules have been identified through direct chemical analyses of the Murchison meteorite, including many amino acids. The molecules

show no or only small chiral preference and include many which have not been identified in living beings, indicative of an abiotic origin. These findings suggest that at least some amounts of more complex molecules are formed in certain regions of space. It should be mentioned in this context that aminoacetonitrile, which is considered to be the most likely precursor of glycine, has recently been detected in the high-mass star-forming region Sagittarius B2(N-LMH).

Soon after the interstellar detection of SiO in 1971, vibrationally excited SiO was detected with an unknown carrier (Snyder and Buhl 1974) but correctly identified soon thereafter. Very highly excited SiO (up to $v = 4$ with a vibrational energy of almost 7000 K), HNC (up to about 6000 K), or HCN (up to almost 11,000 K) have been detected in circumstellar envelopes of late-type stars. In addition, vibrational satellites of many more molecules have been detected in hot-core sources or in circumstellar envelopes. They offer the opportunity to probe exclusively the hottest regions in the interstellar medium.

Low temperatures favor exchange reactions of the heavier isotope in molecules with large differences in zero-point vibrational energies. Such differences are particularly large for D/H exchange. HDO was the first deuterated molecule to be detected in space, by Turner et al. (1975). Since then, not only singly deuterated molecules such as DCN, DNC, DCO^+ , NH, and OD have been detected but also doubly deuterated ones, for example, D_2O , D_2S , D_2CO , D_2CS , and $c\text{-C}_3\text{D}_2$, and even triply deuterated ones, namely, ND_3 and CD_3OH .

Molecules containing metals in the chemical sense (not in the very general astronomical sense: every element heavier than helium) remained elusive for quite a while. The first one to be detected was MgNC (Guélin et al. 1986) in the circumstellar envelope of the evolved star CW Leonis, but its correct identification occurred only much later (Kawaguchi et al. 1993). In the meantime, NaCl, KCl, AlF, and AlCl had been detected in the same source. Later, NaCN, MgCN, AlNC, KCN, FeCN, and most recently HMgNC were also detected in that source. Some of these, MgNC, NaCN, AlF, and NaCl, were also detected in other

circumstellar envelopes. AlO and AlOH were the first two metal-containing molecules that were detected in the circumstellar envelope of an oxygen-rich star, VY Canis Majoris. TiO and TiO_2 have been detected (Kamiński et al. 2013). The detection of TiO_2 is particularly interesting as it is thought to act as seed for dust in oxygen-rich late-type stars. It is worthwhile mentioning that TiO as well as some other metal oxides were detected earlier in emission in optical spectra of late-type stars, which is viewed as indicative of a circumstellar origin, in contrast to absorption features, which are thought to originate in the stellar atmospheres. A more detailed account on these issues is intended for the future.

Even though several transition metal compounds have been identified in stellar atmospheres, the only report of this type of molecule in the interstellar medium or in circumstellar environments is the tentative detection of FeO in absorption toward Sagittarius B2(M). The detection is tentative because only one spectral line has been observed. This would also be the first detection of a metal-containing molecule in the interstellar medium (as opposed to circumstellar envelopes) by radio astronomy, although the tentative detection of NaH mentioned above should be kept in mind.

The first molecular anion detected in space was C_6H^- (Kawaguchi et al. 1995); however, it was identified unambiguously only much later (McCarthy et al. 2006). C_4H^- , C_8H^- , C_3N^- , C_5N^- , and CN^- have also been detected. Interestingly, C_5N^- was identified unambiguously even though no laboratory data have been available to date. All these ions are closed-shell species, which can be derived from HC_{2n+2}H or its isoelectronic HC_{2n}CN by abstraction of a proton. There is one weak feature in solid-state infrared spectra that has been attributed to the OCN^- ion, but this assignment appears to be contested. A different weak solid-state feature was assigned to the CO_2 molecule, and this assignment is secure. Other solid-state molecules that have been identified are discussed in the entries on interstellar ices and interstellar dust.

Molecular oxygen, O_2 , was suggested to be abundant at least in certain regions of the

interstellar medium. Its observation is difficult because it has no permanent electric dipole moment, and the magnetic dipole transitions are rather weak. Moreover, observations of O_2 are not possible from ground-based radio telescopes because of the presence of large amounts of oxygen in Earth's atmosphere. Two reports have been published on the unambiguous detection of O_2 using the HIFI instrument on board of the *Herschel* satellite, albeit at levels much lower than already low model predictions and in sources which display a rather peculiar chemistry. In one of the sources, ρ Ophiuchi A, the related molecules H_2O_2 and HO_2 were detected with APEX (Bergman et al. 2011, Parise et al. 2012).

One of the greatest and longest-lasting mysteries in astronomy is the identity of the Diffuse Interstellar Bands (DIBs), which have been detected in absorption in optical spectra toward stars for the first time in 1922. To date, more than 200 of these are known in the far-UV, visible, and IR regions. A fairly recent review has been published by Herbig (1995). The nature of these absorption lines is not clear. Often, they form small groups. High-resolution contour studies suggest that at least some of the carriers, probably even most, are of molecular origin. Many carriers appear to be present in the diffuse ISM, but some may occur in the dense ISM. Observation toward the star Herschel 36 in Sagittarius revealed very unusual band contours for several DIBs (Dahlstrom et al. 2013). Spectroscopic arguments lead to the conclusion that some carriers are likely small molecules consisting of about three to eight atoms whereas others appear to be much larger molecules.

Another interesting issue is the unidentified aromatic infrared emission bands, which are commonly ascribed to PAHs. It is generally accepted that these are the most likely carriers of these emission bands, but again, the exact nature is not clear, in particular because the features are caused by more than one species and may include neutrals as well as charged species. PAHs are also proposed as one possible group of molecules for the carriers of the DIBs.

Molecules in Extragalactic Sources

The molecules detected in external galaxies are thus far a subset of the molecules detected in the interstellar medium, simply because these objects are farther away than our galaxy. Great progress has been made in recent years in terms of investigations into the chemical complexity of external galaxies. As for molecular clouds, the chemical composition depends to a great extent on details of the galaxy, such as size, age, and star formation activity. Starburst galaxies, such as the nearby NGC 253 or M82, show a particularly rich and varied chemistry.

The first molecule to be detected in an external galaxy was OH as early as 1971 by Weliachew, toward the two galaxies NGC 253 and M82. Many other di- and polyatomic molecules have been detected. In recent years, the field has flourished enormously because of molecular line surveys toward several different galaxies and because of extensive observations with the *Herschel* satellite. Particularly noteworthy in this context was a molecular line survey by Muller et al. (2011) of an unnamed foreground galaxy toward the quasar PKS 1830–211. The observations were carried out with the Australia Telescope Compact Array (ATCA). Rest frequencies from the 4 mm wavelength region were red shifted into the 7 mm region. Several molecules were detected for the first time in an extragalactic source in the course of this study. The list of complex organic molecules includes now formamide, methylamine, and acetaldehyde. In addition, detections of di- and triacetylene as well as benzene appear to be secure. The detection of the fullerene C_{60} was also reported. There have also been several reports on molecules in very distant, high-red-shift galaxies, in particular of CO and H_2O .

Future Directions

As indicated already, ground-based instruments such as APEX, ALMA, the IRAM 30 m instrument, NOEMA, as well as the *Herschel* satellite, along with the Stratospheric Observatory for Infrared Astronomy (SOFIA), have provided

and will continue to provide extensive opportunities to carry out observations in the terahertz (or far-infrared) region which, among other interesting results, are relevant to the detection of light hydride molecules. The ALMA has begun early science observations, and some results have been published already; it will provide unprecedented sensitivity and spatial resolution. This should facilitate studies of complex molecules in dense molecular clouds. It may well become possible to detect much larger molecules, though these are frequently easier to detect at longer wavelengths. Moreover, it will surely be beneficial for the study of circumstellar envelopes, where metal-containing molecules may be easier to detect, or of extragalactic sources. It will also be possible to study comparatively small-scale structures in nearby galaxies. In addition, the increase in sensitivity will open new opportunities to study very distant galaxies routinely. Other radio interferometers, such as the Sub-Millimeter Array (SMA), the Plateau de Bure Interferometer (PdBI), or the Jansky Very Large Array (JVLA) at lower frequencies, will remain or even grow in importance as they undergo various forms of upgrade. In addition, a number of interesting detections have been made with the Green Bank Telescope (GBT) and others at higher frequencies, e.g., with the IRAM 30 m telescope. The field of astrochemistry is thus expected to flourish tremendously in the next few decades.

Cross-References

- Absorption Spectroscopy
- Abundances
- Abundances of Elements
- Acetone (CH_3COCH_3)
- Acetonitrile
- Alcohol
- Aldehyde
- ALMA
- Amino Acid
- Aminoacetonitrile ($\text{NH}_2\text{CH}_2\text{CN}$)
- Ammonia

- Anion
- Complex Organic Molecules
- Cyanamide
- Cyanoacetylene
- Cyanopolyne
- Dense Cloud
- Deuterium/Hydrogen Ratio
- Diffuse Cloud
- Diffuse Interstellar Bands
- Formaldehyde
- Formyl Cation (HCO^+)
- Fullerene
- Glycine
- HCNO Isomers
- Herschel Mission
- Hot Core
- Hot Corino
- Hydrogen Cyanide
- Infrared Astronomy
- Infrared Spectroscopy
- Interstellar Dust
- Interstellar Medium
- ISO
- Isomer
- Isotopic Fractionation (Interstellar Medium)
- Isotopolog
- Meteorite, Murchison
- Methanol
- Methylidyne (CH)
- Methylidyne Cation (CH^+)
- Molecular Cloud
- Organic Molecule
- Polar Molecule
- Polycyclic Aromatic Hydrocarbon
- Radical
- Radio Astronomy
- Silicon Monoxide (SiO)
- Spectral Line
- Spectroscopy
- Star Formation Rate

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Monod's Conception on the Origins of Life

Michel Morange

Centre Cavailles, USR 3308 CIRPHLES, Ecole normale supérieure, Paris Cedex 05, France

Keywords

DNA · Oparin · Origin of life · RNA world

History

Jacques Monod's interest in the question of the origin of life came late in his career, when he tried to summarize the major conceptual transformations resulting from the rise of molecular biology, first in lectures, and then in his influential book *Chance and Necessity*.

For Monod, the formation of the first living organisms had been a highly improbable event, and Earth was probably the only place in the Universe harboring life. The formation of living organisms can be explained by the laws of physics and chemistry, but it was unpredictable. This opinion was based on the results recently obtained in molecular biology, which showed the exquisite nature of the mechanisms involved in the transmission of genetic information through generations, and its use at each generation. An even more serious obstacle to the origin of life was the necessity for organisms to possess two different types of macromolecules: DNA, to store the genetic information; and proteins, the active agents of living cells. The origin of life meant the simultaneous formation of these two types of macromolecules. There are tight relations between these two macromolecules: DNA codes for proteins, and proteins are required for the use of the information encoded in the DNA. Not only did both types of macromolecules have to appear simultaneously, but they had to have from the beginning at least a part of their complex relations.

Monod was probably philosophically happy with this conclusion. It justified scientifically his feeling of an absurd Universe and of the loneliness of human beings in it.

Monod did not see in the scenarios elaborated by the Russian biologist Oparin a way to overcome these difficulties. Not only did these scenarios fail to take into account the most recent molecular descriptions, but their author was compromised by the support he gave to Lysenko under the Soviet regime. Monod distrusted Oparin and his models.

Forty years later, the situation is very different. The discovery of the catalytic role of RNA has led to the hypothesis of the existence of an RNA world that preceded the present living world. The difficulties outlined by Monod have not been totally removed, but ways to overcome them are being explored. Most present-day biologists consider that the formation of simple forms of life was not so difficult, and that the search for these forms of life on other planets deserves to be supported.

Cross-References

- [Genetics, History of](#)
- [Oparin's Conception of Origins of Life](#)

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Monogenic Breccia

- [Monomictic Breccia](#)

Monomictic Breccia

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Monogenic breccia](#)

Definition

A *monomictic* or *monogenic breccia* is a sedimentary rock composed of angular clasts derived from a single lithology. The term monomictic also refers to a specific process of brecciation produced by rock shearing and granulation (cataclasis) during a tectonic event or by dislocation metamorphism (a type of metamorphism of local extent, associated with fault or shear zones). If the dislocation metamorphism is related to a meteorite impact, the breccia may be termed a *monomictic impact breccia*. Reiff (1978) by discussing monomictic breccia complexes in impact structures such as Ries (Germany) coined a new term *monomictic movement breccia*. In impact structures, a drastic brecciation of whole rock complexes to silt fraction grain size (<50 µm) requires intense movement under very high confining pressure.

Cross-References

- [Breccia](#)
- [Crater, Impact](#)
- [Impact Basin](#)
- [Impact Melt Rock](#)
- [Impactite](#)

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Monophyletic

David Moreira and Purificación López-García
Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris,
Orsay Cedex, France

Synonyms

[Holophyletic](#)

Definition

In classical taxonomic and phylogenetic literature, a monophyletic group, also called a clade, is defined as an assemblage that contains an ancestor and all its descendants. This term is most often applied to define groups of organisms that derive from a ► [common ancestor](#), which form monophyletic taxa or clades (e.g., animals or cyanobacteria). However, it is used by molecular phylogeneticists also to define particular groups of DNA, RNA, or protein sequences in ► [phylogenetic trees](#) (e.g., different protein families derived from gene duplications). Monophyletic groups are based on the identification of synapomorphies, which are shared derived characters (e.g., a skull and a distinct head are synapomorphies of vertebrates). This criterion allows differentiating monophyletic groups from paraphyletic groups (those containing an ancestor and part of its descendants, such as the reptiles) and polyphyletic groups (those that do not contain the last common ancestor of their members, such as the flying animals, including disparate members like insects, birds, and bats).

Cross-References

- [Common Ancestor](#)
- [Evolution, Biological](#)
- [Last Common Ancestor](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)
- [Taxonomy](#)

Monosaccharide

Shin Miyakawa
Kamagaya, Chiba, Japan

Synonyms

[Simple sugar](#)

Definition

Monosaccharides are monomeric ► [carbohydrate](#) molecules. Examples include glucose, fructose, galactose, xylose, and ► [ribose](#). 2-Deoxyribose and ribose are constituents of DNA and ► [RNA](#), respectively. Many of the carbon atoms attached to hydroxyl groups are chiral centers, giving rise to a number of isomeric forms. Many monosaccharides are unstable over geological timescales. The half-lives for the decomposition of ribose, for example, are 73 min at 100 °C, and 44 years at 0 °C at pH 7. They can be formed in the ► [formose reaction](#) from ► [formaldehyde](#). Monosaccharide-like compounds have been found in carbonaceous chondrites, and one of the ketoses, dihydroxyacetone ($\text{HOCH}_2\text{COCH}_2\text{OH}$), was identified in the extract of Murchison meteorite.

Cross-References

- [Carbohydrate](#)
- [Carbonaceous Chondrite](#)
- [Chirality](#)
- [Deoxyribose](#)
- [Formaldehyde](#)
- [Formose Reaction](#)
- [Ribose](#)
- [RNA](#)

Mons, Montes

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Rutherfordstrasse 2, Berlin, Germany

Definition

Mons (plural montes) is the term defined by the International Astronomical Union (<http://planetarynames.wr.usgs.gov/jsp/append5.jsp>) to

refer to mountain (mountains). It is used as a descriptor term for naming surface features on the ► [terrestrial planets](#), the Moon, and the Jovian satellite ► [Io](#).

Cross-References

- [Io](#)
- [Moon, The](#)
- [Satellite or Moon](#)
- [Terrestrial Planet](#)

Montmorillonite

Gözen Ertem
National Institutes of Health, Bethesda, MD, USA

Keywords

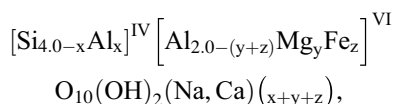
Catalyst · Cation exchange · Clay minerals ·
Oligomerization · Origin of life

Definition

Montmorillonite is a ► [clay](#) mineral of the smectite group, which also includes nontronite and saponite. It was first discovered in 1847 in Montmorillon in the Vienne region of France. It is usually white, gray, or pink with shades of green or yellow as a result of the metal oxide impurities it contains. It is often found in compact or lamellar masses, but never in large individual crystals. Its specific gravity varies between 1.7 and 3.0. It has a hardness of 1–2 in the Mohs scale (the Mohs scale ranges between 1 and 10, where 1 and 10 correspond to talc and diamond, respectively). Chemically, it is a hydrated aluminum silicate containing small amounts of magnesium, iron, sodium, calcium, and potassium as a result of isomorphic substitutions. The nature of these cations and their ratio within the mineral structure vary with the source of montmorillonite.

Overview

Montmorillonite (Grim 1968) has a layer structure with 2:1 arrangement: Each layer is composed of three sheets. Two outside sheets, called tetrahedral sheets, contain silicon ions, Si^{4+} , tetrahedrally coordinated to oxygens. The middle sheet, called the octahedral sheet, is made up of aluminum ions, Al^{3+} , surrounded by oxygens in octahedral coordination. The general formula of montmorillonite may be represented as



where IV and VI denote the tetrahedrally and octahedrally coordinated cations, respectively. The term $(x + y + z)$ is the total of substitutions in the octahedral and tetrahedral sheets. Theoretically, montmorillonite is assumed to have formed from pyrophyllite $[(\text{Al}_2)(\text{Si}_4\text{O}_{10})(\text{OH})_2]$.

During the formation of clay minerals by weathering, some of the Si^{4+} ions in the tetrahedral sheet are replaced by cations of similar size (isomorphic substitution), usually Fe^{3+} , and some of the Al^{3+} cations are replaced by Mg^{2+} . These replacements result in excess negative charge, which is counterbalanced by so-called interlayer cations held between the layers. Since sodium is one of the most abundant cations in nature, most clay minerals contain Na^+ as an exchangeable cation. The extent of isomorphic substitutions is defined as cation-exchange capacity, CEC, of montmorillonite and expressed as milliequivalents of interlayer cation/100 g of clay. Most montmorillonites have a CEC of about 100.

Because of its large surface area, about $800 \text{ m}^2/\text{g}$, montmorillonite is widely used as an absorbent for toxins, hazardous chemicals, and heavy metal cations. Montmorillonites can absorb water and swell to about 20 times of their dry volume and give rise to permanent suspensions of gel-like masses.

Hydration, or solvation, of interlayer cations causes the layers to expand. Due to this expansion, organic molecules, such as amines, alcohols and polyalcohols, nucleic acid bases, nucleosides, and oligomers, can enter the interlayer of

montmorillonite. This expansion capability, which is a result of the isomorphic substitutions, gives the montmorillonite its catalytic properties. Extensive studies have demonstrated that montmorillonite serves as an effective catalyst for the ► [oligomerization](#) of activated nucleic acid monomers (Ertem et al. 2010). These reactions are very significant in terms of ► [origin of life](#) studies as was first suggested by John D. Bernal (1949).

Cross-References

- [Bernal's Conception of Origins of Life](#)
- [Clay](#)
- [Oligomerization](#)
- [Oligonucleotide](#)
- [Origin of Life](#)
- [Phyllosilicates, Extraterrestrial](#)

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Moodies Group

Christoph Heubeck
Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

Definition

The Moodies Group is the uppermost stratigraphic unit in the ► [Barberton Supergroup](#), the sedimentary-volcanic fill of the ► [Barberton Greenstone Belt](#), South Africa and Swaziland. It is one of the oldest well-preserved shallow-water sedimentary sequences on Earth, reaches up to

approximately 3.7 km in thickness and is, north of the Inyoka Fault, $3,224 \pm 1 - 3,219 \pm 10$ Ma old (Heubeck et al. 2013). Its stratigraphic architecture, facies, petrography, age, and style of deformation allow detailed insights in mid-Archean surface conditions. The equivalent to the Moodies Group in Swaziland is the Malolotsha Group (Lamb 1984, 1987).

Overview

Hall (1918) originally defined the Moodies Series, named after a local land surveyor, to include all sedimentary units in the BGB. The modern definition and use of the Fig Tree and Moodies Groups go back to Visser et al. (1956). Anhaeusser (1976) subdivided the Moodies Group in three formally defined formations (Joe's Luck, Clutha, and

Baviaanskop) and a number of informal lithostratigraphic members. Eriksson (1977) suggested an alternative subdivision in five fining-upward sequences (MD1 through MD5).

Structure

Moodies strata are mostly preserved in large (ca. 5–15 km long, several km wide) synclines. Geologists describe them as being “tightly to isoclinally folded, commonly northward overturned, and doubly plunging, refolded about vertical axes. Fold axis plunge may become vertical and even overturned” (Figs. 1 and 2). Figuratively speaking, the synclines appear somewhat like horizontally sliced bananas, the anticlines between them like mushrooms. The resulting high strain is concentrated in brittle shear zones and is presumably also expressed by widespread simple shear in (usually poorly exposed) fine-grained intervals;

Moodies Group,

Fig. 1 Along-strike view of Moodies Group strata in the Saddleback Syncline, central BGB. The fluvial-deltaic and tidal strata dip steeply to the *right*; stratigraphic up is to the *left*



Moodies Group,

Fig. 2 Downplunge view (towards the SW) of the Saddleback Syncline in the central BGB, illustrating tight to isoclinal folding of sandstones and interbedded silty sandstones



in contrast, the sandstone-dominated units on the fold limbs are nearly free of strain. Syn-deformational deposition, expressed as inward-facing progressive unconformities, has been documented from the southern (Lamb 1987) and northern (Heubeck and Lowe 1994b) margins of the BGB, suggesting that at least part of the Moodies Group was eroded from the cover of rising plutons nearby and shed as alluvial fans into subsiding elongate troughs.

It is unclear to which degree Moodies strata represent a single coherent depositional system. The continuity of the key marker unit, the Moodies basaltic lava (MdL), over >60 km along strike and across four structurally separated synclines north of the Inyoka Fault suggests that at least some of the Moodies basins were integrated during middle Moodies time (all of Moodies time may have been only a few Ma long). In contrast, the uneven distribution and thickness and the highly distinctive clast composition of the basal conglomerate and of the stratigraphically highest conglomerates indicate that the Moodies basin was dominated by local, not regional, dispersal processes in early and late Moodies time.

Quartzose sandstones assigned to the Moodies Group south of the mid-BGB Inyoka Fault lack K-feldspar, appear to represent a higher metamorphic grade, lack recognizable marker beds, and are preserved in greatly reduced thickness. Their temporal and paleogeographic relationship to the “classic” Moodies stratigraphy north of the Inyoka Fault is uncertain.

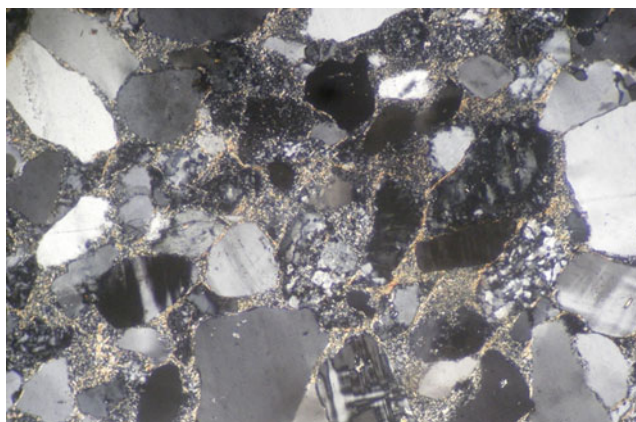
Lithologies and Facies

The Moodies Group is dominated by sandstones. Siltstones and conglomerates are subordinate in most localities; shale is very rare. Volcanic rocks include one regional basaltic lava unit, numerous discontinuous and thin rhyodacitic tuffs, and at least one local ignimbrite. Minor jaspilite and BIFs, interbedded with siltstones, serve as important regional marker units. Sandstone composition varies widely and ranges from quartzarenites to subarkoses (up to 22% feldspar) and to volcanic litharenites and chertarenites (Heubeck and Lowe 1999). Eriksson (1977, 1978, 1979, 1980) and Heubeck and Lowe (1994a) distinguished between alluvial, fluvial, deltaic, shoreline, tidal, and offshore facies. Eriksson et al. (2006) describe a well-exposed fluvial-to-marine facies transition; Eriksson and Simpson (2002) provide data which may bear on Archean tidal cycles, and Simpson et al. (2012) outlined features of likely eolian deposition (Fig. 3).

The base of the Moodies Group is transitional from concordantly underlying volcanics and volcanoclastics of the Schoongezicht Formation (uppermost unit of the Fig Tree Group); conventionally, the contact is placed at the lowest occurrence of polymict (i.e., composed of clasts of many different lithologies) conglomerates, overlying the feldspar-porphyry-dominated Schoongezicht conglomerates. The top of the Moodies Group is not exposed because BGB strata are unconformably overlain by strata of the Transvaal Supergroup. Moodies stratigraphy has been best investigated

Moodies Group,

Fig. 3 Thin section photomicrograph of a subquartzarenite of unit MdQ1, Saddleback Syncline. Grains of monocrystalline quartz, chert, quartz-sericite-mosaic, and microcline are embedded in a sparse sericitic-calcareous matrix



in the thick and subvertically dipping limbs of the Stolzburg, Saddleback, and Eureka Synclines and in the Moodies Hills Block.

Life

Following a cursory description (Heubeck and Lowe 1994a), Noffke et al. (2006) interpreted abundant crinkly laminations in the MdQ1 member of the Moodies Group in the Saddleback Syncline (and beds of uncertain stratigraphic position in the Dycedale Syncline) as microbial mats. Their observations were specified and expanded by Heubeck (2009), Gamper et al. (2012) and Homann et al. (2015). Independently, Javaux et al. (2010) extracted organic-walled macro-spheres up to 300 μ in diameter from stratigraphically poorly constrained siltstones of the Moodies Group from drill cores of a mine; these findings are not yet documented from outcrop.

The microbial laminae (Fig. 4) likely represent extensive photosynthetic ► **microbial mats** in sub-, inter-, and supratidal facies. The stratigraphically lowest microbial mats are interbedded with conglomeratic, poorly channelized cross-bedded sandstones and intervening thin mudcracked shales; they may thus be fluvial in facies. The presumably high tidal ranges, however, likely blurred the distinction between fully marine, tidal, and fully terrestrial facies in the Archean.

Age

Centimeter- to decimeter-thick rhyodacitic ash beds, occasionally lapilli bearing, are not

uncommon in the Moodies Group; in addition, several felsic dikes, probably radiating from the Kaap Valley Pluton or marginally associated sub-volcanic feldspar porphyry bodies, crosscut beds of the Moodies Hills Block and of the Eureka Syncline along the northern margin of the BGB (Layer et al. 1996; Heubeck et al. 2013). Inferred depositional ages of the volcanic beds throughout the Moodies Group obtained through single-zircon U-Pb dating are nearly indistinguishable from each other. They indicate that Moodies deposition began $\sim 3,224 \pm 1$ Ma and had ended by $\sim 3,219 \pm 10$ Ma (Heubeck et al. 2013).

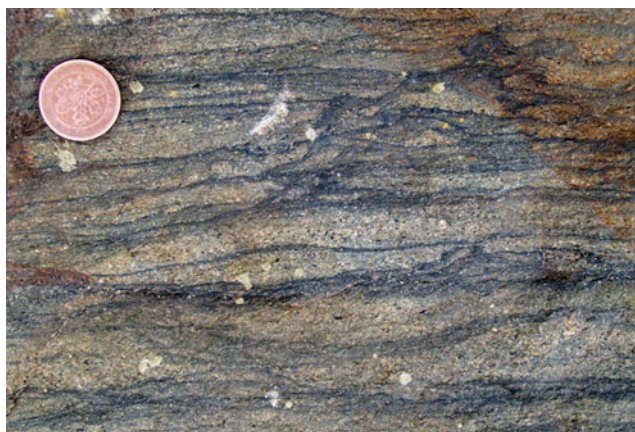
Tectonic Setting

A considerable number of tectonic settings have been proposed to be represented by the Moodies Group. They include a stable continental margin, evolved from a continental rift (Eriksson 1979, 1980); a foreland basin setting north of an ancient orogen made up of the Ancient Gneiss Complex and the Onverwacht rocks (Jackson et al. 1987; Eriksson et al. 1994); an initially extensional and strike-slip-related setting followed by basin collapse (Heubeck and Lowe 1994b); and an arc-related or back-arc basin setting. Kisters et al. (2003, 2010) and Lana et al. (2011) favored a strongly extensional basin. The contemporaneity of solid-state pluton uplift adjacent to the belt along with evidence of syndeformational deposition (Fig. 5) suggests deposition in one or several

M

Moodies Group,

Fig. 4 Outcrop photograph of microbial laminations near the base of the Moodies Group, Saddleback Syncline. *Dark green* laminations consist of kerogen. They form complex domes and isolated tufts, trace microchannels, and foreset laminae in medium-grained tidal and fluvio-deltaic sandstones. Coin is 16 mm in diameter





Moodies Group, Fig. 5 Progressive intraformational angular unconformity along the northern limb of the Saddleback Syncline (Heubeck and Lowe 1994b). *Green arrow* indicates stratigraphic-up direction. Wedge-shaped alluvial conglomerates facing toward the synclinal axis

(to the *left*) are erosionally truncated and in turn overlain by alluvial conglomerates. The angular unconformity dies out toward the synclinal axis. A similar relationship was documented at the southern margin of the BGB by Lamb and Paris (1988)

elongate subsiding troughs between the rising plutons. Such a scenario would relate poorly to modern plate-tectonic settings.

Future Directions

The age data collectively suggest that 3.7 km-thick Moodies strata were deposited syn-tectonically within 1–14 Ma and represent a very highly resolved stratigraphic window into Archean surface processes, comparable in resolution to many Quaternary sections with mean depositional rates of about 1 mm/a. The Moodies Group thus likely preserves numerous examples of short-term bio-geo-atmospheric interactions.

Cross-References

- ▶ [Barberton Greenstone Belt](#)
- ▶ [Barberton Greenstone Belt, Sedimentology](#)
- ▶ [Barberton Greenstone Belt, Traces of Early Life](#)
- ▶ [Barberton Supergroup](#)
- ▶ [Fossilized Microbial Mats](#)
- ▶ [Microbial Mats](#)
- ▶ [Moodies Group, Microbial Mats](#)
- ▶ [Tides, Archean](#)

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Moodies Group, Microbial Mats

Martin Homann

Institut für Geologische Wissenschaften, Freie Universität Berlin, Berlin, Germany

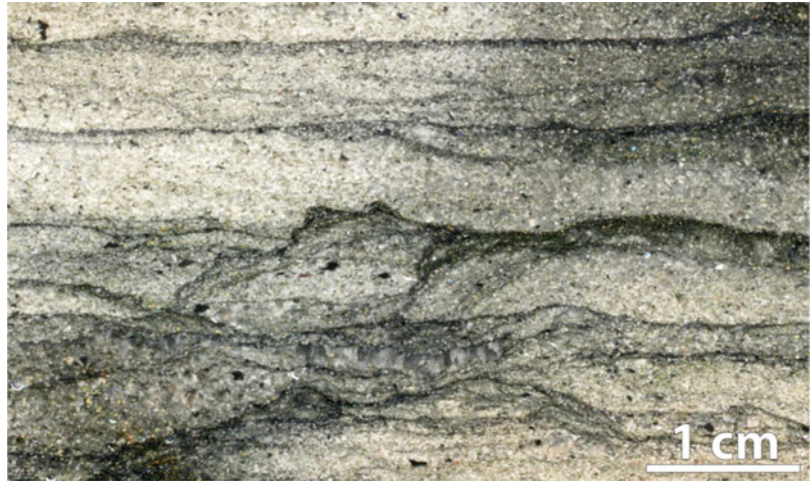
Definition

The Middle Archean ► [Moodies Group](#) (~3.22 Ga, ► [Barberton Greenstone Belt](#), South Africa), Earth's oldest known well-preserved shallow-water siliciclastic sequence, includes several units with common microbial mats which thrived in the photic zone of a tidally influenced shoreline. The fossil mats are preserved as kerogenous laminations up to 1 mm thick, are interbedded with medium- to coarse-grained sandstones and rare gravel beds (Fig. 1), and were early silicified. SEM observations of the laminae show interwoven and bundled microbial filaments (1–3 µm in diameter), confirming mat biogenicity.

Microbial communities in the Moodies Group colonized at least three major depositional settings, each associated with a specific mat morphotype: (1) In the *coastal plain*, mats are typically flat and occasionally overgrew gravel beds; (2) tufted microbial mats, which reach 1–2 cm in height, are exclusively present in the *supratidal zone* and are commonly associated with gas and/or fluid escape structures; and (3) wavy-crinkly morphotypes are characteristic of the *intertidal zone*.

**Moodies Group,
Microbial Mats,**

Fig. 1 Photograph of a part of a polished slab of microbial mats (*dark laminae*) from the Moodies Group. Kerogenous laminae are interbedded with medium- to coarse-grained sandstone. They are of the wavy-crinkly morphotype and show small domes



Modern tufted mats are dominantly built by filamentous cyanobacteria, suggesting that their ancient counterparts may have been constructed by filamentous organisms and required early mineralization for structural support.

It is likely that Moodies microbial mats were (at least in part) photosynthetic communities because other potential metabolic strategies can be excluded, the morphology indicates phototactic behavior, and the mats consistently occur in shallow-water/photoc-zone facies.

Moon Treaty

Klara Anna Capova

Department of Anthropology, Durham University,
Durham, UK

Acronyms

UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs

Definition

The “Agreement Governing the Activities of States on the Moon and Other Celestial Bodies,” also referred to as the Moon Treaty, was adopted by the United Nations General Assembly in 1979.

This multilateral treaty elaborates on the provisions of the Outer Space Treaty as applied to the Moon and other celestial bodies, providing that those bodies should be used exclusively for peaceful purposes and their environments should not be disrupted. The Agreement states that the Moon and its natural resources are the common heritage of mankind and that an international regime should be established to govern the exploitation of such resources.

The United Nations Office for Outer Space Affairs (UNOOSA) is responsible for promoting the international, peaceful use, and exploration of space and the utilization of space science and technology for sustainable economic and social development. UNOOSA also assists the UN Member States to establish legal and regulatory frameworks to govern space activities and strengthens the capacity of developing countries to use space science technology and applications for development.

Cross-References

► [Outer Space Treaty](#)

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- United Nations (1979) Multilateral Agreement governing the activities of States on the moon and other celestial bodies. Adopted by the General Assembly of the United Nations on 5 December 1979

Moon, Origin of

H. Jay Melosh

Departments of Earth, Atmospheric and Planetary Sciences, Physics and Aerospace Engineering, Purdue University, West Lafayette, IN, USA

Keywords

Giant impact hypothesis · Impact cratering · Moon · Origin of the solar system

Definition

The origin of the Moon deals with the process by which our satellite came into existence about 4.5 Gyr before the present. The origin process explains the chemical, isotopic, and geological framework of the Moon, as well as how it attained its initial orbit around the Earth.

History

Planetary scientists' ideas on the origin of the Moon have changed drastically since 1984, in the aftermath of a seminal conference in Kona, Hawaii, when the theory of the "giant impact" emerged (Hartmann et al. 1986). This theory is now widely accepted, although many important questions remain to be answered (Jolliff et al. 2006). The need for a new theory of the Moon's origin grew out of the confrontation between the three "classical" theories (capture, fission, and coaccretion) and the flood of new data on the Moon provided by the U.S. Apollo missions from 1969 to 1972. Analysis of the lunar rocks returned by these missions along with geophysical measurements and photographs made both on the surface and from orbit yielded a picture of the Moon that is incompatible with any of the classical theories and provided the foundation for an entirely new approach to the Moon's origin (Stevenson 1987).

Overview

The Moon's Present State

It has been known for over a century that the Moon is, on average, much less dense than the Earth. The modern value of the Moon's mean density is 3.344 g/cm^3 . Although this is suggestively close to the density of the Earth's mantle, it is less than 0.6 of the Earth's mean density and is taken to indicate that the Moon lacks a significant metallic iron core. The small size of its core is required by the ratio:

$$C/MR^2 = 0.3935 \pm 0.0011$$

where C is the maximum moment of inertia, R the radius, and M the mass of the planet Hartmann et al. (1986). The value measured for the Moon is nearly the same as that of a uniform sphere (0.4000). The Moon's metallic iron core is less than 450 km in radius and comprises less than 4% of the Moon's total mass. Although the Moon has no intrinsic magnetic field at present, remnant magnetism has been found in ancient lunar crustal rocks, suggesting the activity of a dynamo early in its history.

The Moon's crust is composed predominantly of the plagioclase-rich rocks ► [anorthosite](#) (the light-colored areas of the Moon's surface), norite, and troctolite, which appear to have crystallized from melts. Seismic and gravity investigations show that the average thickness of this crust is less than about 60 km. The crust is generally thicker on the farside of the Moon than on the nearside, where it locally thins to 20 km beneath the lava-filled mare basins. The lunar mantle extends to a depth of about 1,000 km and is composed mainly of the minerals olivine and pyroxene. The mantle and crust appear to have separated chemically about 4.5×10^9 years ago in a global melting event known as the lunar "magma ocean." The rare earth element europium (Eu), which has an affinity for plagioclase, is enriched in the crust but depleted in the mantle, a complementary pattern suggesting that the two separated during an era of widespread melting in the ancient Moon. Below about 1,000 km depth, seismic waves are strongly attenuated, indicating

rocks below this depth are partially molten. Very small “moonquakes” occur regularly between 700 and 1,100 km depth in response to tidal stresses.

The estimated bulk chemistry of the Moon shows both striking similarities and differences with the Earth’s mantle. The oxygen, potassium, chromium, and several other isotopic signatures of the Earth and Moon are basically identical, indicating a close relation between the two bodies. The major elements Si and Mg are generally similar in both bodies. Iron oxide, however, appears to be more abundant in the Moon than in the Earth’s mantle. The refractory elements Al, Ca, Cr, Ti, and U may be enriched in the Moon compared to the Earth, while the volatile elements Na, K, and Rb are strongly depleted. The highly volatile molecule H₂O is present at only a few parts per million in the most volatile-rich samples. Elements with an affinity for metallic iron (siderophiles) such as Ni, Ir, Mo, and Ge are much more strongly depleted in the Moon than in the Earth’s mantle. The Earth and Moon are thus chemically distinct at the same time as being isotopically nearly identical.

The ratio between the Moon’s mass and the Earth’s mass is 0.0123, larger than any other planet-satellite pair in the solar system except for Pluto/Charon. The Moon’s mean distance from the Earth is currently 60.3904 Earth radii, and the Moon is receding from the Earth at a rate of 3.74 cm/year due to tidal friction. An important fact is that the Moon is not now in the Earth’s equatorial plane, to which its inclination varies between 18.4 and 28.6° as its orbit precesses. The angular momentum of the Earth-Moon system is anomalously high compared to the other planets (except, again, for the Pluto/Charon system). If all of the mass and angular momentum of the Earth-Moon system were put into the Earth, it would rotate with a period of only about 4 h.

Age of the Moon

Isotopic studies of the lunar rocks show that the Moon and Earth are nearly identical in age, 4.5×10^9 years. High-precision studies using the isotope pair ¹⁸²Hf and ¹⁸²W, however, indicate that the Moon is younger than the Earth by 10–30 Myr (Jacobsen 2005), although the precise

age difference is currently a matter of debate (Touboul et al. 2007).

Classical Theories of Origin

There are three basic models for lunar origin that were under study at the time of the Apollo landings. Although there are many variants of these models and even some hybrids, three pure “end-members” can be described under the headings of Fission, Intact Capture, and Coaccretion.

Fission

One of the best-studied theories of the Moon’s origin is derived from the high angular momentum of the Earth-Moon system. In 1879, G. H. Darwin suggested that if the Earth ever did spin with a period of 4 h, it would be subject to rotational instabilities, and a chunk (or debris ring in more modern theories) would spin off the equator and could eventually clump together outside the Roche limit to form the Moon. This theory neatly predicts the Moon’s depletion in metallic iron and is consistent with the similarity of [▶ oxygen isotopes](#) and major elements in the Earth and Moon. However, it does not account for the differences in refractory or volatile elements, incorrectly predicts that the Moon was once in Earth’s equatorial plane, and altogether sidesteps the question of how the Earth began in a state of such anomalously rapid rotation.

Intact Capture

The most direct way to explain the differences between the Moon and the Earth is to suppose that they were formed in different parts of the solar system under different conditions and that the Earth subsequently captured the Moon. This theory also has a long history of investigation, none of which has succeeded in overcoming the problem that capture of a Moon-size body is a very low-probability process. Capture is plausible only if the relative velocity of the Earth and Moon is very low, and for the velocity to be low, the two bodies must have formed at nearly the same radial distance from the Sun, making it hard to understand how they could differ chemically. Although capture could account for some of the differences between the Earth and Moon, their similarities are unexplained by this theory.

Coaccretion

If the Moon neither broke off the Earth nor came from elsewhere in the solar system, then perhaps it grew along with it. A group of theories posit that the Moon accumulated from debris in orbit around the growing Earth. These theories run immediately into the problem of explaining how the Earth happened to acquire a metallic iron core totaling about 32% of its mass while the Moon remained nearly iron free. Although a variety of “compositional filters” have been proposed, most of which rely on the differences in mechanical strength between iron and silicate planetesimals, none has gained general acceptance as a plausible explanation of the density difference between the Moon and Earth. Coaccretion theories also have difficulty explaining the other chemical differences, predict that the Moon grew in the Earth’s equatorial plane, and, for somewhat more subtle reasons, fail to account for the angular momentum of the Earth-Moon system. Nevertheless, theories of this kind enjoyed widespread support at the time of the Apollo landings.

The Giant Impact Hypothesis

The idea that the Moon might have been formed in an unusually large impact with the proto-Earth was suggested independently by Hartmann and Davis (1975) and by Cameron and Ward (1976). Earlier, in 1970 and 1972, A. E. Ringwood had argued that the chemistry of the Moon indicates that its material was derived from the Earth’s mantle by impacts, but he was unable to propose a plausible dynamic scenario in which this occurred (Ringwood 1970, 1972). Cameron and Ward (1976) noted that the angular momentum problem would be solved if the Earth were struck obliquely by a Mars-size protoplanet at a speed roughly comparable with Earth’s escape velocity, 11.2 km/s. The angular momentum of the Earth-Moon system does not provide enough information to determine separately the angle of impact, mass, and velocity of the projectile, but given plausible values of these parameters, a mass ranging from about 1/2 to 3 times the mass of Mars is probable. Hartmann and Davis (1975) approached the problem by examining the distribution of protoplanetary sizes in the solar nebula near the end

of planetary accretion. They concluded that in addition to a few large protoplanets, there was probably several times that number half as large, still larger numbers one-fourth as large, and so on down to the smallest sizes. In their view, the last stages of planetary accretion in which these objects were swept up must have been characterized by extraordinarily violent collisions among these planetary-size objects. G. W. Wetherill also discussed this view in detail in his 1985 numerical simulations of the final stages of planetary growth (Wetherill 1985).

Current work on the Moon’s origin has focused on computer modeling to evaluate the detailed consequences of an impact with a Mars-sized body. After initial efforts by the teams of A. G. W. Cameron and W. Benz and H. J. Melosh and M. E. Kipp in this area, R. M. Canup has taken this work to much higher resolution and used better material models to provide increasingly realistic simulations of the process (Canup and Righter 2000; Canup 2004). Her results show that the giant impact does explain most of the dynamic features of the Moon and so this model is currently the preferred explanation of the Moon’s origin. These simulations show that the impact initially ejects most of the iron-nickel core material of the projectile but this falls back onto the Earth after a single orbit, merging with the core of the Earth in a catastrophic event that melts most of the Earth’s mantle. Meanwhile, several lunar masses of gas, dust, and molten material from both the Earth’s mantle and the projectile enter an orbit around the Earth, while the bulk of the projectile’s mass merges with the proto-Earth. Later, on a time scale of years, about half of the orbiting debris reimpacts the Earth while a similar mass merges into a single body at a distance of several Earth radii - the proto-Moon.

In spite of the success of the giant impact model, the similarity in oxygen and other isotopes between the Earth and Moon is still not fully explained because even the best computer models predict that approximately 70% of the Moon’s material is derived from the projectile, not from the Earth. Unless the isotopic composition of the projectile was fortuitously nearly identical to that of the Earth, this is inconsistent with the observed

close agreement of the oxygen isotope ratios in the Earth and Moon. Several attempts have been made to resolve this problem, but at present no proposal is universally accepted. The giant impact scenario may require some revision in the future. Nevertheless, it remains the only model that is consistent with most of the dynamic and chemical facts presently known about the Moon.

Evolution of the Moon After Its Formation

The Moon's surface is scarred with thousands of impact craters ranging in size from the South Pole-Aitken basin with a diameter of 2,600 km down to the smallest micrometeoroid craters only a few microns across. The flux of meteoroid impacts has not been constant through time, however. During the era of "heavy bombardment" between the Moon's origin and about 3.8×10^9 years ago, the impact flux was at least several thousand times the present flux. The great basins that form the basis for lunar stratigraphy have ages that date from near the end of this period (Wilhelms 1987). Lava rose from the Moon's mantle and flowed out over its surface, partly filling the low-lying nearside mare basins for nearly 10^9 years after their formation. The bulk of lunar volcanism then ceased about 3×10^9 years ago. The Moon is a one-plate planet: ► [plate tectonics](#) never occurred on the Moon because its small size prevents the vigorous convection necessary to break cold surficial rocks into discrete plates. The Moon's few geologic faults all seem to be related to impact basins or sagging of the crust beneath the load of extruded lavas, although an ancient "tectonic grid" or fabric of faults and fractures in the crust may have developed as it was flexed by tidal forces during the Moon's recession from the Earth. Subsequent to its violent birth and active youth, the Moon has lapsed into a state of geologic senescence marked only by occasional impacts and the regular, tidally triggered moonquakes.

Cross-References

- [Anorthosite](#)
- [Moon, The](#)

- [Oxygen Isotopes](#)
- [Plate Tectonics](#)
- [Rare Earth Elements](#)
- [Siderophile Elements](#)
- [Theia](#)

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Moon, The

Ralf Jaumann
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Keywords

Earth-Moon system

Definition

The Moon is the only large planetary object in the inner solar system to orbit and affect a ► [terrestrial planet](#). It may have supported the *Earth's* specific evolution as a habitable environment. As an integral part of the Earth-Moon system, it is witness to more than 4.5 Ga of solar system history, and it is the only planetary body except Earth for which we have samples from known locations. The Moon's simple composition and its restricted geological activity provide insights into elementary planetary processes. The Moon is thought to be the product of an early planetary collision of a Mars-sized body with Earth (cf. Hartmann et al. 1986; Jolliff et al. 2006; Jaumann et al. 2012).

Earth and Moon form a celestial system with a common center of mass located at about 1700 km beneath the Earth's surface (Fig. 1). With a diameter of 3474 km, the Moon is the fifth largest satellite in the solar system. Its surface covers less than one tenth that of the Earth's surface, its volume is about 2%, and its mass is only 1.2% of that of Earth. Its equatorial surface gravity is 1.622 m/s^2 , about 1/6 (17%) of that on Earth.

The lunar rotation slowed down early in its history due to frictional effects associated with

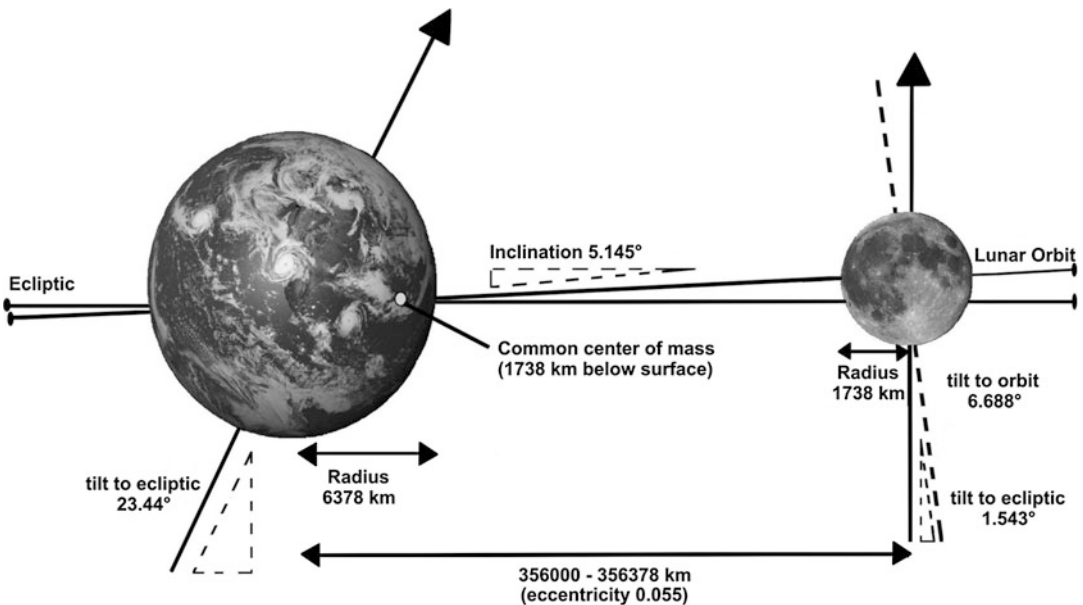
tidal deformations and became locked into a synchronous state, keeping the same face turned toward the Earth at all times. A complete orbit around the Earth takes 27.3 days (the orbital period), whereas periodic variations in the geometry of the Earth-Moon-Sun constellation are responsible for the phases of the Moon, which repeat every 29.5 days (the synodic period).

The Moon's density is 3340 kg/m^3 (=cubic meter) with a bulk crustal density of 2580 kg/m^3 (Wieczorek et al. 2013), and its ► [rocks](#) are of a relatively simple mineralogical composition. Compared to Earth the Moon is depleted in iron and other siderophile elements (cf. Heiken et al. 1991; Jolliff et al. 2006) and shows depletion in ► [volatile](#) elements, in particular H_2O and OH. The lunar topographic relief ranges from -9000 m in the South Pole region to about $+11,000 \text{ m}$ on the northern far side (Scholten et al. 2011; Jaumann et al. 2012).

Basic Methodology

Our knowledge about the moon is based on telescopic observations from Earth, observations by spacecraft from the lunar orbit, measurements on

M



Moon, The, Fig. 1 Earth-Moon relations

the lunar surface by manned and unmanned landing missions, and the analyses of lunar samples brought to Earth by the Apollo (382 kg) and Luna (326 g) missions and about 120 lunar ► [meteorites](#) (48 kg) that have been collected on Earth to date (cf. Jaumann et al. 2012). Remote sensing using passive sensors in the optical wavelength range and active laser and radar detection technology supported by in situ field work yield information concerning the geological processes that formed the Moon, allowing its entire history to be studied with respect to its impact-related, volcanic, tectonic, and ► [space weathering](#) evolution. Spectral measurements in all wavelength ranges from high-energy gamma rays to the mid-infrared provide the overall surface composition and major mineralogical content of rocks, whereas geochemical details and the origin, differentiation, and evolution of the lunar rocks have been deduced from the returned samples.

Key Research Findings

Since the Apollo 11 astronauts returned the first samples, the Moon is known to be a differentiated planetary body as a result of fractional crystallization of a postulated ► [magma](#) ocean (cf. BVSP 1981; Heiken et al. 1991; Jolliff et al. 2006) beginning immediately after its accretion at 4.527 ± 0.01 Ga (Kleine et al. 2005).

The lunar ► [crust](#) is composed of four major distinct rock types developed from geochemical differentiation as well as mechanical destruction and mixing. (1) Pristine highland rocks of igneous origin are composed of older (4.5–4.3 Ga) ferroan anorthosites and slightly younger (4.43–4.17 Ga) troctolites, norites, gabbroanorthosites, and dunites (the Mg-suite) that mark the transition between magma-ocean-related magmatism and serial magmatism (cf. Heiken et al. 1991; Jolliff et al. 2006). (2) Pristine basaltic volcanic rocks are generally enriched in FeO and TiO₂ and depleted in Al₂O₃ (cf. BVSP 1981; Heiken et al. 1991; Jolliff et al. 2006) resulting in olivine and pyroxene-rich and plagioclase-poor mare ► [basalts](#) and pyroclastic deposits. Most of the lunar basalts erupted between 3.9 and 3.0 Ga from partial melts of a non-tholeiitic anhydrous

basaltic magma located at various depths, mostly >350 km (cf. BVSP 1981; Heiken et al. 1991; Jolliff et al. 2006). (3) Polymict clastic breccias were produced by single or multiple impacts and are a mixture of different rock types from different locations containing various fractions of clastic rock fragments and impact melt varying in texture, grain size, and composition (Stöffler et al. 1980).

The uppermost lunar crust consists of an unconsolidated debris layer called regolith of fine-grained pristine crystalline rock and mineral fragments and agglutinates – aggregates of small particles welded together by glass produced in micrometeorite impacts (cf. Heiken et al. 1991; Jolliff et al. 2006).

On a macroscopic scale the lunar surface has been modified by three major processes: impact, volcanism, and tectonics. Impacts are geological events that eject, dislocate, and redistribute material on all scales, building up morphologies from small bowl-shaped to large flat-floored craters partly refilled by fallback material and mass wasting. With increasing impact energy the relaxation of the compressed crust piles up a central peak and even multi-ringed mountain chains. As the number of impacts on a surface unit is correlated with its exposure to the cosmic bombardment, the frequency distribution of craters is a measure of its age (cf. Neukum et al. 2001; Jaumann et al. 2012). The Moon is stratigraphically divided into five time units: Pre-Nectarian (>4.1 Ga), Nectarian (4.1–3.85 Ga), Imbrian (3.85–3.2 Ga), Eratosthenian (3.2–0.8 Ga), and Copernican (<0.8 Ga) (Wilhelms 1987).

Several large impacts penetrated the lunar crust, triggering the major lunar volcanic activity. Unlike Earth the Moon has not had ► [plate tectonics](#) and has thus preserved the witnesses of its thermal history from the beginning through basaltic deposits and volcanic landforms. Lunar basalts are concentrated on the near side mostly in ► [impact basins](#). They cover 17% or 7×10^6 km² of the lunar surface and amount to 1% of the crustal volume (Head 1976). Lunar volcanism was active for almost 3 Ga, starting at about 4.0–3.9 Ga and ceasing at ~1.2 Ga (Hiesinger et al. 2003). Geomorphologic features of volcanic origin include lava flows, volcanic domes, cones, and lava tubes (sinuous rilles). Tectonics is related

to both impact and volcanism and expresses extensional and compressional features such as faults, graben, dikes, and wrinkle ridges.

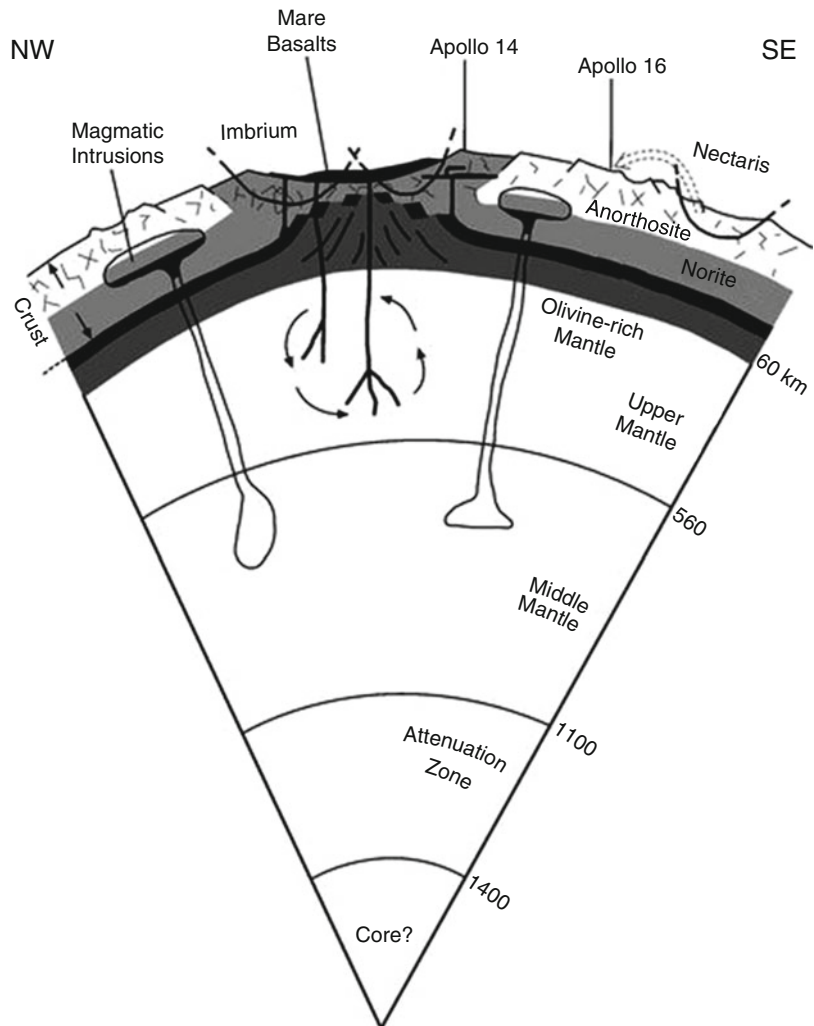
The lunar interior is divided into three major zones: the crust, the ► [mantle](#), and the core (Fig. 2). The thickness of the crust is on average 38.5 ± 4.5 km (Wieczorek et al. 2013), thicker on the far side and thinner on the near side, causing a dichotomy with the center of mass being offset from the geometric center by 1.9 km (cf. Jolliff et al. 2006). Seismic data indicate that velocities are almost constant in the upper mantle down to 560 km. Then there is a discontinuity due to a change in composition: below ~ 1150 km seismic waves are attenuated, suggesting partial melting (cf. Heiken et al. 1991; Jolliff et al. 2006).

Although the existence of a lunar core is still debated, geophysical data are consistent with a core being composed of either a molten Fe-FeS-C metallic alloy with a radius of less than 375 km or a slightly larger molten Fe- and Ti-enriched silicate composite (cf. Heiken et al. 1991; Jolliff et al. 2006). The Moon has no global ► [magnetic field](#), yet all measurements indicate that some rocks of the lunar crust are magnetized (Hood et al. 2001). Although this observation is consistent with the Moon once having possessed a dynamo (which would require a metallic core), it is also consistent with transient magnetic fields generated by impact events (cf. Jolliff et al. 2006).

The atmospheric conditions on the Moon are those of the interplanetary space. Nevertheless

Moon, The,

Fig. 2 Conceptual cross section of the lunar crust and interior. (Adapted from Stöffler 1990; Konopliv et al. 1998; Kahn et al. 2000)



10^5 – 10^7 molecules/cm³ (from solar wind, surface sputtering, and radioactive decay) or a total of 10^4 kg gas is in a neutral lunar “atmosphere” (Heiken et al. 1991). More common in the lunar environment is dust generated by hypervelocity impacts of fast projectiles (13–18 km/s) producing secondary material by striking the surface, of which a fraction leaves the surface, forming a lunar dust envelope (Heiken et al. 1991). There also are a variety of energetic particles (solar wind and galactic cosmic rays, mostly consisting of protons, electrons, and heavier nuclei) in the Moon’s environment. The lack of an essential atmosphere and the weak remnant magnetic field cause this radiation to directly interact with the surface, yielding measurable alterations of the uppermost material (Heiken et al. 1991).

Numerous models have been proposed to explain the origin and formation of the Moon (Hartmann et al. 1986), including fission from Earth, co-accretion with Earth, gravitational capture, and giant impact (cf. Hartmann et al. 1986; Cameron and Benz 1991). The most striking constraints for the formation of the Moon are its bulk composition and the high angular momentum of the Earth-Moon system (Jolliff et al. 2006), which can best be explained by a giant collision of the proto-Earth with a large object in the early solar system history (cf. Hartmann et al. 1986; Jolliff et al. 2006; Jaumann et al. 2012). This large object, like the proto-Earth, must have been already differentiated with the iron and siderophile elements concentrated in the core. After collision most of the dense material was incorporated in the Earth’s mantle and core, while the outer portions of the impactor and the crust and upper mantle of the Earth have been ejected into an Earth orbit where the material re-accreted to form the Moon. The energy released by the impact and the re-accretion produced large-scale melting that formed the magma ocean. Cooling and density segregation of crystals from the melt formed the primordial low-density plagioclase-rich lunar crust, accompanied by the sinking of mafic minerals to the bottom of the magma ocean, followed later by a concentration of potassium (K) and rare earth elements and

phosphorus (KREEP)-rich materials (cf. Jolliff et al. 2006). The melts produced from the Moon’s heterogeneous interior were extruded, triggered, and facilitated by crustal weakening and excavation due to massive impacts.

Recently H₂O and OH have been confirmed in the south polar crater Cabeus (Jonas 2009; Colaprete et al. 2010). In addition, absorptions at 2.8–3.0 μm have been detected in cooler high-latitude surface regions associated with fresh craters (Pieters et al. 2009). For silicate bodies, such features are typically attributed to OH- and/or H₂O-bearing materials. It is assumed that the formation and retention of this OH and H₂O are either a result of hydration processes in the lunar surface, or else it is created continuously by solar-wind protons interacting with oxygen-rich surfaces produced during micrometeorite impact on lunar soil particles (Pieters et al. 2009). Due to the fact that the lunar axis is almost perpendicular to the ► [ecliptic](#) (Fig. 1), the larger polar craters are permanently in shadow. These cold traps accumulate ► [water](#) ice molecules either resulting from impacts or from hydration or solar-wind-related OH/H₂O production processes (cf. Anand et al. 2012; Jaumann et al. 2012). Although these discoveries demonstrate that the Moon has water, the small amounts, of the order of parts per million (ppm), still show that the Moon is extremely dry. Nevertheless the polar cold traps and the lunar regolith are candidate sources of volatiles for human exploration (cf. Anand et al. 2012).

Given that the Moon is very likely to be responsible for the 24-h rotation period of Earth that it stabilizes Earth’s obliquity, which otherwise would be subject to large chaotic variation (Laskar et al. 1993), and that it raises substantial tides in the Earth’s oceans, the Moon acts as a climate regulator, supporting the habitability of Earth for complex life forms and catalyzing the evolution of life on our planet.

Cross-References

- [Anorthosite](#)
- [Apollo Mission](#)

- ▶ Basalt
- ▶ Chronostratigraphy
- ▶ Core, Planetary
- ▶ Crater, Impact
- ▶ Crust
- ▶ Dichotomy, Planetary
- ▶ Differentiation, Planetary
- ▶ Dynamo, Planetary
- ▶ Earth
- ▶ Ecliptic
- ▶ Geological Time Scale, History of
- ▶ Geological Timescale
- ▶ Giant Impact
- ▶ Heat Flow, Planetary
- ▶ Heat Transfer, Planetary
- ▶ Impact Basin
- ▶ Interior Structure, Planetary
- ▶ Iron
- ▶ Landing Site
- ▶ Late Heavy Bombardment
- ▶ Magma
- ▶ Magnetic Field, Planetary
- ▶ Mantle
- ▶ Mare, Maria
- ▶ Meteorites
- ▶ Orbital Period
- ▶ Planet Formation
- ▶ Plate Tectonics
- ▶ Primordial Heat
- ▶ Rare Earth Elements
- ▶ Regolith, Planetary
- ▶ Rille
- ▶ Rima, Rimae
- ▶ Rock
- ▶ Rotation Planet
- ▶ Satellite or Moon
- ▶ Selenology
- ▶ Siderophile Elements
- ▶ Solar System, Inner
- ▶ Space Weathering
- ▶ Surface Gravity
- ▶ Terra, Terrae
- ▶ Terrestrial Planet
- ▶ Tides, Planetary
- ▶ Volatile
- ▶ Water
- ▶ Water Activity

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MORB

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Synonyms

Mid-ocean ridge basalt

Definition

MORB is the rock (basaltic in composition) formed by eruption of magma at the oceanic spreading centers (► [mid-ocean ridges](#)) to form the ► [oceanic crust](#). It forms as the upper mantle passively upwells and partially melts where lithospheric plates diverge at the oceanic spreading centers. It is commonly porphyritic with plagioclase or more rarely ► [olivine](#) phenocrysts. Eruption under water produces ► [pillow lava](#) interspersed with rare sheet flows. The basalt is relatively magnesian (5–11% MgO) and characterized by high Al₂O₃ content (12–18%) and low concentrations of K₂O. In N-MORB (normal MORB), the incompatible elements are depleted relative to more compatible elements, reflecting derivation from depleted (previously melted) upper mantle.

Cross-References

- [Basalt](#)
- [Crust](#)
- [Magma](#)
- [Mantle](#)
- [Mid-Ocean Ridge](#)
- [Olivine](#)
- [Peridotite](#)
- [Pillow Lava](#)
- [Plate Tectonics](#)

Morphological Fossil

- [Biomarkers](#)

Most Recent Common Ancestor

- [Common Ancestor](#)

Motility

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Actin · ATPase · Axoneme · Cilia · Gliding ·
Flagella · Flagellin · Flagellum ·
Microfilaments · Microtubules · Tubulin

Synonyms

Cell motility

Definition

Motility refers to the ability of organisms to move actively, consuming energy in the process. There are structural and functional differences between prokaryotic and eukaryotic motilities.

Overview

Prokaryotic motility. Many ► [prokaryotes](#) are motile due to the presence of a special structure, the flagellum; certain prokaryotic ► [cells](#) can move along solid substances by gliding, and planktonic microorganisms can also regulate their position in a water column using gas vesicles. Prokaryotic flagella are long, thin helical appendages attached to the cell at one end. Flagella can have a polar (attached to one or both cellular ends) or a peritrichous (inserted around the cell) position. The filaments of prokaryotic flagella are composed of subunits of a protein called flagellin. In ► [Bacteria](#), flagellin is highly conserved, suggesting that motility has deep evolutionary roots. However, in Archaea, several different flagellins have been described, and the flagellar structure seems to be quite different from that of Bacteria, although the flagellar

function seems to be similar. In addition to the filament, the flagellum has a motor with two components: the rotor (basal body) and the stator. The motor is anchored in the cytoplasmic ► [membrane](#) and cell wall through a series of rings. In gram-negative bacteria, a third ring is anchored to the lipopolysaccharide membrane. The rotary motion of the flagellum is imparted from the basal body. The energy required for rotation comes from the proton motive force.

Some prokaryotes move across solid surfaces in a process called gliding. In cyanobacteria, it is known that a polysaccharidic slime is secreted. As the excreted slime adheres to the surface, the cell is pulled along. In other systems, specific motile proteins anchored in the cytoplasmic and in the outer membrane seem to propel the cell forward, in a type of continuous ratcheting mechanism. Gliding motility plays an important role in cell-to-cell interaction. Spirochetes have an unusual mode of motility, based on a torque-like motion produced by a special type of flagella called endoflagella.

Cellular motility. The internal structural network of eukaryotes comes from proteins that form filamentous structures called microfilaments and microtubules. Together, these structures form the cell cytoskeleton. Microfilaments are about 8 nm in diameter and are polymers of the protein actin. These fibers form scaffolds throughout the cell. Microtubules are larger filaments, about 25 nm in diameter, and are composed of the protein tubulin. Microtubules assist microfilaments in maintaining cell structure. Microfilaments and microtubules also play an important role in cell motility, both in the movement of internal cell structures and in the movement of the organism itself. Prokaryotic cells, although much smaller than eukaryotic cells, produce structural and functional homologues of actin and tubulin.

Eukaryotic motility. Cilia and flagella are organelles of motility present in many groups of eukaryotic microorganisms. Cilia are essentially short flagella that beat in synchrony to propel the cell, usually quite rapidly, through the medium. Flagella are long appendages that push the cell, more slowly than cilia, by means of a whiplike

motion. The flagella of eukaryotic cells are structurally quite distinct from bacterial flagella and do not rotate. In cross section, cilia and eukaryotic flagella are quite similar. Each contains a bundle of nine pairs of microtubules surrounding a central pair of microtubules called the axoneme. A protein, dynein, is attached to the tubulin of the microtubules and functions as an ► [ATPase](#). Movement of both cilia and flagella is similar. In both cases, movement involves the coordinated sliding of axonemal microtubules against one another in a direction toward or away from the base of the cell. This movement confers the whip-like action that propels the cell. A number of algae and protozoa are motile, using filaments; some protozoa use cilia; and some diatoms have gliding motility, similar to that of prokaryotes. Most cells in plants and complex animals are immobile. However, animal cell motility is responsible for muscle contraction.

Cross-References

- [Archaea](#)
- [ATP](#)
- [ATPase](#)
- [Bacteria](#)
- [Bioenergetics](#)
- [Cell](#)
- [Chemotaxis](#)
- [Eukaryote](#)
- [Membrane](#)
- [Prokaryote](#)
- [Proton Motive Force](#)

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Mount McRae Shale

Nicholas Arndt

Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The *Mount McRae Shale* is a 2.5-Ga-old unit of mudstone, siltstone, chert, iron formation, and dolomite in the Hamersley basin of the ► [Pilbara craton](#), Western Australia. It is characterized by a high concentration of organic carbon (~2–8 wt%), abundant disseminated pyrite (~1 to ~10 wt% S in the bulk rocks), and pyrite nodules (~1–10 cm radius). Analysis of S and Fe isotopic compositions of carbonaceous pyritic shale recovered in the NASA-sponsored Astrobiology Drilling Program, as well as Os, Tl, and Mo isotopes, revealed variations in isotopic compositions. These later have been linked to changes in the composition of the ocean and the atmosphere as well as to fluctuations and a temporary and episodic rises of atmospheric oxygen that preceded the ► [Great Oxygenation Event](#) (GOE) at 2.32 Ga.

Cross-References

- [Archean Drilling Projects](#)
- [Great Oxidation Event](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Pilbara Craton](#)

MRCA

- [Common Ancestor](#)

mRNA Display

Burckhard Seelig

Department of Biochemistry, Molecular Biology and Biophysics & BioTechnology Institute, University of Minnesota, St. Paul, MN, USA

Definition

The mRNA display method is an *in vitro* selection technique that allows the isolation of functional proteins from large combinatorial libraries of polypeptide variants (Roberts and Szostak 1997; Nemoto et al. 1997). This technology has been used to determine the probability of occurrence of proteins with a specific function in the vast sequence space of all possible polypeptides.

Overview

Functional proteins might have originated from early peptides that initially were synthesized as random amino acid polymers. In order to test the likelihood of such random mixtures containing functional polypeptides, a large number of polypeptides need to be tested as this likelihood might be low. While there are numerous methods to sample mixtures of proteins, the approach that can search the largest number of mutants is most suited to address this question. mRNA display is a technique that can sample libraries of up to 10^{13} randomized protein variants. In mRNA display, the messenger RNA is covalently attached to the very protein that it encodes (Fig. 1), thereby



mRNA Display, Fig. 1 mRNA-displayed protein.

A protein is covalently linked to its encoding messenger RNA. This link is established during the *in vitro* translation reaction of the mRNA, which prior has been modified with puromycin (P)

rendering each single protein molecule directly amplifiable (Roberts and Szostak 1997; Nemoto et al. 1997). This stable link of genotype and phenotype enables the selection of novel protein binders or enzymes. mRNA display was instrumental to show that about 1 in 10^{11} random sequence proteins have the ability to bind ATP (Keefe and Szostak 2001), and that an enzyme with a novel activity and structure can be found in randomized protein libraries (Seelig and Szostak 2007; Chao et al. 2013).

Cross-References

- [ATP](#)
- [Combinatorial Library](#)
- [RNA Ligase](#)

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MRO

- [Mars Reconnaissance Orbiter](#)

MS

► [Mass Spectrometry](#)

Mucin

Daniel A. Petrash
Environmental Geochemistry and
Biogeochemistry, Czech Geological Survey,
Prague, Czech Republic

Definition

Mucin is a deeply branched and compositionally conserved type of glycoprotein secreted by the epithelial cells of animals. Approximately 80% of mucin's molecular weight is comprised of oligosaccharides attached by *O*-glycosidic bonds to threonine, serine, or proline residues in the polypeptide backbone of the protein core. At the amino and carboxyl terminals, regions can be high in cysteine with extensive disulfide bonding. In marine realms, this polyanionic biomacromolecule forms a gel-like substrate that regulates the speciation and mobility of dissolved metals in bioturbated sediments. Such capability is relevant for distinctive biomineralization processes that occur at the vicinity of burrow walls.

History

Early in the twentieth century, mucins were already known as a compositionally conserved class of “proteid” compound with carbohydrates exhibiting an “ethereal acidic nature” (e.g., Levene 1900). For a long time, glycoproteins, such as mucins, did only receive minor scientific attention. Yet, as summarized by Montreuil (1980), several attempts to define the structure of the glycoproteins had been completed by the 1960s. During the 1970s, the scientific community discovered many other aspects of their

properties and structural characteristics. Researchers working on such macromolecules during the 1980s refined previous structural considerations and elucidated some of their functions. They observed that mucins appear to exert a critical role in the movement of mineral ions and organic compounds of low molecular weight at the level of cell-surface membranes (Montreuil 1980). It is now known that glycoproteins are involved in nearly all biological processes. The structure and function of the different compounds categorized as mucin glycoproteins are reviewed by Strous and Dekker (1992). In environmental samples, the specific role and contributions to dissolved organic carbon (DOC) remineralization and biomineralization of mucin-type glycoproteins remain to be fully explored (but see Lalonde et al. 2010; Petrash et al. 2011; Verdugo 2012; Hannides and Aller 2016).

Cross-References

- [Biomineralization](#)
- [Carboxylic Acid](#)
- [Cysteine](#)
- [Hydroxyl Group](#)
- [Proline](#)
- [Protein](#)
- [Serine](#)
- [Threonine](#)

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cryovolcanic extrusions on icy bodies in the Solar System (Brož et al. 2020).

Cross-References

- [Ceres](#)
- [Cryovolcanism](#)

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Mud Volcanism

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Sedimentary volcanism](#)

Definition

Mud volcanism is the extrusion at the surface of Earth of mud and water driven by gases (dominantly CH₄, CO₂ or N₂) in hydrocarbon-bearing basins (Mazzini and Etiope 2017). Mud and water can accumulate in specific places, forming a little “volcano-like” edifice, then the term “mud volcanoes.” Around mud volcanoes, communities of thermophilic prokaryotes and biofilms develop. Pitted cones, mounds, and flows occurring in the northern lowlands of Mars may have formed through processes akin to terrestrial mud volcanism with release of gas from sedimentary strata via gravity destabilization. Similar processes have been suggested for

Multicellular Organisms

Alberto G. Fairén

NASA Ames Research Center, Moffett Field, CA, USA

Keywords

Atmospheric oxygen · Body size · Cambrian · Ediacara · Multicellular · Paleoproterozoic · Specialization

Synonyms

[Complex organisms](#); [Pluricellular organisms](#)

Definition

Multicellular organisms are those composed by multiple ► [cells](#). They are classified in 13 major groups of terrestrial living beings, including animals, plants, fungi, ciliates, algae, and foraminifera. The number of cells per organism range from some tens to up to several million. The cells in a multicellular organism are usually varied, differentiated, and specialized.

Overview

The evolutive path toward multicellularity seems to be not particularly challenging, as different groups of multicellular organisms seem to have evolved independently (Rokas 2008). Also, it is possible to follow the invention of multicellularity in separate major clusters of organisms within the 13 main groups, as they are well known to be polyphyletic. In general, aquatic organisms became multicellular because the daughter cells did not separate completely during cell division, while land multicellular organisms formed by the aggregation of a multinucleate syncytium (a multinucleated mass of cytoplasm that is not separated into individual cells). The ultimate cause for the origin of multicellularity may be found in the advantages that an increase in body size brings. Becoming large makes it easier to be shielded from variations in physico-chemical conditions of the external surroundings, as the multicellular organisms build their own internal environment (Bonner 1999). Also, the division of labor among different groups of specialized cells may pose some selective advantages (Michod and Roze 2001). Multicellularity requires cell-to-cell communication, cooperation, and specialization (Niklas and Newman 2013).

The primeval multicellular organisms first emerged during the Paleoproterozoic period. Techniques of molecular chronology suggest that multicellular organisms originated about 2–2.5 Gyr ago. And molecular analyses are coincident with the fossil record, pointing to evidence for macroscopic life during the Paleoproterozoic era (2.5–1.6 Gyr ago). But the available fossil record of the development of early multicellular organisms is sparse. It is noteworthy that the microscopic fossil record of unicellular protists and bacteria is extensive in the sedimentary rocks of almost any age, but fossils of multicellular organisms are extremely rare in Pre-Ediacaran sediments (the Ediacaran is the period that precedes the Cambrian, from 630 to 540 Ma ago). The reason may be that Precambrian animals were soft-bodied, thin, and small, with no hard covers or skeletons that would have been easily preserved in the sediments. This is so because Proterozoic animals thrived in an atmosphere dominated by greenhouse gases with a very

low concentration of oxygen (Donoghue and Antcliffe 2010). The oxygen reached their tissues by diffusion, a slow and ineffective mechanism, and they lacked a circulatory system. Consequently, small size was a reasonable evolutive solution to take advantage of the atmospheric composition of the Earth at that time.

It was only at the beginning of the Ediacaran that some of these soft-bodied animals began to leave a record in the fossil sequence: the footprint of their bodies in the mud. These first animal remainders are now called the *Ediacaran fauna*. Some of them were similar to modern jellyfish, worms, arthropods, or starfish, and therefore started to include some harder parts, such as articulated legs or primitive shells. The beginning of the Cambrian period witnessed a rapid increase in the fossil record of multicellular life on the surface of the Earth. This boost in the fossil evidence, known as the Cambrian explosion, was probably triggered by a significant rise in the concentration of atmospheric oxygen (Smith and Szathmáry 1997). As they were able to grow larger and thicker bodies, animals began to develop hard body parts, such as external skeletons or shells, to gain advantages against competitors or predators. Therefore, it is very likely that the widespread fossil record of the Cambrian animals, compared with their meager Precambrian ancestors, has more to do with the ease of fossilization of the new hard parts of their bodies than with an actual increase in the animal populations in the biosphere at the beginning of the Phanerozoic.

Cross-References

- [Cell](#)
- [Eukarya](#)
- [Unicellular Organisms](#)

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Multiple Aperture Astronomy

- [Interferometry](#)

Murchison

- [Meteorite, Murchison](#)

Mutagen

Ester Lázaro
Molecular Evolution Laboratory, Centro de
Astrobiología (CSIC-INTA), Madrid, Spain

Keywords

Base analogs · Evolution · Genetic damage ·
Genetic diversity · Mutation · Radiation

Definition

A mutagen is a physical, chemical, or biological agent able to increase the occurrence of ► [mutations](#) above the spontaneous level. Mutations produced by the action of mutagens are called induced mutations. The effect of most mutagens is due to their ability to modify a particular ► [nucleic acid base](#) or to become incorporated into the nucleic acid. As a high amount of mutations have deleterious effects on ► [fitness](#), exposure to mutagens usually has negative consequences. Nonetheless, at early evolutionary stages, certain environmental mutagens could have had a positive effect, increasing the extent of genetic diversity accessible to ► [natural selection](#).

Overview

Among chemical mutagens, the most important are nucleic acid base analogs – which due to their similitude with natural bases can be incorporated into DNA or RNA during replication – and compounds that produce chemical alterations in the bases (Drake and Baltz 1976). The result in both cases is the induction of erroneous base pairing at the next replication round. Intercalating agents are another type of chemical mutagens that insert themselves between adjacent bases or base pairs, increasing the frequency of insertions and frame-shift mutations. In turn, the main physical mutagens are ultraviolet light and ionizing radiation (X and gamma rays); the latter also includes the atomic and subatomic particles emitted by radioactive elements. ► [UV radiation](#) is mutagenic because of its potential to cause cross-linking between adjacent thymine or cytosine bases and to produce free radicals that can alter the bases in the nucleic acids. Ionizing radiation also generates free radicals and reactive ions able to act directly in the nucleic acids by breaking certain chemical bonds. Regarding biological mutagens, the most relevant ones are viruses or genetic elements that can be incorporated into the genomic DNA (Leib-Mösch and Seifarth 1995). However, the number of molecules and physical agents that can interfere with the faithful replication of the genetic material or with the mechanisms able to repair the damage is probably much higher than is currently known (Friedberg et al. 2005). As an example, compounds that interfere with the pathways of synthesis of nucleotides can cause nucleotide concentration imbalances that may also be mutagenic.

Some mutagens could have played a relevant role in evolution, especially in the early Earth prior to the emergence of cellular life. At those stages, all the biochemical processes, including nucleic acid replication, were strictly dependent on the physical-chemical conditions of the environment, which probably had a strong mutagenic potential due, among others effects, to limited availability of substrates, presence of diverse chemical compounds, or absence of an ozone layer protecting the Earth's surface from ultraviolet light (Rothschild and Cockell 1999). At these early times, increased generation of mutations could have had positive effects,

contributing to the large genetic diversity that would be necessary to select new functions, increasing the biological diversity in this way. Mutagens could also have played an important role as a selective pressure, causing the emergence and fixation of current mechanisms able to prevent or repair the damage produced in the genetic material.

Cross-References

- [DNA Repair](#)
- [Error Rate](#)
- [Evolution, Biological](#)
- [Fitness](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Natural Selection](#)
- [Nucleic Acid Base](#)
- [Replication \(Genetics\)](#)

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Mutagenesis

Ester Lázaro
Molecular Evolution Laboratory, Centro de Astrobiología (CSIC-INTA), Madrid, Spain

Definition

Mutagenesis is the process by which the genetic information of an organism is modified in a heritable way. It includes the generation of spontaneous and ► [mutagen-induced](#) ► [mutations](#). As most mutations have deleterious effects on fitness, mutagenesis usually has negative consequences,

which can even result in population extinctions when selective processes are not able to compensate the mutational force. Mutagenesis induced by ultraviolet light and other environmental agents could have played a relevant role in shaping the broadness and nature of the diversity attained by the first systems containing genetic information that arose in the primitive Earth. Site-directed mutagenesis is a powerful technique that allows scientists to introduce mutations at defined positions in the genomic sequence.

Cross-References

- [Mutagen](#)
- [Mutation](#)

Mutant

Ester Lázaro
Molecular Evolution Laboratory, Centro de Astrobiología (CSIC-INTA), Madrid, Spain

Definition

A mutant is a gene or an individual bearing a ► [genotype](#) that differs from the reference wild-type sequence in one or more positions. The genotypic differences can give rise to new phenotypic characteristics or not, depending on the effects that ► [mutations](#) have on fitness. The frequency at which a specific mutant is represented in a population depends on the rate at which the particular mutations it carries are produced and on its selective value. The presence of a certain amount of mutant individuals is beneficial for a population, as it makes possible ► [adaptation](#) to the continuous changes in the selective pressures.

Cross-References

- [Adaptation](#)
- [Genetics](#)
- [Genotype](#)
- [Mutation](#)
- [Phenotype](#)

Mutation

Ester Lázaro

Molecular Evolution Laboratory, Centro de Astrobiología (CSIC-INTA), Madrid, Spain

Keywords

Adaptation · Evolution · Fitness · Genetic alteration · Replication error

Definition

A mutation is any inheritable change in the genetic information (DNA or RNA) of biological entities, be they cells, viruses, or replicating molecules. In multicellular organisms, only mutations produced in the gametes (germinal cells) are transmitted to the progeny. Despite the negative effects that most mutations have on ► [fitness](#), they play an essential role in living systems, contributing to the generation of the genetic diversity necessary for the action of ► [natural selection](#) (Bell 2008). In the long term, the concerted action of mutation and ► [selection](#) has made biological evolution possible (Woodruff and Thompson 1998), from the first replicating molecules to the complex organisms living in the current world.

Overview

Mutations can be produced spontaneously as a result of natural cellular processes, such as the generation of errors during genome replication or the occurrence of modifications in the nucleic acid bases (Lewin 2008). The replication ► [errorrate](#) largely depends on the presence of corrector or “proofreading” activities in the enzymes that carry out the copying process. Mutations can also be induced by the action of physical or chemical agents known as mutagens.

Mutations can be classified according to the extent of the genetic material affected. Those affecting only one or a few nucleotides are referred to as the following: (1) point mutations, when a single nucleotide is exchanged for another; (2) insertions, when one or more extra nucleotides

are added; and (3) deletions, when one or more nucleotides are eliminated. Point mutations can be transitions (substitution of a purine by a purine or of a pyrimidine by a pyrimidine) or transversions (substitutions of a purine by a pyrimidine or vice versa). Insertions and deletions, when produced in the coding region of a gene, can cause changes in the reading frame (frameshifts), giving rise to genic products that differ largely from the original. Alterations that involve large genomic regions often are the result of either ► [recombination](#) or the movement of transposable elements. Relevant examples are gene duplication (an important mechanism of generation of new functions) and loss of genes.

Mutations in the coding regions of genes can be non-synonymous (when they change the encoded amino acid), synonymous (when the mutated ► [codon](#) codes for the same amino acid), or nonsense mutations (producing stop codons). Non-synonymous changes often change the function of the encoded protein, whereas synonymous changes are frequently assumed to be neutral. This, however, can be uncertain, since they can affect nucleotides involved in functions different from coding, such as transcription regulation or interaction with other molecules.

The effects of mutations on fitness can be deleterious, beneficial, or neutral, although their sign often depends on the environment, on the degree of adaptation of the population, and on the genomic context (Eyre-Walker and Keightley 2007). Therefore, many neutral or even deleterious mutations can have a selective value when the environment changes. In general, beneficial mutations are very rare, although they can reach high frequencies in populations or even become fixed, thanks to the action of natural selection.

Cross-References

- [Codon](#)
- [DNA Damage](#).
- [Error Rate](#)
- [Evolution, Biological](#)
- [Evolution, In Vitro](#)
- [Fitness](#)
- [Genetics](#)
- [Mutagen](#)

- ▶ [Mutant](#)
- ▶ [Natural Selection](#)
- ▶ [Purine Bases](#)
- ▶ [Pyrimidine Base](#)
- ▶ [Recombination](#)
- ▶ [Replication \(Genetics\)](#)
- ▶ [Selection](#)

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Mutual Neutralization

Steven B. Charnley
Solar System Exploration Division,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Mutual neutralization is a chemical reaction between a positive ion (cation) and a negative

ion (▶ [anion](#)), leading to their annihilation and the formation of neutral products.

Cross-References

- ▶ [Anion](#)

Mutualism

- ▶ [Symbiosis](#)

Mythology

Stéphane Tirard
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Faculté des Sciences et
des Techniques de Nantes, Nantes, France

Definition

Mythology studies the myths, which are narratives based on imaginary facts that present collective significations in a civilization. Myths have no scientific fundaments, but they are interesting for the understanding of prescientific representation of civilizations.

N

***N*-Carbamoyl Amino Acid**

Laurent Boiteau
Institut des Biomolécules Max Mousseron,
Montpellier, France

Synonyms

[CAA](#)

Definition

N-carbamoyl amino acids (CAAs) are prebiotically relevant organic compounds bearing both carboxylic (–COOH) and ureido (–NH–CO–NH₂) functional groups. They are precursors to amino acids (in which an amino group –NH₂ replaces the ureido group) and to hydantoins, the latter being cyclic, dehydrated forms of CAAs. CAAs are products of the ► [Bücherer-Bergs synthesis](#), hence possible side products of the prebiotic formation of amino acids. Alternately, CAAs are also reversibly formed by spontaneous reaction of ► [urea](#) or cyanic acid with amino acids. CAAs are possible prebiotic precursors of peptides through the formation of *N*-carboxyanhydrides (NCAs), for example, by nitrosation. Since the ureido group bears chemical energy, the spontaneous hydrolytic decomposition of CAAs is also able

to induce NCA formation, which is suggested by the formation of peptides in low yield from CAAs.

Cross-References

- [Amino Acid](#)
- [Amino Acid *N*-Carboxy Anhydride](#)
- [Bücherer-Bergs Synthesis](#)
- [Hydantoin](#)
- [Peptide](#)
- [Prebiotic Chemistry](#)
- [Urea](#)

***N*-Cyanoamine**

- [Cyanamide](#)

N

- [Nitrogen](#)

***N*-(Pyrimidinyl)formamide**

- [Formamido Pyrimidines](#)

N₂

- [Dinitrogen](#)

N₂H⁺

- [Diazenylium \(N₂H⁺\)](#)

NADH, NADPH

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

Nicotinamide adenine dinucleotide (oxidized form: NAD⁺; reduced form: NADH) and nicotinamide adenine dinucleotide phosphate (oxidized form: NADP⁺; reduced form: NADPH) are two universal ► [coenzymes](#) functioning as hydride (H[−]) carriers at a standard reduction potential of −320 mV. The pair NAD⁺/NADH essentially works in oxidation reactions in ► [catabolism](#) (like synthesis of aldehyde and ketone functions from alcohols, or organic acids from aldehydes). On the contrary, the pair NADP⁺/NADPH serves as a reducing agent during anabolic processes (for example, in formation of saturated C-C bonds from double bonds). In addition to its role as an electron carrier, NAD⁺ also acts as an ADP-ribosyl donor.

History

The coenzyme NAD⁺ was formerly known as diphosphopyridine nucleotide (DPN) and NADP⁺ as triphosphopyridine nucleotide (TPN).

Cross-References

- [Anabolism](#)
- [Catabolism](#)
- [Coenzyme](#)
- [Metabolism](#)

Nadir

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Nadir is a term coming from the Arabian astronomers that designates the opposite direction of the ► [zenith](#) for an observer at a given location on Earth. It corresponds to a direction “between the feet of the observer” pointing to the center of the Earth.

Cross-References

- [Coordinate Systems](#)
- [Zenith](#)

NAI

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The NASA Astrobiology Institute (NAI) was established by the US National Aeronautics and Space Administration in 1998 in order to develop the field of astrobiology and provide a scientific framework for future spaceflight missions. The NAI consisted of a set of competitively selected “teams” at research institutes distributed

throughout the United States, with affiliated institutions in 12 other countries; ► [NASA](#) referred to this network as a “virtual” institute. Each team typically included scientists from several institutions who collaborated on related astrobiological questions. The NAI Director and a small staff were located at the NASA Ames Research Center in Mountain View, California. The NAI concluded activities at the end of 2019, at which time the remaining teams were folded into what NASA calls Research Coordination Networks (RCNs). The RCNs will bring together researchers who are funded from a variety of sources into interdisciplinary, topically focused research groups. NASA currently plans to have five RCNs, which will focus on the following research topics: prebiotic chemistry and the early Earth; early metabolism, evolution, and complexity; life detection on other worlds; habitable worlds (initially focused on ocean worlds); and exoplanet system science.

References and Further Reading

<http://astrobiology.nasa.gov/nai/>

Nakhla

Ana-Catalina Plesa
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

Nakhla is an 18-kg Martian meteorite discovered in El Nakhla, Egypt, in 1911. It is the first of the nakhlites subgroup of the SNC meteorites and the first one to suggest aqueous processes on Mars. Its crystallization age has been estimated to 1.38 Ga using different isotopic systems. This clinopyroxenite is thought to have crystallized in thick lava flows (thicker than 125 m) or shallow intrusions (less than 1 km deep), conditions which are common for the Tharsis region. Other possible ejection sites are Elysium or Syrtis Major. In terms

of rare earth elements (REE), *Nakhla* shows a pattern similar to terrestrial basalts.

Cross-References

- [Crater, Impact](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Meteorites](#)
- [Meteoritics](#)
- [SNC Meteorites](#)

Nakhlites

Ana-Catalina Plesa
Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

Keywords

SNC meteorites · Rare Earth elements · Cosmic-ray exposure age · Amazonian

Definition

The nakhlites are a subgroup of the SNC meteorites named after the first sample found, the Nakhla meteorite. The nakhlite subgroup contains a total of 12 samples, which are classified as clinopyroxene rich rocks (Udry et al. 2020).

Overview

The nakhlites come most likely from a single impact event, sampling the same region, since they all exhibit cosmic ray exposure ages of 10.6 ± 1 Ma (Eugster et al. 2006). They are enriched in light rare earth elements (LREE) and other highly incompatible elements but are derived from a mantle source strongly depleted in them (Treiman 2005; Nakamura et al. 1982), similar to the MORB-source region and the lunar mare basalt-source region.

The crystallization age of the nakhlites has been estimated to 1.3 Ga (middle Amazonian)

using different isotopic systems (Podosek 1973; Nakamura et al. 1982; Treiman 2005). These clinopyroxenites are thought to have crystallized in thick lava flows (thicker than 125 m) or shallow intrusions (less than 1 km deep), conditions which are common for the Tharsis region (Treiman 1987). Other possible ejection sites are Elysium or Syrtis Major (Treiman 2005; Harvey and Hamilton 2005). Spectral signatures near the detection limit from regions in the eastern Valles Marineris (Juventae, Capri, and Eos chasmata), Terra Tyrrhena, and Syrtis Major Planum (surrounding Nili and Meroe Paterna) have been found consistent with the nakhlitic samples (Hamilton et al. 2003).

Cross-References

- ▶ [Crater, Impact](#)
- ▶ [Isotopic Fractionation \(Planetary Process\)](#)
- ▶ [Isotopic Ratio](#)
- ▶ [Meteorites](#)
- ▶ [Meteoritics](#)
- ▶ [Nakhla](#)
- ▶ [SNC Meteorites](#)

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Nanoarchaeota

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Nanoarchaeota is a phylum of the DPANN Archaea superphylum that branches closest to the root of the archaeal phylogenetic tree. Cells of *Nanoarchaeum*, the only genus in this phylum, are small coccoids that live as parasites, or possibly as symbionts, of the crenarchaeota *Ignicoccus*. Cells of *Nanoarchaeum* are about 0.4 µm in diameter and replicate only when attached to the surface of *Ignicoccus*. *Nanoarchaeum* is hyperthermophilic, with an optimal growth of about 90 °C. The metabolism of *Nanoarchaeum* is unknown, but its host is an autotroph, growing with H₂ as electron donor and elemental sulfur as electron acceptor. Isolates from *Nanoarchaeum* have been obtained from submarine hydrothermal vents as well as terrestrial hot springs. The genome of *Nanoarchaeum* is only 0.49 Mbp and lacks genes for most known metabolic functions. In addition to the small size of its genome, it is also the most compact of any organism known.

Cross-References

- ▶ [Archaea](#)
- ▶ [Deep-Sea Microbiology](#)
- ▶ [DPANN, Archaea](#)
- ▶ [Genome, Minimal](#)
- ▶ [Hot Spring Microbiology](#)
- ▶ [Hyperthermophile](#)

Nanodiamond

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

Diamond is one of the three basic ordered allotropes (polymorphs) of carbon, the others being ► [graphite](#) and ► [fullerene](#) (graphene can be described as a one-atom-thick layer of graphite). A diamond crystal has the carbon atoms arranged tetrahedrally in a cubic structure. Diamonds with dimensions of order 2 nm have been identified in meteorites and have been called nanodiamonds. They are thought to be portions of preserved interstellar grains. An absorption feature at a wavelength of 3.47 μm in the spectra of stars partially obscured by ► [interstellar dust](#) has been assigned by some to nanodiamonds in the icy mantles of interstellar grains.

Cross-References

- [Fullerene](#)
- [Graphite](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)

References and Further Reading

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Nanoparticle

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

Nanometer-sized particles are called nanoparticles. They are found in meteorites and there

is evidence of particles of this size as components of ► [interstellar dust](#).

Cross-References

- [Interstellar Dust](#)
- [Nanodiamond](#)

NAP-Astrobio, Brazil

Douglas Galante

Brazilian Center for Research in Energy and Materials, Campinas, Sao Paulo, Brazil

University of Sao Paulo, Sao Paulo, Brazil

Acronyms

NAP-Astrobio: Núcleo de Pesquisa em Astrobiologia (Portuguese); Brazilian Research Unit in Astrobiology

Definition

NAP-Astrobio is a Brazilian virtual network based at the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of Sao Paulo (USP). It encompasses various Brazilian research centers, such as other institutes of USP and different institutions: the Brazilian Center for Research in Energy and Materials, Federal University of Rio de Janeiro, Federal University of Sao Carlos, Federal University of Santa Catarina, State University of Londrina, and others. The main goals of the network are to foster the interdisciplinary collaboration of researchers, the formation of the next generation of astrobiologists, and the consolidation of the research field in Brazil.

History

NAP-Astrobio was created in 2011 at the University of Sao Paulo (USP) as part of an effort to

organize the Brazilian research community working with different branches of astrobiology. It started with the inauguration of the Astrobiology Laboratory at the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) of USP and the organization of the first international school in astrobiology in Brazil, the Sao Paulo Advanced School of Astrobiology Galante et al (2013). At the same year, it was accepted as an international partner of the NASA Astrobiology Institute (NAI) and the European Astrobiology Network Association (EANA).

Cross-References

- [EANA](#)
- [NAI](#)

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NASA

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The National Aeronautics and Space Administration (NASA) was established in 1958 as the agency of the US government responsible for civilian space exploration. In 1959, NASA funded its first investigation in what was then called exobiology, a life-detection experiment for a ► [Viking](#) mission to Mars. In 1960, the agency formally established an exobiology program, aimed at advancing this field of study by funding multidisciplinary research projects that other funding sources tended to judge as too

risky. By the 1980s and 1990s, NASA expanded its exobiology program to encompass studies of evolutionary biology and subsequently extended this field to establish “astrobiology” as a program encompassing studies of chemical evolution in interstellar space, the formation and evolution of planets, and the natural history of Earth, in addition to exobiology and evolutionary biology. Today, NASA’s Astrobiology Program addresses these fundamental questions: How does life begin and evolve? Is there life beyond Earth? If so, where should we search for it and how can we detect it? NASA is actively involved in a variety of scientific missions of interest to astrobiology. This includes an ambitious program to explore ► [Mars](#) that has included the Mars Science Laboratory called Curiosity, the land rover Perseverance with its helicopter Ingenuity, and plans for eventual return of samples to the Earth with Mars Sample Return (MSR). To look for habitable planets beyond the solar system, the Kepler Mission was launched in 2006 and the TESS mission in 2018. Possible future missions to characterize exoplanets by direct detection are in the planning stages, as are further missions to solar system targets such as ► [Europa](#), ► [Titan](#), and ► [Enceladus](#).

Cross-References

- [ESA Solar Orbiter Mission](#)
- [Kepler](#)
- [Mars](#)
- [Mars Exploration Rovers](#)
- [Mars Global Surveyor](#)
- [Mars Odyssey](#)
- [Mars Pathfinder](#)
- [Mars Reconnaissance Orbiter](#)
- [Mars Sample Return Mission](#)
- [Mars Science Laboratory](#)
- [Viking](#)

Reference

<http://www.nasa.gov/>

NASA Lunar Landing Mission

- ▶ [Apollo Mission](#)

National Space Institute, Denmark

- ▶ [DTU Space, Denmark](#)

Natron

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Natronite](#)

Chemical Formula

$\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$

Definition

Natron is a non-marine evaporite. It is a sodium carbonate of the monoclinic crystal system. Its name means “soda” in Latin. Together with thermonatrite and trona, it is one of the minerals which precipitate in soda lakes. These strongly alkaline environments have often been proposed as models for the composition of Hadean oceans. Spectral images from the PanCam instrument onboard of the Mars Exploration Rovers Spirit have identified natron among several hydrated minerals in silica-rich, opaline deposits in the Inner Basin of the Columbia Hills at Gusev Crater, Mars.

Cross-References

- ▶ [Evaporite](#)
- ▶ [Oceans, Origin of](#)
- ▶ [Soda Lake](#)
- ▶ [Thermonatrite](#)
- ▶ [Trona](#)

Natronite

- ▶ [Natron](#)

Natural Polymer

- ▶ [Biopolymer](#)

Natural Selection

Susanna Manrubia
Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Keywords

Adaptation · Competition · Evolution · Genotype · Heritable traits · Mutation · Phenotype

Definition

Natural ▶ [selection](#) is the process by which heritable traits (present in the ▶ [genotype](#) but reflected in the ▶ [phenotype](#)), raising the likeliness that one organism reproduces successfully, increase their presence in a population. Natural selection requires a population to be intrinsically variable such that different individuals have a different reproductive success. Competition for limited environmental resources privileges the genomes of those producing more progeny, promoting adaptation of the population and, eventually, speciation. Natural selection is a key mechanism of evolution. The development of resistance to antibiotics and pesticides observed in many

microorganisms is an example of natural selection in action.

Overview

The idea of natural selection as the main process behind evolution and adaptation is attributed to Charles R. Darwin (Darwin 1859). Almost simultaneously, Alfred Russell Wallace proposed the mechanism of natural selection as an explanation for biogeographical diversity (Wallace 1858). Although natural selection relies on the inheritance of traits from parents to offspring, a theory of heredity arose only about half a century later (Huxley 1942; Mayr and Provine 1980).

The constructive action of natural selection requires a sufficient amount of heritable individual variation. Variation results from processes that change the genomic composition of populations. Such processes are mutations (arising from errors in the process of genome copying), migration (reproduction between individuals belonging to separated populations or horizontal transfer of genetic elements), and genetic drift (small populations experience stochastic fluctuations that modify gene frequencies). A large number of mutations do not have a direct effect on phenotype (they are neutral) but increase the genomic diversity of populations.

Traits that are positively selected increase their frequency in the population. Due to pleiotropy (occurring when a gene influences multiple phenotypic traits) or genetic linkage, other traits that do not confer any advantage may also become more abundant. This selection of nonadaptive traits might lead to organs that are by-products of natural selection (or spandrels). The reuse of these organs is called exaptation (Gould 2002): feathers evolved to provide insulation but their function was co-opted for display and bird flight. Traits that were once positively selected but are no longer useful usually degenerate into vestigial traits – for example, muscles of the human ear, leg bones in whales, or eyes in the blind mole rat.

Natural selection acts at all levels through the hierarchical organization of biological systems:

The unit of selection can be a molecule, a gene, a cell, a group of individuals, etc. Intragenomic conflict occurs when selection at the level of genes (Dawkins 1976) has deleterious effects on the organism that carries them. The result of natural selection operating at all levels finally determines the fitness of individuals and the success of species in the long run (Okasha 2006). All mechanisms of selection involving environmental features and the structure and behavior of populations are termed ecological selection. This process is different from sexual selection, which refers to intraspecific competition for mates and includes intrasexual competition (usually male to male combat) and intersexual competition (mate choice) (Andersson 1995).

Cross-References

- [Adaptation](#)
- [Darwin's Conception of the Origins of Life](#)
- [Evolution, Biological](#)
- [Genotype](#)
- [Life](#)
- [Origin of Life](#)
- [Phenotype](#)
- [Selection](#)
- [Survival](#)

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NCA

- ▶ [Amino Acid *N*-Carboxy Anhydride](#)

Near Infrared (Near IR)

- ▶ [Infrared Astronomy](#)

Near-Earth Objects

Alan W. Harris
DLR Institute of Planetary Research, Berlin,
Germany

Acronyms

NEO

Definition

A near-Earth object (NEO) is an asteroid or comet with a perihelion distance of less than 1.3 astronomical units (au, the mean Sun–Earth distance). The orbits of NEOs can evolve to intersect that of the Earth; the associated impact hazard is very small but scientifically well-founded. The impact of a NEO with a diameter of just 50 m could cause a major catastrophe. Depending on its orbital parameters, a NEO is categorized as an Amor, Apollo, Aten, or Atira (inner Earth object). As of September 2021, the number of known NEOs is approaching 27,000, of which some 900 have diameters of 1 km or more. The vast majority of the NEOs are asteroids, that is, NEAs. The term “potentially hazardous asteroid” (PHA) is reserved for those with diameters above some 140 m and orbits that bring them within 0.05 au of the Earth’s orbit. PHAs are large enough to survive passage through the Earth’s atmosphere and cause extensive damage on impact. As of September 2021, some 2200 PHAs have been discovered.

Cross-References

- ▶ [Apollo Asteroid](#)
- ▶ [Asteroid](#)

Near-Field Cosmology

- ▶ [Galactic Archaeology](#)

Needle Ironstone

- ▶ [Goethite](#)

Neptune

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Keywords

Giant planets

Definition

Orbiting the Sun at a mean distance of 30 AU, with a revolution period of almost 165 years, Neptune is the outmost of the ▶ [giant planets](#) and also the smallest. Its diameter is 49,530 km, i.e., 3.9 times the terrestrial value. Still, its mass (17 terrestrial masses) is slightly greater than ▶ [Uranus](#), and its density (1.64 g/cm³) is thus also larger. Both Uranus and Neptune are called “ice giants” because their gaseous envelope consists mostly of water, methane and ammonium compounds, collectively called planetary ices. As all other giant planets, Neptune is surrounded by a system of rings and satellites.

Overview

History of Observations

Neptune was first identified in 1846 by Johannes Galle, who followed the prediction of Urbain Le

Verrier, based on celestial mechanics calculations. The quest for Neptune had started after the discovery of Uranus in 1781, as it was realized that Uranus' orbit was perturbed by another more distant heavy body. John Couch Adam from Cambridge University and Urbain Le Verrier from Paris Observatory came independently to the same conclusion about the position of this distant planet. John Adam, however, did not receive immediate attention from his director. Both predictions were very accurate, as the planet was found within 1° of its predicted position.

Little information was retrieved from visual observations in the following century, as the disk of Neptune is only 2.5 arcsec in diameter on the sky. Atmospheric methane was identified by Rupert Wildt in 1932, and hydrogen, suspected by Gerard Kuiper in 1952 on a theoretical basis, was identified in the 1970s.

Most of our knowledge about Neptune comes from the Voyager 2 spacecraft which encountered the planet in 1989. The Voyager camera revealed an amazing deep blue planet, patched with white cirrus clouds (probably due to methane) and showing a prominent cloud pattern, the "Great Dark Spot," analogous to Jupiter's Great Red Spot (Fig. 1). Voyager determined the temperature structure of Neptune's atmosphere, measured its zonal winds and its helium abundance, and

explored its magnetosphere. Voyager also discovered six new satellites and directly imaged Neptune's rings, which were found to be fully circular and not "arcs," as initially suggested from ground-based observations. Finally, Voyager encountered Neptune's satellite ► [Triton](#) and discovered ► [cryovolcanism](#) at its surface.

The space exploration of Uranus and Neptune has stopped after Voyager, and no mission is presently planned to visit these distant planets. Our knowledge of Uranus and Neptune has benefited from Earth-orbit observations (Hubble Space Telescope, ► [Infrared Space Observatory](#) [ISO], Spitzer) and ground-based telescopic observations from the visible to the millimeter range.

Composition and Structure

The vertical thermal profile of Neptune is very similar to the Uranus profile. As for Uranus, the tropopause, at a pressure of 100 mbar, shows a temperature minimum of about 50 K. Below this tropopause, the ► [tropospheres](#) of the two planets are very similar, while in the ► [stratosphere](#), the thermal profiles strongly differ; Neptune's stratosphere is significantly warmer than the Uranus one. A possible explanation might be the higher stratospheric content of CH_4 and aerosols (hydrocarbon condensates derived from methane photodissociation) in Neptune. Indeed, infrared observations from ISO, Spitzer, Herschel and from the ground have shown that methane is supersaturated in Neptune's atmosphere. The tropopause at the South Pole has been found to be significantly warmer than the rest of the planet, which might be the consequence of its continuous insolation over the last 40 years, as Neptune came to southern summer solstice in 2004. As a consequence, methane, instead of being trapped at the tropopause, is expected to be released into the stratosphere at the South Pole and to spread toward midlatitudes.

The cloud structure of Neptune, as predicted by thermochemical equilibrium models, is very similar to the Uranus one, with a CH_4 cloud at a pressure level of about 1 bar ($T = 80$ K), an H_2S cloud at about a few bars, and deeper clouds of NH_4SH and H_2O between 10 and 100 bar.



Neptune, Fig. 1 The planet Neptune, as observed by Voyager 2 in 1989. (© NASA)

The atmospheric composition of Neptune is similar to that of Uranus with two main differences. First, as mentioned above, stratospheric methane is more abundant, resulting in a more active photochemistry and in greater abundances of hydrocarbons, some of them forming clouds and haze. Second, other stratospheric species have been discovered on Neptune. In 1992, high abundances of CO and HCN were detected in Neptune's stratosphere, by far larger than theoretical predictions. H₂O and CO₂ were detected in 1997 by ISO, and water was later studied by Herschel. A plausible source for this oxygen could be a comet or a flux of ► [micrometeorites](#).

From tropospheric measurements, the C/H ratio was found to be, as in the case of Uranus, enriched by a factor of about 30 with respect to its protosolar value, which is fully consistent with the core accretion model of giant planets' formation. Further evidence is provided by the D/H measured in HD (deuterated molecular hydrogen), first detected by the ISO satellite and more recently by Herschel, which indicates, as for Uranus, an enhancement of D/H with respect to the protosolar value; this enhancement implies the presence of a significant icy core. The helium abundance, measured by Voyager, was found to be in agreement with its protosolar value.

Dynamics and Internal Structure

A striking characteristic of Neptune's atmosphere is its intense dynamical activity. Although more distant from the Sun than Uranus, Neptune shows much more vertical dynamical mixing and a changing climate. The disk of Neptune shows a variety of bright and dark features which vary over time; the white spots, presumably methane ice clouds, may dissipate over timescales of a few days or less. The Great Dark Spot which was identified by Voyager in 1989 had disappeared a few years later when Neptune was observed with the ► [HST](#).

What is the origin of Neptune's dynamical activity? Neptune is known to have a significant source of internal energy. The heat flow, as measured by Voyager from its integrated infrared emission, accounts to 2.6 times the solar energy

absorbed by the planet. The most plausible source for his internal energy is radiative cooling following the heating generated during the accretion phase of the planet. The open question is then to understand why the same process is not active on Uranus, while both planets exhibit very similar physical conditions.

As in the case of Uranus, Neptune's interior, according to theoretical models constrained by the planet's physical parameters, includes a central core of rocks and ices, surrounded by a mixture of ices and by a layer of molecular hydrogen, mixed with helium. At the center, the pressure might reach 8 Mbars and the temperature about 7000 K.

The Magnetosphere of Neptune

The magnetic field of Neptune, discovered and explored by Voyager 2, is, to first approximation, well described by a dipole. As in the case of Uranus, the dipole axis shows a large tilt with respect to the rotation axis (47° in the case of Neptune) and an offset with respect to the planet center (0.5 planetary radii). The dipole representation is valid at distances from 3 to 20 planetary radii. At shorter distances, higher-order multiple moments must be taken into account.

The peculiar configuration of the ► [magnetosphere](#) induces its rapid changes as the planet rotates in the solar wind. At every rotation, i.e., every 16 h, the tilt of the dipole axis, combined with the planetary obliquity of 29°, makes the magnetic pole change from a direction perpendicular to the ► [ecliptic](#) (and thus to the solar wind) to a direction aligned with the Sun-planet axis. As a result, the plasma dynamics are very complex. Auroral regions have been identified at midlatitudes, very different from the auroral ovals of Jupiter and Saturn which appear close to the polar regions.

There is a strong interaction between Neptune's magnetosphere and its largest satellite Triton, which orbits at a distance of 14 planetary radii. Triton is the main source of magnetospheric plasma. Neutral atoms escape Triton's tenuous atmosphere and are ionized in the magnetosphere; the dominant ions are H⁺ and N⁺.

Origin and Migration

Neptune, like the other giant planets, is believed to have formed through the accretion of an icy core of about 10–15 terrestrial masses, and the subsequent collapse of the surrounding gaseous nebula. According to this scenario, however, it is difficult to form such a massive core at the rather large heliocentric distance of Neptune (30 AU). There is also a contradiction in the fact that Neptune, more massive than Uranus, is presently more distant from the Sun. An explanation is proposed by the dynamical model recently developed at Nice Observatory. In this scenario, both Uranus and Neptune would have been formed closer to the Sun (with Neptune possibly closer to the Sun than Uranus) but migrated outward following the dissipation of the ► [protoplanetary disk](#). This migration mechanism would explain, in particular, the structure of the ► [Kuiper Belt](#) and the Late Heavy Bombardment.

Cross-References

- [Giant Planets](#)
- [Interior Structure, Planetary](#)
- [Late Heavy Bombardment](#)
- [Planet Formation](#)
- [Triton](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)

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Nereid

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Neptune's satellite Nereid was discovered by Gerard Kuiper in 1949. It orbits in the outer system of ► [Neptune](#), at a distance of 551,300 km (or 222 Neptunian radii), with a high ► [eccentricity](#) ($e = 0.75$) and a high inclination ($i = 27^\circ$). Its diameter is 370 km and its density is 1.5 g/cm^3 ; its surface is dark (with an albedo of 0.12) and heavily cratered. The high ellipticity of Nereid's orbit suggests that, as in the case of ► [Triton](#), Nereid is probably a captured object. The only image taken by Voyager was from a large distance (almost five million kilometers), so very little is known about the surface properties of this satellite.

Cross-References

- [Giant Planets](#)
- [Neptune](#)
- [Orbit](#)
- [Triton](#)
- [Voyager, Spacecraft](#)

Nernst Potential

- [Membrane Potential](#)

Netherlands Space Office

- [NSO, The Netherlands](#)

Neutral Atmosphere

Franck Selsis

CNRS, Laboratoire d'astrophysique de Bordeaux,
Passac, France

Definition

In physics, a neutral atmosphere is an atmosphere consisting of neutral gas, in contrast with the ionosphere. In chemistry, it is an atmosphere which neither oxidizes nor reduces immersed compounds. A planetary atmosphere is rarely chemically neutral because of the photodissociation by stellar UV radiation that produces oxidizing and/or reducing radicals and atoms. An atmosphere dominated by carbon dioxide (CO₂), nitrogen (N₂), and water vapor (H₂O), which many believe to be a good model for the prebiotic Earth's atmosphere, is often referred to as a neutral atmosphere, as it contains neither molecular oxygen (O₂) nor reduced forms of carbon gases, such as methane (CH₄) or carbon monoxide (CO), nor reduced nitrogen species, such as ammonia (NH₃).

Cross-References

- [Mildly Reducing Atmosphere](#)
- [Oxidizing Atmosphere](#)

Neutral-Neutral Reaction

Ian W. M. Smith

Chemistry Laboratory, University of Cambridge,
Cambridge, UK

Keywords

Chemical kinetics · Interstellar medium · Low temperatures · Rate coefficients

Ian W. M. Smith: deceased.

Definition

A neutral-neutral reaction is a chemical reaction that occurs in collisions between atomic or molecular species that carry no electrical charge. Because of the extremely low gas densities that characterize even the densest regions of the ► [interstellar medium](#), it is only necessary in this environment to consider bimolecular reactions that occur in binary collisions. The crucial properties that are sought in kinetic experiments are the *rate coefficient* and its dependence on temperature, denoted by $k(T)$, and, in cases where two or more sets of products are possible, the *branching ratio*—that is, the fractions of the overall reaction that proceed via different channels. For a bimolecular reaction, say $A + B \rightarrow C + D$, the rate of the loss of A may be written as $-d[A]/dt = k(T)[A][B]$, where the square brackets denoted concentrations, usually expressed in cm⁻³ so that the units of $k(T)$ are cm³ s⁻¹.

History

Chemical kinetics is a relatively mature branch of physical chemistry. The study of neutral-neutral reactions received a boost in the 1960s with the development of methods to study elementary reactions directly and with a burgeoning interest in the chemistry of the terrestrial atmosphere. These experimental methods were adapted fairly easily to the measurement of rate coefficients at temperatures between 200 and 500 K. The results of these studies are reviewed periodically with the evaluated data posted on two websites: <http://www.iupac-kinetic.ch.cam.ac.uk> and <http://jpldataeval.jpl.nasa.gov>. The discovery of the rich chemistry that leads to the presence of molecules in the interstellar medium, particularly in the cold ($T \approx 10$ K) environment of the cold cores of dense, dark, interstellar molecular clouds, has provided another stimulus to laboratory work designed to provide the basic information that serves as input to chemical models of different regions of the interstellar medium. Although the ionization of molecular hydrogen by cosmic rays and subsequent reactions between ions and

neutral species provide much of the driving force for the synthesis of molecular species, there is an increasing appreciation of the potential role of neutral-neutral reactions in this chemistry. This entry focuses on the experimental study of these reactions at temperatures approaching 10 K.

Overview

It is useful to distinguish three kinds of neutral species that can participate in neutral-neutral reactions: (1) *saturated molecules*, in which all the electrons are paired and the atoms are joined by single chemical bonds, examples include H_2 , H_2O , and CH_4 ; (2) *unsaturated molecules*, in which all the electrons are paired but some of the atoms are joined by double or triple bonds, as in HCN , C_2H_2 , and C_2H_4 ; and (3) *free radicals* (hereafter, *radicals*) such as CH and CN , which generally have unpaired electrons and are highly reactive.

Reactions between molecules, for example, $\text{H}_2 + \text{D}_2 \rightarrow 2\text{HD}$, require substantial electronic rearrangement and consequently are characterized by high energy barriers to reaction, the rate coefficients increase strongly with temperature, and at anything but very high temperatures, reaction only occurs in a very small fraction of the collisions between the potential reactants. Reactions between radicals and saturated molecules generally are characterized by barriers in the range $4\text{--}20\text{ kJ mol}^{-1}$, which require temperatures of $500\text{--}2500\text{ K}$ to be overcome. At the low temperatures of dense interstellar clouds (ISCs), the rate coefficients are therefore expected to be extremely small, and these reactions are usually ignored in the chemical models of these astronomical regions. Quite recently, however, laboratory experiments have shown that quantum mechanical tunneling through the barrier is very efficient at temperatures below 200 K for reactions involving the formation of an hydrogen bonded pre-reactive complex along the reaction pathway (Heard 2018; Sims 2013). As a matter of example the rate coefficient of the $\text{OH} + \text{CH}_3\text{OH}$ reaction was found to increase by about two orders of magnitude when the

temperature drops from 200 K to less than 100 K (Heard 2018; Canosa 2019).

Reactions between radicals and unsaturated molecules and between pairs of radicals, which require less electronic rearrangement, frequently do not exhibit energy barriers. For the former case, Smith et al. (2006) have reviewed the kinetic data and recommended two criteria, which might allow one to decide whether the rate coefficient for a particular reaction, for which room temperature kinetic data are available, is (or is not) close to the collision limit at low temperatures. These hypotheses were tested and confirmed in low-temperature measurements (down to 23 K) on the reactions of O atoms with alkenes (Sabbah et al. 2007).

Generally, the rate of reaction between two radicals is determined by their long-range attraction. Such reactions are difficult to study experimentally, but indications are that their rates will generally increase as the temperature is lowered (Hickson and Bergeat 2012; Hickson and Heard 2022).

Basic Methodology

Most rate coefficients for neutral-neutral reactions at and around room temperature have been provided by the application of two experimental techniques (Smith 2011).

The first employs a cylindrical tube (typically 1 m long and 3 cm in diameter). Radical atoms (H , O , N , C) or some small molecular radicals (e.g., OH) are created upstream of the main flow tube in a large excess of “carrier gas” (usually He or Ar). A measured flow of the co-reactant is added to the gas in the main flow tube, and changes in the radical concentration as a result of reaction can be measured by ► [mass spectrometry](#) or a variety of spectroscopic techniques at the downstream end of the flow tube. Because one observes a steady-state concentration of the radicals, a variety of methods can be used to measure the relative concentrations of the radicals that reach the observation point. Knowing the linear flow velocity, the time that elapses between the co-reactant being added and the gas reaching the

observation point can be estimated and hence the rate coefficient for the reaction calculated.

The second method relies on pulsed photolysis, using a laser, of a precursor to create the desired radical in the presence of a much larger known concentration of the neutral co-reactant. The subsequent decay of the radical concentration is observed using a suitable spectroscopic technique. Observing the rate constants for the radical decay in the presence of different concentrations of the co-reactant makes it possible to determine the rate coefficient for the reaction. The pulsed photolysis method has advantages over the flow method in that experiments can be performed over a wide range of total pressures and reactions at the wall of the reactor can be eliminated.

The experimental study of neutral-neutral reactions at low temperatures (<80 K) depends on the application of the CRESU (Cinétique de Reaction en Ecoulement Supersonique Uniforme, for Reaction Kinetics in Uniform Supersonic Flows) technique (Sims et al. 1994; Smith and Rowe 2000; Smith 2006; Potapov et al. 2017; Rowe et al. 2022). Gas (predominantly nonreactive gas such as helium, argon, or nitrogen) is expanded from a gas reservoir through a convergent-divergent Laval nozzle into a large chamber to provide a jet of gas moving at supersonic speed. The density is quite high (typically, $10^{16} - 2 \times 10^{17} \text{ cm}^{-3}$), collisions are therefore frequent, and thermal equilibrium is maintained. The kinetic temperature depends principally on the design of the nozzle. Temperatures as low as 12 K have been achieved with the reservoir at room temperature; lower temperatures can be reached by cooling the reservoir in liquid nitrogen, but that limits what gases can be introduced into the gas flow. The gas in the center of the jet remains uniform in density and temperature for several decimeters, corresponding to around 200 μs when helium is used as a carrier gas and 500–1000 μs for heavier gases such as argon or nitrogen.

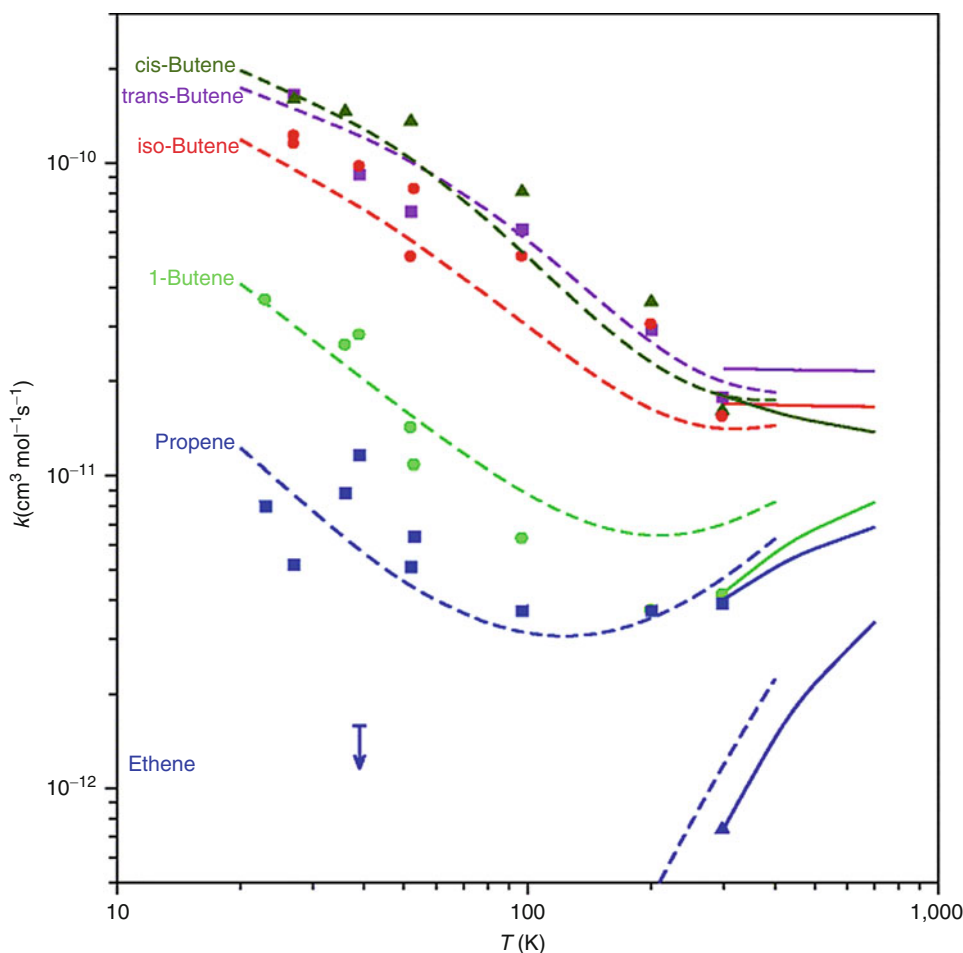
The CRESU technique was originally developed for the study of ion-molecule reactions, but during the 1990s, it was adapted (Sims et al. 1994) for the study of neutral-neutral reactions. For ► [ion-molecule](#) reactions, flow methods were adopted: that is, changes in the concentration of

the ionic reactant were measured as a function of either the concentration of the co-reactant or the distance downstream of the mass spectrometer used for observation. For neutral-neutral reactions, pulsed laser photolysis has been deployed to generate radicals, with detection of the changes in their concentration observed by laser-induced ► [fluorescence](#) or by observing chemiluminescence from an electronically excited reaction product. In this way, reactions of the following atomic and molecular radicals – C, Al, Si, B, O, N, S, Cl, F, CN, OH, CH, NH, C_2H , C_2 , C_4H , and CH_2 – have been measured routinely at temperatures down to about 25 K and as low as 6 K in some cases, with a variety of molecular co-reactants (Smith 2006, 2011; Canosa et al. 2008; Potapov et al. 2017; Hickson and Heard 2022).

Key Research Findings

The most important finding from CRESU experiments is the discovery that the rate coefficients for many neutral-neutral reactions, especially those between radicals and unsaturated species and between pairs of radicals, actually *increase* as the temperature is lowered, reaching values close to those estimated by simple collision theory. In detail, however, the form of the variation of $k(T)$ with temperature varies from reaction to reaction. As an example, Fig. 1 shows how the rate coefficients for the reactions of oxygen atoms with alkenes vary with temperature (Sabbah et al. 2007). In this case, the experimental data are well matched by theoretical calculations.

Only limited information has been obtained so far about reactions between pairs of radicals. One of the first studies gave the rate coefficients for the reaction $\text{CN} + \text{O}_2 \rightarrow \text{NCO} + \text{O.O}_2$ has two unpaired electrons, and this reaction proceeds via the transient formation of NCOO radicals, as the unpaired electron on CN and one of the unpaired electrons on O_2 “pair up” to form a chemical bond. The rate coefficient rises monotonically as the temperature is lowered from 298 to 13 K. The values of $k(T)$ agree with theory (Georgievskii and Klippenstein 2005). In an



Neutral-Neutral Reaction, Fig. 1 The points show the experimentally determined values of the rate coefficients for the reactions of $O(^3P)$ atoms with the indicated alkenes at different temperatures, and the *dashed lines* show the results of theoretical calculations using an advanced form

of transition state theory (Georgievskii and Klippenstein 2005). The *solid lines* to the right of the diagram represent Arrhenius expressions that fit the rate coefficients measured between 300 and 700 K

experimental *tour de force*, rate coefficients have been obtained for temperatures down to 38 K for the reaction between the two unstable radicals O atoms and OH (Carty et al. 2006). More recently, a relative technique has been developed to obtain the rate coefficient of the $N(^4S)$ atom reactions with a series of unstable radicals such as CN, CH, OH, C_2 , and C_2N at temperature as low as 54 K using the $N + NO$ reaction as a cornerstone (Hickson and Bergeat 2012; Hickson and Heard 2022).

More information about the rate coefficients for the numerous reactions studied at low

temperatures by the CRESU technique can be obtained from the recent reviews by Smith (2006, 2011), Canosa et al. (2008), Potapov et al. 2017, Cooke and Sims 2019 and the book dedicated to the CRESU technique (Rowe et al. 2022).

Applications

The results from CRESU experiments on neutral-neutral reactions have impacted on work in two other fields. First, it has stimulated a number of

theoretical approaches designed to understand, in detail, the factors that control the rates of reactions under these conditions (e.g., Georgievskii and Klippenstein 2005 and references therein). It is worth pointing out here the considerable interest brought very recently to the $\text{OH} + \text{CH}_3\text{OH}$ reaction by the theoretician community to understand how a reaction with an activation barrier along its reaction pathway could become so efficient at low temperatures (Canosa 2019). Second, although the experiments have not been able to study the neutral-neutral reactions that are likely to be most important in the ► [interstellar medium](#), the experiments have demonstrated that many neutral-neutral reactions remain rapid at very low temperatures and should be included in models of dense interstellar clouds (Smith et al. 2004, 2006).

Recent chemical models of interstellar clouds (Wakelam et al. 2006, 2010, 2015) have been extended in two connected ways: (1) to estimate the errors in the predicted abundances arising from uncertainties in the rate coefficients for reactions included in the model and (2) to show which reactions are likely to have the most influence on the predicted abundances. Such calculations can serve to focus the attention of laboratory astrochemists on the “key” processes in the interstellar medium.

Future Directions

Most of the kinetic experiments on neutral-neutral reactions reach a lowest temperature of ca. 25 K (Potapov et al. 2017; Cooke and Sims 2019). Consequently, there is some uncertainty in predicting the rate coefficients at 10 K for use in models of dense interstellar clouds and pre-stellar cores. The recent development of a new pulsed version of the CRESU technique (Jiménez et al. 2015; Ocaña et al. 2019) based on an aerodynamic chopper opens however the possibility to routinely measure rate coefficients at temperatures as low as 12 K. Further, because of the reduced flows of gases, it could become possible to investigate reactions that involve species that are not readily available (e.g., deuterated molecules) and which can be costly. In addition, attempts are

being made in several laboratories to measure rate coefficients for reactions at much, much lower temperatures (Bell and Softley 2009; Schnell and Meijer 2009; Heazlewood and Softley 2021). These will provide stringent tests of rate theories, which incorporate the quantum mechanical nature of molecular collisions.

Besides the determination of the rate coefficients, obtaining the branching ratios of chemical reactions at interstellar temperatures is essential since these can also be temperature dependent. The field is almost empty but a great deal of new instrumentations including chirped pulse microwave spectroscopy and infrared frequency combs or use of synchrotrons coupled to a CRESU reactor open very promising opportunities in the very near future (Rowe et al. 2022).

Cross-References

- [Arrhenius Plot](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecular Beams](#)
- [Molecular Cloud](#)
- [Reaction Rate Coefficient](#)
- [Supersonic Jet Expansions](#)

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Neutron Star

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

A neutron ► [star](#) is a compact object composed mainly of neutrons having a typical mass of 1.4 M_☉ and a typical radius of 10 km. Neutrons are abundantly produced through electron capture by protons in the final gravitational collapse of the dense Fe-core of a massive star. At densities 10¹⁴ g cm^{−3}, the high pressure of the degenerate gas of neutrons resists further collapse, producing a neutron star, provided the mass of the compact object is less than the Oppenheimer-Volkoff limit of 2–3 M_☉; otherwise, the object collapses to a ► [black hole](#). Rapidly rotating neutron stars emit beams of electromagnetic radiation and are known as ► [pulsars](#).

Cross-References

- [Black Holes](#)
- [Pulsar](#)
- [Stars](#)
- [Stellar Evolution](#)
- [Supernova](#)

New Horizons

Olivier Witasse
ESA-ESTEC, Noordwijk, The Netherlands

Keywords

Space Mission · NASA · Pluto · Kuiper belt

Definition

NEW HORIZONS is a NASA space mission to explore for the first time the Pluto system and the Kuiper belt. The spacecraft was launched in January 2006. It flew by Jupiter for a gravity boost in February 2007. It conducted a six-month-long reconnaissance flyby study of Pluto and its moons that started in early 2015, which culminated in the Pluto closest approach on July 14, 2015. A flyby of the Kuiper belt object 486958 Arrokoth, also named Ultima Thule, took place on January 1, 2019, at a distance of 43.4 AU from the Sun.

Overview

NEW HORIZONS is a space mission to explore for the first time the Pluto system and the Kuiper belt. It belongs to the category of NASA's New Frontiers Program.

The science payload includes:

- Ralph: Visible and infrared imager/spectrometer
- Alice: Ultraviolet imaging spectrometer

- REX: Radio Science Experiment
- LORRI: Long Range Reconnaissance Imager
- SWAP: Solar Wind Around Pluto
- PEPSSI: Pluto Energetic Particle Spectrometer Science Investigation

The spacecraft was launched on January 19, 2006, from Cape Canaveral. This was the fastest spacecraft ever launched. Thirteen months later, a gravity assist flyby of Jupiter at 32 Jovian radii took place to put the spacecraft into the correct trajectory to reach Pluto in 2015. The Jupiter flyby gave the opportunity to observe the giant planet system. One particular outcome was that most of the Io volcanoes frequently active during the Galileo era continued to be active during the New Horizons flyby.

During its long cruise phase, the spacecraft was put in hibernation, with regular checkouts of the instruments and platform subsystems. The exploration of the Pluto system began 6-month before the closest approach, which occurred on July 14, 2015, at a distance of 12,500 km. Stunning images were returned from this distant world. The data set gathered by the New Horizons instruments revolutionized our knowledge of the Pluto system. Pluto has been surprisingly geologically and climatologically active throughout the past 4+ Gyr and exhibits a remarkably complex range of atmospheric phenomenology and geological expressions. In contrast, the satellite Charon, though also geologically complex, has no detected active surface volatiles, has no detectable atmosphere, and exhibits only ancient terrains.

On January 1, 2019, the New Horizons spacecraft flew close to (486958) 2014 MU69, a cold classical Kuiper Belt object approximately 30 kilometers in diameter. Such objects have never been substantially heated by the Sun and are therefore well preserved since their formation. MU69 is a bilobed contact binary with a flattened shape, discrete geological units, and noticeable albedo heterogeneity. No evidence for satellites, rings or other dust structures, a gas coma, or solar wind interactions was

detected. MU69's origin appears consistent with pebble cloud collapse followed by a low-velocity merger of its two lobes.

The trajectory of New Horizons in the solar system allows to acquire also a unique data set on the solar wind variability in the heliosphere.

Cross-References

- [Jupiter](#)
- [Kuiper belt](#)
- [NASA](#)
- [Pluto](#)

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Next-Generation Space Telescope

- [JWST](#)

NGST

- [JWST](#)

NH

- [Imidogen \(NH\)](#)

NH₂

- [Amino Radical](#)

NH₂CH₂CN

- [Aminoacetonitrile \(NH₂CH₂CN\)](#)

NH₂CH₂COOH

- [Glycine](#)

NH₂CHO

- [Formamide \(NH₂CHO\)](#)

New Worlds Observer

- [TPF/Darwin](#)

NH₂CONH₂

- [Urea](#)

Nice Model

Alessandro Morbidelli¹ and Sean N. Raymond²

¹Observatoire de la Cote d'Azur, Nice, France

²Laboratoire d'Astrophysique de Bordeaux, CNRS, Universite de Bordeaux, Bordeaux, France

Definition

The so-called “Nice model” describes dynamical evolution of the outer Solar System since the time when the gas was removed from the ► [protoplanetary disk](#). In this model, the ► [giant planets](#) underwent a dynamical instability which played a major role in shaping the present-day Solar System. This instability could have happened several 100 million years after the planets formed. The Nice model can explain several observations in the Solar System, including the orbits of the giant planets, the existence and the orbital structure of several small body populations (e.g., Jupiter’s Trojans), and the ► [late heavy bombardment](#).

Overview

There are two versions of the Nice model.

The first one (*Nice I*) was presented in 2005 in a trilogy of papers published on the *Journal Nature*. In that version of the model, the assumption was made that the giant planets formed in a more compact configuration than their current one, with a ratio between the orbital periods of Saturn and Jupiter smaller than 2 (when the period ratio is exactly 2, the planets are said to be in 2:1 ► [mean motion resonance](#); the current period ratio is almost 2.5). The model also assumes that exterior to Neptune there was a massive primordial disk of small bodies (planetesimals), totaling perhaps 50 Earth masses. The long-term evolution simulated on computers proceeded as follows. Over time, Neptune’s gravity perturbed the orbits of nearby planetesimals onto crossing orbits and

led to scattering events. Due to its relatively small mass, Neptune preferentially scattered planetesimals inward. Due to a combination of their masses and orbits, Uranus and Saturn also preferentially scattered planetesimals inward, but Jupiter’s very large mass enabled it to preferentially scatter planetesimals outward (onto hyperbolic orbits and thus out of the solar system). The back-reaction of these scattering events caused the planetary system to slowly spread out, with Jupiter migrating inward and Neptune, Uranus, and Saturn moving outward. After a long delay, the system’s spreading caused Jupiter and Saturn to cross that 2:1 resonance, leading to an impulsive increase in the orbital eccentricities of those planets. This led to a rapid destabilization of the orbits of Uranus and Neptune and also of the remaining planetesimals in the outer system. Jupiter dynamically ejected the vast majority of these small cometary bodies from the system, but a small fraction collided with the terrestrial planets in an event known as the “Late Heavy Bombardment” (LHB). A contribution (possibly a dominant one) to the LHB also came from asteroids ejected from the asteroid belt during the migration of Jupiter and the excitation of the eccentricity of its orbit.

The second version was presented in 2007 and was subsequently refined in a series of papers. The main reason for promoting a new version of the model is that the initial orbits of the giant planets assumed in the 2005 model do not seem to be supported by hydrodynamical simulations of the evolution of said planets in the disk of gas in which they formed. The hydrodynamical simulations show that the giant planets migrate in the disk of gas relative to each other until they reach a fully resonant configuration. Saturn is typically locked in the 3:2 resonance with Jupiter (i.e., the period ratio is 3/2), while Neptune and Uranus can occupy a series of resonances with Saturn and with each other: 3:2, 4:3, 5:4, etc. This multi-resonant configuration is also consistent with the end-state of the Grand Tack Model (see ► [“Planet Formation”](#)). The new version of the Nice model (known as “*Nice II*”) uses these multiresonant configurations as initial conditions for the

planetary orbits. In this way, there are no arbitrary and ad-hoc assumptions on the initial orbits of the planets, unlike in *Nice I*.

Like in *Nice I*, the planets are assumed to be surrounded by a disk of planetesimals, extended from a few Astronomical Units (AU) beyond the orbit of Neptune up to about 30–35 AU. Computer simulations show that the distant interactions between the planets and the planetesimals slowly perturb the planetary orbits. Eventually, after a time that can be as large as a billion years, one planet is extracted from a resonance. When this happens, the planetary system immediately becomes unstable. The planetary orbits, in fact, are so close to each other that they can be stable only as long as the planets are all in resonance with each other. A good analogy to this situation is the Sun-Neptune-Pluto system. The system is stable because Pluto is in the 3/2 resonance with Neptune. But if Pluto were extracted from the resonance, its orbit would immediately become unstable.

Once the system of giant planets is destabilized, the subsequent evolution can follow one of three possible general trends. A first possibility is that Saturn and Jupiter have close encounters with each other. This in general leads to the ejection of all planets except Jupiter, who survives on a very eccentric orbit. This obviously did not happen in reality in our Solar System, but the final orbit of Jupiter in these cases is consistent with those of many giant planets that are observed around other stars. A second possibility is that Jupiter does not encounter any other planet. Only Saturn, Uranus, and Neptune are involved in mutual close encounters. We can exclude that also this possibility happened in the real Solar System. In fact, in this case, the ratio of orbital periods between Saturn and Jupiter would have increased slowly, on a timescale of millions of years. This would have destabilized the orbits of the terrestrial planets and would have sculpted the asteroid belt into an orbital structure very different from the one we observe today. The third possibility, the only one that is consistent with the current structure of the Solar System, is that Jupiter had close encounters with either Uranus, or

Neptune, or an additional planet of similar mass (eventually ejected to interstellar space). In particular, Saturn injects the Uranus-mass planet toward the inner solar system and Jupiter ejects it further out. In this process, the period ratio between Jupiter and Saturn “jumps” impulsively. This kind of evolution (dubbed “*Jumping Jupiter*”) preserves the stability of the terrestrial planets, does not produce weird orbital structures in the asteroid belt and also best reproduces the current orbits of the giant planets in terms of mutual orbital spacing, eccentricities, and inclinations.

Like in the case of the *Nice I* model, during the planet instability phase, Uranus and Neptune are eventually scattered outward and disperse the planetesimal disk. The interaction between the planets and the dispersing disk eventually parks the former on quasi-circular and quasi-coplanar orbits similar to the current ones. The dispersal of the trans-Neptunian disk and the partial destabilization of the asteroid belt trigger a heavy bombardment on the terrestrial planets.

Overall, the Nice model can explain many attributes of the Solar System. It explains the current orbits of the giant planets, in terms of mutual spacing and eccentricity and inclination excitation. In fact, the Nice II model is the bridge linking the multiresonant orbits that the giant planets should have had when they emerged from the gas-disk phase to the current orbits. Other Solar System characteristics that the model explains include: the timing of the LHB, the orbital distribution of Jupiter’s Trojan population, the characteristics of the irregular satellites of the giant planets, and many of the dynamical properties of the ► [Kuiper belt](#).

Cross-References

- [Giant Planets](#)
- [Late Heavy Bombardment](#)
- [Mean Motion Resonance](#)
- [Planet Formation](#)
- [Planet V Hypothesis](#)
- [Planetary Migration](#)
- [Trojans \(Asteroids\)](#)

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Nitrate Reduction

Aubrey L. Zerkle

School of Earth and Environmental Sciences and Centre for Exoplanet Science, University of St Andrews, St Andrews, UK

Keywords

Anaerobic respiration · Denitrification · DNRA · Nitrogen cycling · Oxygen minimum zones · Great Oxidation Event

Synonyms

Autotrophic denitrification; Dissimilatory nitrate reduction to ammonium (DNRA); Heterotrophic denitrification

Acronyms

DNRA

Definition

Nitrate reduction refers to biological processes in which the most oxidized form of nitrogen, nitrate (NO_3^-), serves as an electron acceptor during chemotrophy, either heterotrophically (with organic carbon) or autotrophically (e.g., with reduced sulfur compounds).

Overview

Nitrate (NO_3^-) is a common form of dissolved inorganic nitrogen that builds up in modern

aqueous systems. Nitrate is generally produced by the oxidation of ammonium (NH_4^+) and provides an important source of the nutrient nitrogen for life. As such, nitrate forms a key component of the global nitrogen cycle (e.g., see Galloway 2014). Nitrate reduction proceeds via a variety of pathways, most of which are mediated by microorganisms. In particular, nitrate can serve as the terminal electron acceptor during the anaerobic respiration of organic carbon. This process, termed *heterotrophic denitrification*, is confined to environments where oxygen is depleted. On the modern Earth, this includes marine sediments, particularly continental margins and hemipelagic sediments, and oxygen minimum zones (OMZs). The canonical heterotrophic denitrification pathway has been well described and generally follows the enzymatic reduction of nitrate to nitrite, nitric oxide, nitrous oxide, and finally to gaseous N_2 (Zumft and Korer 1997). Nitrous oxide (N_2O) can accumulate as an intermediate during denitrification, providing a source of this potent greenhouse gas. The capacity for heterotrophic denitrification is widespread among microorganisms, mainly within the *Proteobacteria* (Zumft 1997).

Nitrate reduction can also be coupled to the oxidation of reduced sulfur compounds during *autotrophic denitrification*, which can produce either N_2 or ammonium. The capacity to reduce nitrate or nitrite to ammonium (*DNRA*) is spread across a range of anaerobic and aerobic genera (Tiedje 1988), although DNRA has been reported mainly in anoxic sediments and in sediments with substantial free sulfide, where nitrification and heterotrophic denitrification are inhibited. Organisms such as *Thioploca* and *Thiomargarita* commonly perform DNRA in sediments underlying major OMZs, such as off the coast of Namibia (Fossing et al. 1995). These organisms accumulate the elemental sulfur products of sulfide oxidation and can concentrate nitrate to >100 mM levels in large vacuoles within their cells. As such, *Thiomargarita* is currently the largest known bacteria and is visible to the naked eye (Schulz et al. 1999). Notably, biologically available nitrogen

is removed from the biosphere through denitrification or the related pathway of anaerobic ammonium oxidation (*anammox*; reduction of nitrite to N_2 with ammonium), while DNRA retains it. Recent studies suggest that the balance between N_2 and NH_4^+ production during nitrate reduction generally depends on environmental parameters such as organic carbon, nitrite, and nitrate availability (Kraft et al. 2014). Nitrate reduction coupled to methane oxidation has also been recently described in freshwater settings (Nordi and Thamdrup 2014), but the importance of this process in global nitrogen and methane budgets remains unclear.

Nitrate was unlikely to have been widely available in the anoxic environments that characterized the early Earth, since the oxidation of ammonium (*nitrification*) generally requires molecular oxygen. Nitrogen isotopes preserved in the sedimentary rock record are consistent with N cycling processes that utilized oxidized nitrogen species, including denitrification and anammox, back to 2.4 billion years ago (Kipp et al. 2018) and possibly to 2.7 billion years ago (Godfrey and Falkowski 2009), but interpretations of these data are non-unique. Regardless, nitrate would presumably have become widespread in the oxygenated surface oceans that developed immediately following Earth's Great Oxidation Event (GOE), from ~ 2.3 billion years ago (Farquhar et al. 2014; Zerkle et al. 2017). Increased availability of nitrate after the GOE, coupled with widespread ferruginous bottom waters, could have led to high rates of denitrification and enhanced losses of fixed N. Thus nitrogen limitation has been implicated in hindering biological evolution, as well as the continued oxygenation of Earth's surface environments, throughout much of the Proterozoic (Fennel et al. 2005).

Cross-References

- [Denitrification](#)
- [Great Oxidation Event](#)
- [Nitrogen Isotopes](#)

- [Nutrient Cycling](#)
- [Oxygen Minimum Zone](#)

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Nitrates on Mars

Daniela Tirsch¹ and Alessandro Airo²

¹German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

²Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Definition

Nitrates are salts of the nitric acid (HNO₃). It has been estimated that one quarter of the initial Martian atmospheric molecular nitrogen today is fixed in the form of nitrates in the soil. A possible formation process of these nitrates is the dissociation of the atmospheric molecular nitrogen through shock heating caused by impacts or through photochemical reactions (Smith et al. 2014). Nitrates are highly soluble in water, hence nitrates entrained in the Martian ► [cryosphere](#) may contribute to the generation of brines near the surface. Because nitrates are a fundamental source of nitrogen for life on Earth, the detection of nitrates on Mars is an important parameter for the assessment of potential habitable environments. Recent analyses of “Rocknest” sand samples at Gale crater by the NASA rover “Curiosity” tentatively indicate the presence of nitrates.

Cross-References

- [Perchlorates on Mars](#)

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Nitrification

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Nitrification is an oxidative biological process that converts ammonia into nitrate. The whole process is composed of two different steps which are performed by different microorganisms: ammonia to nitrite and nitrite to nitrate. The first step is performed by organisms of two domains: ► [Bacteria](#) (genera *Nitrosomonas* and *Nitrosococcus*) and ► [Archaea](#) (Crenarchaeota phylum). The second step is driven by Bacteria (gen. *Nitrobacter*). Nitrification is an important part of the nitrogen cycle.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Nitrogen Cycle, Biological](#)
- [Respiration](#)

Nitrile

Piergiorgio Casavecchia and Nadia Balucani
Dipartimento di Chimica, Università degli Studi di Perugia, Perugia, Italy

Keywords

Miller-Urey experiment · Prebiotic chemistry

Synonyms

[Organic cyanide](#)

Definition

According to the recommendations of the IUPAC Nomenclature of Organic Chemistry, *nitriles* are

organic compounds containing the group $\text{—C}\equiv\text{N}$ (substitutive nomenclature scheme). Alternatively, the same compounds are called *cyanides* in the radicofunctional nomenclature scheme.

History

The term *nitrile* was first used by Fehling in 1844 in his work on benzonitrile.

Overview

The relevance of nitriles in astrobiology and in the study of the origin of life in our planet is related to their alleged role in ► [prebiotic chemistry](#) that preceded the appearance of life on Earth. Two points are in favor of this suggestion. First, there are efficient reaction schemes that start from simple nitriles, such as $\text{H—C}\equiv\text{N}$, and lead to the synthesis of ► [amino acids](#) and nucleic bases, which are amongst the most important building blocks of a living cell. Second, simple nitriles, such as $\text{CH}_3\text{—C}\equiv\text{N}$ and $\text{C}_2\text{H}_5\text{—C}\equiv\text{N}$, and more exotic ones, such as cyanopolyynes from $\text{HCC—C}\equiv\text{N}$ to $\text{HC}_{10}\text{—C}\equiv\text{N}$, have been observed in a variety of extraterrestrial environments (Ehrenfreund et al. 2002), thus suggesting that several gas-phase reactions easily produce them from simple parent species widely spread in the Universe (Balucani 2009). ► [Hydrogen cyanide](#), $\text{H—C}\equiv\text{N}$, can be considered the first member of the nitrile homologous series, but its properties are quite different compared to higher nitriles because of the ability to produce CN— ion. HCN has been identified in numerous extraterrestrial locations, ranging from ► [interstellar clouds](#) to planetary atmospheres and ► [comets](#). Exceptionally widespread has been the observation of the CN radical, which was among the first molecular species ever observed in the ► [interstellar medium](#). The prebiotic character of hydrogen cyanide has been clearly assessed (Delaye and Lazcano 2005; Eschenmoser 2007; Ehrenfreund et al. 2002). In aqueous solution containing imines (or aldehydes and ammonia), it leads to the synthesis of alpha amino acids following the

► **Strecker synthesis** scheme (this is the accepted explanation for the formation of amino acids in the Miller-Urey experiment). Also, adenine and guanine, important RNA and DNA bases, can be formed by the polymerization of HCN in water. Cyanoacetylene ($\text{HCC}-\text{C} \equiv \text{N}$, identified in interstellar clouds and in the atmosphere of ► **Titan**) can be involved in reactions producing cytosine and uracil in the aqueous phase (Ehrenfreund et al. 2002). Aqueous solutions of acetonitrile ($\text{CH}_3-\text{C} \equiv \text{N}$) and propionitrile ($\text{C}_2\text{H}_5-\text{C} \equiv \text{N}$), under the action of ionizing radiations, lead to the formation of oligomers, which upon hydrolysis release amino acids (Draganic et al. 1977). Finally, ionizing radiation produces amino acid precursors in icy environments that contain CH_3CN (Hudson et al. 2008).

Cross-References

- [Amino Acid](#)
- [Comet](#)
- [Cyanopolyne](#)
- [HCN Polymer](#)
- [Hydrogen Cyanide](#)
- [Miller, Stanley](#)
- [Nucleic Acid Base](#)
- [Prebiotic Chemistry](#)
- [Strecker Synthesis](#)
- [Titan](#)

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Nitriloacetonitrile

- [Cyanogen](#)

Nitrogen

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Keywords

Ammonia · Dinitrogen · Molecular nitrogen · Nitrogen cycle

Synonyms

[Atomic nitrogen](#); [N](#)

Definition

Nitrogen (elemental symbol: N) is the seventh chemical element in the periodic table. Nitrogen nuclei contain seven protons, and most commonly seven neutrons (the most abundant isotope, ^{14}N , has a monoisotopic mass of 14.00674 amu; the second most important nonradiogenic isotope, ^{15}N , has eight neutrons). It is the seventh most abundant element in the universe, but the fourth most abundant element in biochemical systems. It is the most abundant component (in the form

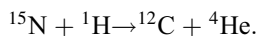
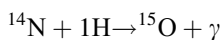
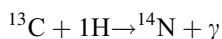
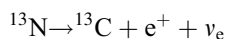
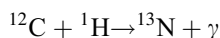
dinitrogen, N₂) of the atmospheres of the Earth (78.08% by volume) and of Saturn's moon Titan, and a significant component of the atmospheres of Mars and Venus. It is also common in the form of ammonia (NH₃) in comets and the gas giant planets of the solar system.

History

The name nitrogen derives from the Latin *nitrogenium*, which is itself derived from *nitrum*, from the Greek *nitron*, meaning “saltpeter,” and *genes* meaning “forming.” Nitrogen is usually considered to have been discovered by Daniel Rutherford in 1772.

Overview

Elemental nitrogen is believed to be primarily synthesized by stellar nucleosynthesis during the CNO cycle via the following set of reactions (γ : gamma photon; ν_e : electron neutrino):



When the cycle is run to equilibrium, ¹⁴N becomes the most abundant nucleus, regardless of the initial composition.

The nitrogen atom has the electron configuration 1s²2s²2p³; it would need to add three electrons to achieve the neon noble gas stable electron configuration. This can be achieved, for example, by the addition of three hydrogen atoms to yield the ammonia molecule (NH₃). In addition to this molecular form, nitrogen is also found in a variety of oxidation states from −3 to +5 as a component

Nitrogen, Table 1 Some commonly encountered small nitrogen-containing molecules

Compound	Formula	Oxidation state
Ammonia/nitride/cyanide	NH ₃ /N ^{3−} /CN [−]	−3
Hydrazine	H ₂ N-NH ₂	−2
Hydroxylamine	HONH ₂	−1
Dinitrogen	N ₂	0
Dinitrogen monoxide	N ₂ O	+1
Nitrogen monoxide	NO	+2
Nitrous acid	HNO ₂	+3
Nitrogen dioxide	NO ₂	+4
Nitric acid	HNO ₃	+5

Note: Molecules are found in all of the oxidation states from −3 to +5

of simple molecular compounds, most of which are gases at STP, though many of them readily dissolve in water (Table 1). The peculiar chemical reactivity of most nitrogen-containing compounds is very often connected to the presence of a lone, nonbonding electron pair on the nitrogen atoms.

Nitrogen is extremely important in biological systems, being a major component of common biochemical compounds including amino acids and proteins, the nitrogenous bases found in nucleic acids, and various other compounds including the alkaloids and biopolymers such as chitin. Indeed, biological tissue commonly contains as much as 14 wt% nitrogen, making it the fourth most abundant biologically important element. This represents a many thousand-fold enrichment relative to its cosmic and solar abundances.

One possible reason for this biological enrichment, in addition to cosmic abundance and prebiotic reactivity arguments, is that nitrogen in its reduced form can form C–N–C bonds, which offer novel geometric arrangements for molecules, and useful chemical reactivity. For example, organic compounds containing reduced nitrogen provide nucleophilic amine groups, which offer the possibility of simple addition chemistry in water, due to the relatively high basicity of amines relative to the corresponding oxygen-containing analogues. For these and other

reasons, it has been argued that searches for extra-terrestrial life should “follow the nitrogen” (Capone et al. 2006), that is, that reduced nitrogen may offer a signature of biological activity – although the rich H/C/N-based chemistry on Titan offers an abiotic counterexample.

The vast majority of the biologically important N-containing molecules contain nitrogen in the -3 oxidation state, while the most abundant form of nitrogen found on Earth is in the 0-oxidation state (Earth’s largest N reservoir is believed to be in the atmosphere as N_2), highlighting the importance of nitrogen reduction and the biological nitrogen cycle. In spite of the variety of nitrogen-containing molecular compounds, and of the variety of nitrogen oxidation states therein, it seems likely, as proposed initially by Mendeleev, that the majority of the Earth’s nitrogen was delivered in its -3 oxidation state, principally in the form of nitrides and ammonia (Hutsemekers et al. 2009). However, it also seems likely that nitrogen was fairly rapidly equilibrated and removed from mineral reservoirs: while nitrides are stable forms under the low T and low P conditions of the early solar systems, they are much lesser under the high T and P conditions of rocky planets’ mantles and cores. Nitrogen was likely rapidly outgassed from the early mantle, and NH_3 was removed from atmospheric reservoirs via photolysis. Studies of the solubility of nitrogen in magmatic melts (Miyazaki et al. 2004), and studies of the photochemical stability of ammonia (Ferris and Nicodem 1972) also support this notion, thus the general chemical stability of ► [dinitrogen](#) makes it a likely reservoir where kinetic effects dominate environmental nitrogen cycling.

Nitrogen occurs naturally in many terrestrial minerals, such as potassium nitrate, sodium nitrate, and ammonium chloride; however these are fairly uncommon since they are extremely water soluble.

In interstellar molecular clouds, nitrogen is thought to be mostly present as dinitrogen (N_2), whose presence is deduced from observations of N_2H^+ . Other nitrogen compounds, including ammonia, various nitriles, and cyanopolynes are also present (see “► [Molecules in Space](#)”).

Cross-References

- [Ammonia](#)
- [Dinitrogen](#)
- [Molecules in Space](#)
- [Nitrogen Cycle, Biological](#)

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Nitrogen Cycle, Biological

José Olivares and Juan Sanjuán
Estación Experimental del Zaidín. CSIC,
Granada, Spain

Keywords

Ammonification · Nitrification ·
Denitrification · Nitrogen fixation · Anammox

Synonyms

[Biogeochemical cycle of nitrogen](#)

Definition

The circulation of the various chemical forms of nitrogen among the atmosphere and aquatic and terrestrial ecosystems. The cycle essentially consists of the transformation, through several not sequential steps, of the organic nitrogen forming

part of the soil, plant, and animal debris into mineral and gaseous forms and viceversa, with the key participation of diverse bacteria and fungi.

History

It was not until the end of nineteenth century that the transformation of nitrogen compounds that occurred in the soil was related to microbial activities. T. Schloesing and A. Muntz discovered the process of nitrification in 1877. U. Gayon and G. Dupetit in 1886 were the first reporting denitrifying bacteria, whereas M. Hellriegel and M. Wilfarth in 1888 were also pioneers reporting the biological character of nitrogen fixation. The anammox (anaerobic ammonia oxidation) process was first observed in a pilot plant for the treatment of wastewater and reported in 1995 by the group of J. Kuenen. Anthropogenic activities, especially since the mid-twentieth century, have dramatically altered the nitrogen cycle, particularly by enhancing the amounts of reactive nitrogen circulating at regional and global scales, and the eventual accumulation of reactive nitrogen forms in certain ecological reservoirs (Galloway et al. 2004; Erisman et al. 2015).

Overview

The biogeochemical cycle of nitrogen is especially complex due to this element forming stable compounds in several valence states (from 5^+ to 3^-). Besides plants, many soil and water microorganisms are able to use nitrogen as a nutrient in mineral form, mainly as nitrate or ammonia coming from the mineralization of the organic matter. The mineralization begins with the transformation of the organic nitrogen (i.e., amino acids, nucleic acids) into ammonia. This step of the cycle is known as ammonification in which many bacteria, most of them heterotrophic, as well as some fungi participate. The resulting ammonia is either used by plants and bacteria (transitory immobilization) or oxidized to nitrate. This process called nitrification occurs in two stages, first from ammonia to nitrite and afterward

from nitrite to nitrate. Both steps are carried out by chemolithoautotrophs such as *Nitrosomonas* and *Nitrobacter* species, respectively, although there is evidence of the involvement of some heterotrophs. The final compounds can also be transitorily immobilized being assimilated by bacteria or absorbed by plant roots. Part of the nitrate produced is, however, reduced to molecular nitrogen through various steps in the denitrification process (NO_2^- , NO , N_2O , N_2). Denitrification is a form of respiration, and the microorganisms involved are either strict anaerobes or facultative anaerobes growing in the absence of oxygen. Denitrification has been well studied in *Paracoccus denitrificans* and some *Pseudomonas* species as well as in *Bradyrhizobium japonicum*, which is a nitrogen fixer but also a denitrifying bacterium. Nitrogen fixation, the reduction of molecular nitrogen to ammonia carried out by nitrogen fixers, free living or in symbiosis with plants, can recover the dinitrogen evolved by denitrification, thereby closing the cycle. The anammox process is the oxidation of ammonia to molecular nitrogen in anaerobiosis using nitrite as an electron acceptor, and that mainly occurs in wastewater treatment. All steps of the nitrogen cycle play an important role in the fertility of soil, either increasing the available nitrogen for plants or causing its loss as in the case of denitrification. Some microbial activities like denitrification also release to the atmosphere nitrogen oxides involved in climatic change, acid rain, and integrity of the ozone layer.

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Nitrogen Fixation

José Olivares and Juan Sanjuán
Estación Experimental del Zaidín. CSIC,
Granada, Spain

Keywords

Nitrogen transformations · Nitrogenase ·
Nitrogen-fixing bacteria · *Rhizobium* ·
Symbiosis

Synonyms

[Atmospheric dinitrogen fixation](#)

Definition

The term nitrogen fixation involves the combination of molecular nitrogen (dinitrogen, N_2) with oxygen or hydrogen to give nitrogen oxides (NO , N_2O) or ammonia (NH_3), respectively. Molecular nitrogen is the main component of the atmosphere, albeit it is considered an unreactive form and cannot be directly used by most living organisms, which generally can only use oxidized or reduced forms of nitrogen. In other words, nitrogen fixation is the conversion of molecular nitrogen into reactive nitrogen forms.

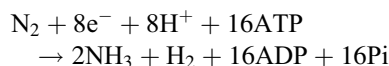
History

Although Malpighi had reported already in 1679 the presence of “small tumors” in the roots of legumes, it was not until 1888 that M. Hellriegel and M. Wilfarth recognized that nodules in

legume roots were responsible for the conversion of atmospheric nitrogen to ammonia. Also in 1888, M. Beijerinck was the first to isolate bacteria from several legume root nodules and confirmed their involvement in nitrogen fixation and plant nitrogen nutrition. This same author discovered in 1901 the ability of *Azotobacter* and *Clostridium* to fix nitrogen in free-living conditions. In the early 1900s, F. Haber invented and C. Bosch developed the Haber-Bosch process for the catalytic synthesis of ammonia from dihydrogen and dinitrogen under conditions of high temperature and pressure, so-called industrial nitrogen fixation. In the twenty-first century, new approaches involving electrocatalytic reduction of dinitrogen for a more sustainable industrial synthesis of ammonia are being explored (Martin et al. 2019).

Overview

Dinitrogen can be oxidized or reduced by physic-chemical processes, forming N oxides produced by electrical discharges or by combustion of fossil fuels, or the reduced-form ammonia produced by the industrial Haber-Bosch process. It can also be reduced to ammonia by bacteria free-living or in symbiosis with plants, through a process known as biological nitrogen fixation (BNF). The ammonia produced is either assimilated by free-living bacteria, or in the case of symbiotic fixation, transferred directly to the host plant. Nitrogen fixation may globally account for 250 million Tn per year, roughly 50% of this quantity corresponds to biological processes. Most of the remaining 50% originates from H-B industrial production of fertilizers for agriculture. BNF is a highly energy-consuming and oxygen-sensitive process, and is a capacity restricted to prokaryotic organisms, bacteria and archaea, so-called diazotrophs or nitrogen fixers. The reduction of N_2 is catalyzed by the enzyme nitrogenase, constituted by two metalloproteins, ferroprotein and molybdoferroprotein, well conserved among all nitrogen fixers. The reaction proceeds according to the following equation:



The nitrogenase shows a wide range of activity on molecules containing triple bonds, which has led to think on its possible detoxifying role in the early-earth environment, and has provided an easy detection and measurement method of this activity based on the reduction of acetylene to ethylene. Besides ammonia, H_2 is released as a byproduct of the nitrogenase activity, which causes a loss of efficiency in the process. BNF has great importance from ecological/environmental and economical points of view. It occurs in all habitats, terrestrial and aquatic ecosystems, and balances the biogeochemical nitrogen cycle by retrieving from the atmosphere, the nitrogen lost by denitrification. BNF carried out by free-living bacteria has a limited agricultural significance due to its high energetic requirements, in contrast to BNF by plant symbiotic bacteria, where the microorganisms use carbon and energy sources from plant photosynthesis. Among plant species which are able to fix nitrogen are the legumes, of great importance for animal feeding and human nutrition. Legumes associate with nitrogen-fixing bacteria of diverse genera and species collectively known as Rhizobia. Exploitation of this capacity, achieved through bacterial selection and inoculation of agriculturally important species, is a practice that greatly contributes to agroecosystem sustainability (Olivares et al. 2013).

Cross-References

- [Diazotrophy](#)
- [Dinitrogen](#)
- [Nitrogen Cycle, Biological](#)

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Nitrogen Gas

- [Dinitrogen](#)

Nitrogen Hydride

- [Imidogen \(NH\)](#)

Nitrogen Isotopes

Ko Hashizume

Faculty of Science, Ibaraki University, Ibaraki, Japan

Keywords

Nitrogen cycle (biological) · Isotope anomaly · Isotope fractionation · Organic formation · Solar composition

Definition

Nitrogen has two stable isotopes, nitrogen-14 and nitrogen-15. The abundance ratios of the two isotopes among geological samples, both extraterrestrial and terrestrial, exhibit wide variations, despite the first-order expectation of its stable

nature. This expectation derives from the absence of important sinks or sources of these nuclides by any known nuclear reactions that may naturally occur, apart from their nucleosynthesis in several kinds of stellar environments. Nitrogen is one of the most important elements in organic matter preserved in geological samples. The isotopic variations of nitrogen may provide important clues to decipher the formation processes for these samples.

Overview

The abundance ratios of nitrogen-14 and nitrogen-15 among extraterrestrial samples exhibit more than a factor of 2 variation, the largest among all elements except for hydrogen. Interesting isotopic variations are also observed among nitrogen from various terrestrial samples that represent the compositions of different reservoirs in the Earth, such as the nitrogen in the mantle, in the atmosphere, or in the biosphere present and past. Although the exact reasons for the variations are yet unresolved, growing evidence suggests that a better understanding of the variations may have important astrobiological implications in the evolutions both of the early solar system and of the Earth.

Basic Methodology

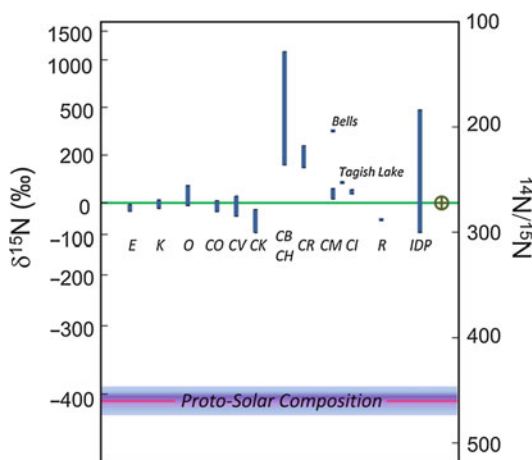
The nitrogen isotopic ratios ($R = {}^{15}\text{N}/{}^{14}\text{N}$) among geological samples are normally expressed in the δ -notation, that is, by the difference of the ratio in per mil units relative to the ratio of the reference standard; $\delta {}^{15}\text{N} \equiv (R/R_{\text{std}} - 1) \times 1000$. The international reference standard for nitrogen is the terrestrial atmosphere with R_{std} of 3.676×10^{-3} .

Key Research Findings

Nitrogen Isotopes in the Early Solar System

Nitrogen is abundant, typically at 0.1–1.0% levels, in primitive planetary materials, that is, chondritic meteorites, interplanetary dust

particles, and cometary dust. Their isotopic compositions can be regarded as representing those of the building blocks forming rocky planets in the solar system. The nitrogen isotopic ratios among meteorites of different chemical groups, which likely correspond to those from different asteroids, show widely different $\delta {}^{15}\text{N}$ values, ranging from -95 to $+1122\text{‰}$ among bulk samples (Fig. 1). Interestingly, only a limited number of meteorites known so far show $\delta {}^{15}\text{N}$ values with near terrestrial compositions ($\sim 0\text{‰}$). This may either suggest that (1) the Earth has sampled kinds of building blocks different from the known meteoritic populations; (2) the Earth was produced from melanges of several different kinds of building blocks; or (3) the terrestrial composition was altered by planetary processes after the accretion. A good example for the third possibility is seen on Mars and Titan, where the atmosphere is highly enriched in ${}^{15}\text{N}$ ($\delta {}^{15}\text{N} \sim +750\text{‰}$ (Mars) or $+490\text{‰}$ (Titan); see references in Marty et al.



Nitrogen Isotopes, Fig. 1 Nitrogen isotopic compositions among chondrites and interplanetary dust particles (IDPs) compared with the proto-solar composition (Respective data are taken from literatures referenced by Busemann et al. (2006), Floss et al. (2004), Hashizume et al. (2000), Marty et al. (2011), and Nakamura-Messenger et al. (2006). Note that the values for the meteorites and IDPs are the “bulk” compositions, somewhat rounded by mixture of several isotopically distinct components, including the terrestrial contaminations. Within respective chondrites, numbers of subcomponents, besides the nitrogen from the identified presolar grains (Zinner 2005), are observed exhibiting a wide $\delta {}^{15}\text{N}$ range from -230‰ to $+3200\text{‰}$)

2011). This is due to the preferential escape of the lighter isotope from the planetary atmospheres, although whether such a process may have occurred on larger-mass planets like the Earth is still an issue.

A couple of possibilities are proposed to explain the variations among the extraterrestrial samples. (1) Isotopic variations are caused by heterogeneous distribution of “exotic” nitrogen-bearing compounds among the planetary materials, which reflect the isotopic compositions unique to the source reservoirs for each compound, such as stars with different nucleosynthetic productions. (2) Large isotopic fractionation occurred in the formation process of the nitrogen-bearing compounds. Although several kinds of presolar grains (diamonds, graphite, silicon carbides, or silicon nitrides) are identified so far among the primitive meteorites (Zinner 2005), exhibiting strikingly anomalous nitrogen isotopic ratios, their abundances are generally too low to explain the overall isotopic variations observed among the bulk meteorites. The dominant fraction of nitrogen in primitive planetary materials is in the form of highly polymerized organic matter. By recent isotope studies of extraterrestrial organic matter using high space-resolution ion microprobes, submicron-sized organic grains with highly positive $\delta^{15}\text{N}$ values, up to +3200‰, are identified among primitive meteorites (Busemann et al. 2006; Nakamura-Messenger et al. 2006), interplanetary dust particles (Floss et al. 2004), and cometary dust (Stadermann et al. 2008). Some of such grains are enriched also in deuterium, which is generally considered to suggest that the organic formation occurred at low temperature, for example, in the molecular cloud or in the outer region of the proto-solar nebula. However, interestingly, not all of the grains are associated with the D enrichment, possibly suggesting the provenance of such ^{15}N -rich organic grains from several different sources (Marty et al., 2011). Part of the reasons for the deviation between the ^{15}N and D enrichments could be due to the presence of important isotope fractionation processes peculiar to the element, for instance the one produced by photochemical

processing of nitrogen reservoirs within the solar nebula (Chakraborty et al. 2014).

The nitrogen isotopic composition of the Sun plays a pivotal role in constructing the framework. The proto-solar nebula corresponds to the ultimate source material of all solid compounds generated in the Solar System. Nitrogen isotope studies of the solar wind implanted in lunar regolith samples (Hashizume et al. 2000), of Jupiter’s atmosphere (the nebular gas trapped by the giant planet; Abbas et al. 2004; Wong et al. 2004), of a refractory mineral in meteorites considered to be in equilibrium with the nebular gas (Meibom et al. 2007), and of the contemporary solar wind collected by a solar-circling spacecraft (Marty et al. 2011), all arrived to the same conclusion that the solar composition has much lower $^{15}\text{N}/^{14}\text{N}$ ratio than any planetary materials. The best estimate of the solar $\delta^{15}\text{N}$ value is $-407 \pm 7\text{‰}$ (Marty et al. 2011). These results suggest that essentially all nitrogen-bearing solid compounds contained in asteroidal materials or naturally including the Earth-forming building blocks are enriched in ^{15}N .

Nitrogen Isotopes on the Earth

Although the extent of nitrogen isotope variations among terrestrial samples is much smaller than among the extraterrestrial ones, likely reflecting the isotope homogenization produced by intensive heating and mixing of the accreted materials, important variations in the isotopic ratio are still observed; for instance, between nitrogen in the mantle layers (-3‰ for the MORB source mantle, or $+3\text{‰}$ for the OIB source mantle; reference in Marty and Dauphas 2003) and the atmosphere ($\equiv 0\text{‰}$), or between nitrogen trapped in contemporary sediments ($+7\text{‰}$) and Archean sediments (-7 to $+40\text{‰}$; compiled by Thomazo et al. 2009).

The possibilities proposed so far to explain these isotopic variations can be divided into two groups with the keywords somewhat similar to the extraterrestrial case: “heterogeneity” or “fractionation.” The hypotheses belonging to the first group (e.g., Jia and Kerrich 2004) refer to the contrasting isotopic compositions among chondrites as analogues for the Earth-forming building blocks. The typical end-member compositions

assumed in such models are the bulk compositions of the Enstatite chondrites ($-22 \pm 11\%$; average and standard deviation in the distributions among bulk $\delta^{15}\text{N}$ values) and the carbonaceous (CI/CM) chondrites ($+35 \pm 11\%$). The other group attempts to explain the variations by isotopic fractionation on the Earth, particularly at its surface, where nitrogen actively circulates between the atmosphere and the biosphere. It is commonly accepted that the average of 5‰ enrichment of ^{15}N in the contemporary marine biosphere, relative to the atmosphere, is caused by a biological cycle of N. This cycle involves *fixation* ($\text{N}_2 \rightarrow \text{NH}_4^+$), *nitrification* ($\text{NH}_4^+ \rightarrow \text{NO}_3^-$), and *denitrification* ($\text{NO}_3^- \rightarrow \text{N}_2$), where the biological N ($\text{NH}_4^+ + \text{NO}_3^-$) is enriched in ^{15}N due to the preferential consumption of ^{14}N in the last process (Sigman et al. 2008). Several workers (e.g., Shen et al. 2006) argue that part of the $\delta^{15}\text{N}$ variations (7–40‰) observed among the sedimentary rocks of different ages can be explained by a similar cycle but with different fluxes composing the cycle, possibly reflecting the different environmental settings. For instance, we may expect higher mean $\delta^{15}\text{N}$ values for the biosphere when the flux of *denitrification* in the cycle was larger. Such a situation may happen when the abundance of free oxygen was lower in the atmosphere and in the ocean, where the nitrate ion, an electron acceptor substituting for the role of free-oxygen, was more important for life than at present. Alternatively, the negative $\delta^{15}\text{N}$ values can be produced by the isotope fractionation involved in chemosynthesis: organic production uses chemical energy instead of sunlight (deep-sea hydrothermal vents) (Pinti and Hashizume 2001). Other models (Marty and Dauphas 2003; Goldblatt et al. 2009) the isotopic differences among the mantle layers and the atmosphere relate to the biological isotope fractionation. These authors suggest that nitrogen delivery takes place as NH_4^+ ions substituting for K^+ ions in the subducting crustal rocks. Ammonium ions are predominantly produced through life. By this mechanism, the peculiar isotopic signatures of present and past living organisms may be propagated to the mantle.

Nitrogen Isotope Fractionation

The prominent isotope variations that occur for nitrogen may not be absolutely indifferent to the geochemical nature of nitrogen. The most abundant phase of nitrogen in the proto-solar nebula or at the surface of the Earth, in a wide range of pressure-temperature conditions, is the exceedingly stable gas phase, the triple-bonded nitrogen bimolecule N_2 . The bimolecular nitrogen is so inert that little is trapped among the solid materials. The dominant fraction of nitrogen observed in the planetary solid materials or N-rich terrestrial rocks is trapped as chemically active nitrogen-bearing compounds. The formation processes of these compounds probably bear the key to understanding the origin of the nitrogen isotope fractionation. To yield any nitrogen-bearing solid compounds from N_2 , it is indispensable to first go through a particularly energy-consuming elementary process to cut the triple bonds. The elementary processes proposed so far involve excitation sources or catalysts peculiar to the specific environments, such as cosmic rays (for ion-molecule reactions), ultraviolet light (for photodissociation), or enzymes available in limited kinds of microorganisms (for nitrogen fixation in the ocean). The observed nitrogen isotope variations are directly associated with these processes (e.g., Clayton 2002), and/or, as a consequence of the limitations caused by the existence of this energy barrier: nitrogen-bearing solid compounds are effectively produced only through a few pathways involving the bond-cutting elementary processes. The isotopic signatures specific to each pathway (e.g., Rodgers and Charnley 2008; Sigman et al. 2008) could be therefore easily preserved.

Future Directions

The overall situation of current nitrogen isotope studies is not specific to nitrogen. Remarkable isotope variations observed among the planetary and terrestrial samples, and some contrasting and unresolved explanations presented, are often shared by other elements. This is the case of volatile elements in extraterrestrial samples (e.g., H, C, and O; Clayton 2002) and of

biologically important and/or redox-sensitive elements in terrestrial rocks (e.g., C, S, and Fe; Thomazo et al. 2009). The similarity and dissimilarity isotope signatures for elements from various samples are the most promising clues to the entire stable isotope puzzle.

Cross-References

- [Earth's Atmosphere, Origin and Evolution of](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Interplanetary Dust Particle](#)
- [Interstellar Chemical Processes](#)
- [Ion-Molecule Reaction](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Nitrogen Cycle, Biological](#)
- [Nitrogen Fixation](#)
- [Oxygen Isotopes](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Photochemistry](#)
- [Protoplanetary Disk, Chemistry](#)
- [Stardust Mission](#)

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Nitrogen Sulfide (NS)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

NS

Definition

The term nitrogen sulfide is used both for solid N_4S_4 (also called nitrogen tetrasulfide), which is unstable under laboratory conditions, and by astronomers for the diatomic, gas phase molecule NS. The latter is widespread in interstellar ► [molecular clouds](#), with an enhanced abundance in ► [“hot cores”](#), the regions where massive stars are forming. Gaseous NS has been observed in the ► [Milky Way](#) and in external galaxies as well as in ► [Comets](#).

History

Interstellar NS was first detected by radio astronomers in 1975 by Gottlieb et al. (1975) and Kuiper et al. (1975).

Cross-References

- [Comet](#)
- [Hot Core](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

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Nitro-sil

- [Ammonia](#)

N-Methylglycine

- [Sarcosine](#)

Noachian

Ernst Hauber

Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Definition

The oldest of three systems (of time-stratigraphic units) or periods (the chronologic equivalents to systems) in the Martian stratigraphic scheme, named after the region of Noachis Terra (*Noachis*: Biblical; “Noah’s (Region)”; see U.S. Geological Survey Gazetteer of Planetary Nomenclature). Depending on the different models to determine absolute ages on planetary surfaces by crater statistics, the Noachian began at some time more than 4.1 billion years ago and ended about 3.8 billion years ago. The recent detection of a population of large buried ► [impact basins](#) in the northern lowlands suggests the existence of a “pre-Noachian” period.

Cross-References

- [Amazonian](#)
- [Cratering Chronology](#)

- [Crater, Impact](#)
- [Hesperian](#)
- [Impact Basin](#)
- [Mars](#)
- [Mars Stratigraphy](#)

Noble Gases

Bernard Marty

Institut Universitaire de France, Ecole Nationale Supérieure de Géologie, Centre de Recherches Pétrographiques et Géochimiques (CRPG), CNRS, Vandoeuvre les Nancy Cedex, France

Keywords

Terrestrial mantle · Volatile elements · Geochemical tracers · Origin of Earth's atmosphere · Geochronology · Mars

Synonyms

[Rare gases](#)

Definition

The noble gases are a group of chemical elements with a very low chemical reactivity. In most natural conditions, they cannot form chemical compounds and their abundances and isotopic ratios are only affected by physical processes such as phase changes, kinetic effects, and nuclear reactions including radioactivity. Due to their inertness, they are used as cosmochemical and geochemical tracers when investigating the origin and the processing of their host phases or of other volatile elements.

Overview

The noble gases – helium (symbol: He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn) – have all their electronic shells saturated and therefore cannot readily make

compounds. Radon isotopes are all instable and this element is generally not used as a geochemical tracer. Although they are abundant in stars (helium is the second most abundant element in the universe), they are highly depleted in metals and silicates, and therefore in inner planets and meteorites, due to their impossibility to make chemical bonds with other elements. For instance, terrestrial noble gases, when normalized to a reference element like silicon, are depleted by factors of 10^{-6} – 10^{-10} relative to the solar photosphere. They are particularly useful as cosmochemical and geochemical tracers because of their inertness and their low natural background. They record physical processes such as fractionation during phase changes or irradiation, or nuclear production of some of their isotopes, by spallation or neutron/proton activation in space or at the Earth's surface, or by decay of naturally occurring radioactive isotopes. The well-known K-Ar geochronological method makes use of the decay of potassium-40, a rare isotope of the otherwise relatively abundant element potassium, to ^{40}Ar (half life $T_{1/2} = 1.25$ Ga), an isotope of argon that was in very low abundance compared to the other isotopes of argon, ^{36}Ar and ^{38}Ar , when the Earth formed. Noble gases are also excellent tracers of the formation and evolution of the atmospheres of the terrestrial planets. For instance, air contains 0.934% of Ar, formed almost exclusively of ^{40}Ar produced by the decay of radioactive potassium in the solid Earth, which testifies of the degassing of the mantle into the atmosphere through time. Other noble gas isotopic systems including extant and extinct radioactivities, such as ^{129}I - ^{129}Xe ($T_{1/2} = 16$ Ma), ^{244}Pu - $^{131-136}\text{Xe}$ ($T_{1/2} = 82$ Ma), and ^{238}U - $^{131-136}\text{Xe}$ ($T_{1/2} = 4.45$ Ga), have allowed considerable refinement in modeling the origin and evolution of the atmospheres of Earth and ► [Mars](#). Noble gases in the Sun and in meteorites present elemental and isotopic variations that can be used to set constraints on the origin of terrestrial volatiles. Noble gas elemental and/or isotopic fractionation during phase change and kinetic processing permits investigation of the responsible processes, such as oil–water–gas interactions in the crust, or atmospheric escape early in Earth's history.

Cross-References

- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Geochronology](#)
- ▶ [Mantle Volatiles](#)
- ▶ [Mars](#)
- ▶ [SNC Meteorites](#)
- ▶ [Spallation Reaction](#)

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Noise

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Noise is an unwanted and random perturbation on a signal of interest. Any measurement is affected by noise, which can be fundamental (e.g., shot noise), instrumental (e.g., vibrations), or due to a perturbing medium (e.g., atmospheric turbulence). When noise sources are independent, their signals add in a quadratic way. The signal-to-noise ratio (usually noted S/N) is the ratio of the magnitude of the useful signal to the noise amplitude: it is a convenient way to assess the relative importance of a disturbing effect. The result of an experiment established with a $S/N < 5$ is generally considered as not reliable.

Non-aerobic

- ▶ [Anaerobe](#)

Non-coded Amino Acids

- ▶ [Nonprotein Amino Acids](#)

Non-enzymatic Rearrangement

- ▶ [Abiotic Recombination](#)

Nonenzymatic Template-Directed Polymerization

- ▶ [Template-Directed Polymerization](#)

Nonpolar Molecule

- ▶ [Apolar Molecule](#)

Nonprotein Amino Acids

Sandra Pizzarello
Department of Chemistry & Biochemistry,
Arizona State University, Tempe, AZ, USA

Keywords

Amino and carboxyl functional groups · Amino acids · Enantiomer · Free amino acids · Peptides · Racemization · Rare amino acids · Zwitterions · Abiotic syntheses · Chemical evolution

Synonyms

[Non-coded amino acids](#); [Non-proteinogenic amino acids](#)

Definition

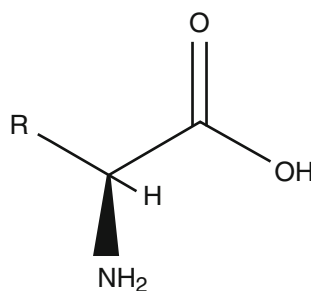
Amino acids are multifunctional organic compounds that contain at least one amino and one carboxyl group attached to a central carbon atom,

whose side chains may vary in length and branching as well as in content of other functional groups or aromatic rings. Amino acids may form numerous molecular structures, where the relative position of the amino and carboxyl function allows their general classification as 2-, 3-, 4-, etc. (also referred to as α , β , γ , etc.) amino acids. Most amino acids have at least one asymmetric carbon and are chiral. Amino acids are classified as nonprotein when they are not part of the 22 such molecules that are translated into proteins by the standard [genetic code](#). They are found in nature, both in biology and extraterrestrial chemistry.

Overview

A large and diverse number of amino acid molecular species not found in proteins have been discovered in the biosphere and in extraterrestrial environments. The finding of amino acids synthesized via abiotic processes has particular astrobiological significance, as it shows that compounds similar or identical to the biomolecules indispensable to extant life's structure and function can be formed abiotically and outside of the Earth's biochemistry.

Amino acids are abundant compounds in the biosphere as the monomeric constituents of proteins where they are assembled according to genetic instructions that originate in a distinct DNA triplet code for each. Evolution has limited their number to 20 species and their type to L-[enantiomers](#) of α -amino acids with the general formula shown in Scheme 1, where R is H for the simplest compound (2-carbon [glycine](#)) or an alkyl chain of variable composition. In the only exception of proline (Scheme 2f), the amino group is secondary and the alkyl chain is cyclic. Two additional amino acids of rare distribution, *selenocysteine* and *pyrrolysine*, were recently discovered in several bacteria and are also genetically encoded. The finding would suggest that the standard 20-amino acid alphabet could be expanded during certain evolutionary contingencies and more amino acids may still remain to be found in translated protein chains.



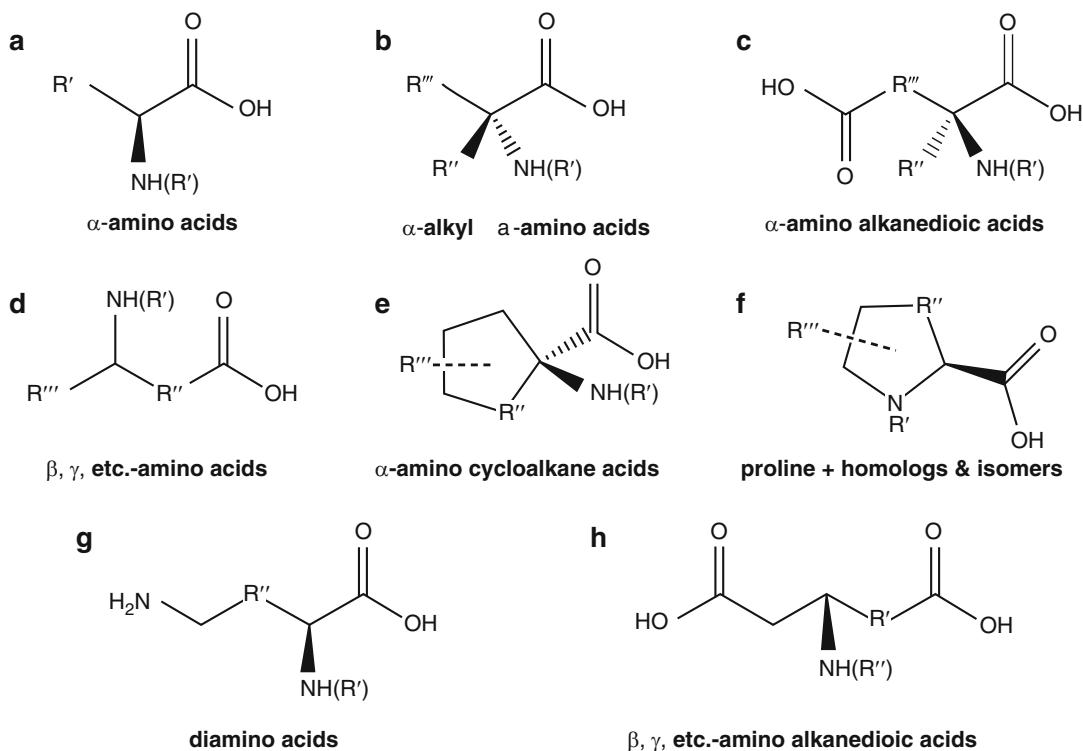
Nonprotein Amino Acids, Scheme 1 The general structural formula of the α -amino acids found in proteins

Some rare amino acids of distinctive composition are also observed in the hydrolyzates of specialized functional proteins but are formed by enzymatic modification of amino acids already transcribed in the polypeptide chains. They have limited distribution and are necessary to the specific function of the protein. The often quoted examples are the unusual *desmosine* and *isodesmosine* molecules that occur in the fibrous chains of the elastin. These amino acids have a central pyridine molecule with four amino acid branches of various chain lengths (C2–C4), which can crosslink in a radial setting to other polypeptide chains and help the protein to contract and expand.

Nonprotein Amino Acids

Amino acids can occur as molecular species of numerous structural arrangements, where the varying amino to carboxyl relative position, extent of alkyl chain elongation, substitution along the chain or the amino group, and additional functional groups and/or chiral carbons in the R-chain allow several homologous series of a large number of compounds (Scheme 2). It is in the free form or combined with other compounds, but not as protein or with L-configuration only, that diverse types of amino acids are found in nature as part of biochemistry as well as extraterrestrial chemistry. As biological and abiotic processes usually dictate, they have distinctive metabolic functions in the first case and stochastic diversity in the latter.

Nonprotein amino acids in biology are frequently variations of protein amino acids, some



Nonprotein Amino Acids, Scheme 2 The possible structural formulas of nonprotein amino acids (b–h)

are metabolites or intermediates in metabolism and others can be part of biological structures. Examples are β -alanine [$CH_2(NH_2)CH_2COOH$], a building block of pantothenic acid (vitamin B_5); γ -amino butyric acid [$CH_2(NH_2)CH_2CH_2COOH$], a neurotransmitter in the brain of mammals that is produced by decarboxylation of glutamic acid; and D- α -alanine, a constituent of the complex cell walls of some bacteria. Fungi, bacteria, and plants also contain a large variety of other amino acids. Many of these are toxic to foreign organisms, by inhibiting or disrupting existing proteins; these toxic effects may fulfill an ecological role in the plants that produce them, for example, as deterrents toward predators or by inhibiting the growth of competing plant species (Bell 2003).

A subgroup of α -amino acids, the 2-amino-2-methyl acids (Scheme 2b), have been studied in particular detail because they are constituents of antibiotics. These compounds are found in a number of fungi *genera* as short helical peptides exhibiting antibiotic activity against bacteria as

well as fungi and are called peptaibols because they contain α -aminoisobutyric acid (AIB) or peptabiotics to summarize their properties. About 850 peptaibols have been described, whose antibiotic function is based on their ability to insert in the lipid layers of bacterial/fungal membranes and form voltage-dependent ion channels through which cytoplasmic material can leak, eventually leading to cell death (Toniolo and Brückner 2009).

Nonprotein Amino Acids in Cosmochemistry

Amino acids can form in extraterrestrial environments, and the largest variety of their possible molecular species has been found in a group of carbon-containing meteorites, the carbonaceous chondrites (CC). Like most meteorites, CC are fragments of asteroids, the odd-sized and shaped planetesimals that orbit the sun in great number between Mars and Jupiter. They represent the remnants of a planet that never formed due to Jupiter's large interfering gravity and, by the

frequent collisions of their crowded trajectories, frequently send fragments into the Earth's orbit as meteors and meteorites. Not having suffered the extreme physicochemical conditions of planet formation or having reached a large enough size to separate matter on the basis of density, CC parent bodies are aggregate rocks that may contain a pristine record of early solar system processes. In fact, some of these planetesimals have been recently discovered in the main asteroid belt that behave like comets, by emitting comae of dust fueled by sublimation (Hsieh and Jewitt 2006).

As a result of their provenance and carbon content, CC meteoritic fragments offer unique samples of extraterrestrial organic chemistry, as it came to be in the solar system at the time the Earth was formed and before life began on Earth (see also meteorite (Orgueil), carbonaceous chondrites (organic chemistry of), ► carbonation). CC meteorites are often collected in large enough quantities for detailed laboratory analyses and have been extensively studied since the first recorded fall of the Alais meteorite in 1806. The modern era of these studies started in 1969 with the fall of the Murchison meteorite because, at the time, the laboratories of the National Aeronautics and Space Administration were preparing for the return of lunar samples and were able to analyze this meteorite shortly after its fall. The first surprising revelation of these analyses was the discovery of racemic amino acids and, since proteins are made up of only L-amino acids, this finding excluded terrestrial contamination as their source. The finding also established the first analytical understanding of prebiotic chemistry and suggested a possible exobiology. Over 100 amino acids have been observed in the Murchison meteorite and similar CC by gas chromatographic analyses with mass spectroscopy detection (GC/MS), and at least 80 have been identified on the basis of reference standards. They represent nearly all possible isomeric and homologous species with the basic formulas listed in Scheme 2 and up to their limit of solubility in water (approximately eight-carbon chain length). Eight protein amino acids were also found in Murchison: ► glycine, ► alanine, ► valine, ► leucine, ► isoleucine, ► proline, and aspartic and glutamic acids. Four more (► serine,

► threonine, tyrosine, and phenylalanine) were recently found in another type of CC (see below). Besides the diversity of molecular species, Murchison amino acids are also characterized by declining abundances with increased molecular weight, a compositional trait suggesting that the growth of their carbon chains might have involved the stepwise addition of smaller carbon moieties.

In another family of CC, the Renazzo-type or CR, amino acids have shown a different distribution, with overall larger abundance of the compounds but with their number restricted to fewer and smaller amino acid species, such as glycine, alanine, and AIB. As mentioned above, some protein amino acids not found in the Murchison-type meteorites were detected in CRs bringing to 12 the total number of meteoritic amino acids having biological counterparts in terrestrial proteins. This selective composition and the fact that amino acids and ammonia are the most abundant soluble components of these meteorites have a particular prebiotic significance because it suggests that their abundance might have led to association into oligopeptides under prebiotic conditions.

Another notable subgroup of amino acids present in Murchison and similar type of meteorites might also have held an important advantage in prebiotic times. These are the α -substituted α -amino acids shown in Scheme 2b that, when chiral as in ► isovaline, were found to be non-racemic and to display varying enantiomeric excesses (ee) that, if not as large, have the same sign, L-, of the amino acids in terrestrial proteins (Cronin and Pizzarello 1997). The finding was validated by isotopic analyses (see below) and represents the only case of molecular asymmetry measured so far outside the biosphere. Because meteoritic amino acids have abundantly showered the early Earth and amino acids can be asymmetric catalysts (Pizzarello and Weber 2004), it has been proposed that these compounds might have contributed to terrestrial molecular evolution and the induction of homochirality.

The origin of amino acids e.e. in meteorites is not known and may be related to several physicochemical influences encountered by the compounds during their syntheses in cosmic

environments. One often proposed hypothesis is that of their partial photolysis by ultraviolet (UV) circular polarized light (CPL). This radiation possesses true ► [chirality](#) and interacts differently with the enantiomers of a chiral molecule. If the energy of the radiation is high, as in the case of UV, the two enantiomers will be destroyed at different rates and extent with resulting e.e. for the molecule.

Because the biosphere is pervasive on the Earth and meteorites fall protected only by a thin ► [fusion crust](#) that easily fissures with impact, the indigeneity of meteoritic amino acids having counterpart in terrestrial proteins has been questioned in some cases, especially in regard to the abundance of their L-enantiomers. However, their extraterrestrial origin has been established unequivocally by measurement of their isotopic composition. As explained in isotopic fractionation, the zero-point energy differences between isotopes' bonds may lead to mass-dependent isotopic fractionation in molecules during reactions that, in turn, becomes a possible indicator of the synthetic reactions undergone by a molecule. Since this fractionation takes the form $\exp^{\Delta E/T}$, it is expected to be highest for ► [deuterium](#) (D) and to decrease with temperature. This expectation is confirmed by the large D/H (► [deuterium/hydrogen ratio](#)) fractionation observed spectroscopically for the molecules in the dense clouds of the interstellar medium (ISM), where T may be as low as 5–10 K. By the analyses of their D, ^{13}C , and ^{14}N composition, all meteoritic amino acids have shown an enrichment of the heavy isotopes of these elements that excludes their terrestrial formation. The origin of meteoritic amino acids was also elucidated, albeit in general terms, by these analyses and, in particular, their D/H content. As these compounds were found to be enriched in deuterium, with D/H values that sometimes near those determined for ISM molecules, the finding was interpreted to indicate their general lineage to

cold cosmic regimes, such as those of the ISM. It is interesting to note that the higher values between Murchison and CR amino acids were found to belong to AIB and non-racemic isovaline.

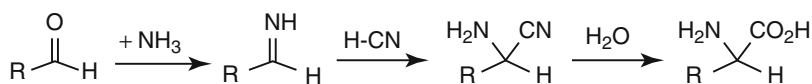
Certainly, the synthetic routes that lead to meteoritic amino acids' formation were not direct and might have involved several precursor molecules as well as periods of water availability in the asteroidal parent body. Also, the variety of amino acid molecular species determined in Murchison-type meteorites preclude a single explanation for the synthetic routes responsible for their formation. One pathway to α -amino acids might have been important and that is the cyanohydrin addition of HCN to aldehydes and ketones in the presence of water and ammonia as shown in Scheme 3.

The occurrence of this reaction seems confirmed by the presence in meteorites of hydroxy acids, compounds that differ from amino acids in having a hydroxyl (OH) instead of an amino group and would have formed concomitant to amino acid during a parent body aqueous phase. This synthetic route also relates both groups of compounds to aldehydes and ketones, a class of extraterrestrial compounds that have been detected in a variety of cosmic environments, including the ISM.

Basic Methodology

Amino acids contain both acidic and basic functional groups, i.e., amphoteric compounds that can ionize at different pHs to be present as cations, zwitterions, or anions. In water and at physiological pH, they are present as zwitterions and have different charges at the amino and carboxyl groups with a net charge of zero.

Based on these molecular properties, amino acids are readily soluble in water and



Nonprotein Amino Acids, Scheme 3 The cyanohydrin reaction

methodologies for their extraction, separation from other molecular species, and characterization start with water solutions. When isolated, and concentrated or dried as needed, amino acids are analyzed by a variety of liquid as well as gas chromatographic methodologies. In either method, columns coated with chiral phases can be used to establish amino acid's enantiomeric D/L ratios.

Applications

AIB, isovaline, and some of their higher homologues have been used in small peptides with pharmacological function (e.g., as antibiotics). Some plant amino acids are also mentioned that are toxic to animals and insects and can be used in agriculture as pesticides.

Future Directions

Future studies of nonprotein amino acids will expand on the current applications in the drug, chemical, and biosynthetic industries. In the research field of astrobiology, they will focus on establishing these amino acids' origin and their prebiotic traits, such as chiral asymmetry.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Amino Acid Precursors](#)
- ▶ [Aminoisobutyric Acid](#)
- ▶ [Anion](#)
- ▶ [Chirality](#)
- ▶ [Chromatography](#)
- ▶ [Circular Dichroism](#)
- ▶ [Enantiomers](#)
- ▶ [Hydrolysis](#)
- ▶ [Interstellar Medium](#)
- ▶ [Isotopic Exchange Reaction](#)
- ▶ [Isotopolog](#)
- ▶ [Meteorite, Orgueil](#)
- ▶ [Meteorites](#)
- ▶ [Murchison](#)

- ▶ [Mutagenesis](#)
- ▶ [Polarized Light and Homochirality](#)
- ▶ [Prebiotic Chemistry](#)
- ▶ [Zwitterion](#)

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Non-proteinogenic Amino Acids

- ▶ [Nonprotein Amino Acids](#)

Non-superimposable Mirror Image Object

- ▶ [Chirality](#)

Nordic Network of Astrobiology

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Definition

The Nordic Network of Astrobiology is a network of some 20 research institutions in the Nordic and Baltic countries. Among its aims are promoting research in astrobiology, fostering cooperation in

research and graduate training, organizing courses and holding scientific conferences in astrobiology, promoting public awareness of the field, informing national and international science funding and space research agencies about research in astrobiology, and collaborating with other astrobiology institutions worldwide. The Nordic Network is an Affiliated Partner of the NASA Astrobiology Institute (NAI).

Cross-References

- [Astrobiology](#)
- [NAI](#)

North American Shield

- [Canadian Precambrian Shield](#)

North Pole Dome (Pilbara, Western Australia)

Daniele L. Pinti¹ and Nicholas Arndt²

¹Geotop, Research Center on the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

²Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

Keywords

Hydrothermal environments · Microfossils · Pilbara Craton · Stromatolites · Warrawoona Group

Synonyms

[Panorama Formation](#)

Definition

The North Pole Dome, located at the center of the East Pilbara Granite-Greenstone Terrane, Western

Australia (North Shaw, AMG 746500E 7663100N), is an Archean terrane containing little-deformed, dominantly mafic volcanic rocks of the ► [Warrawoona Group](#), which form the Panorama greenstone belt. These successions, covering a ca. 25×35 km area, are arranged in a broad dome around a central nucleus occupied by a 3.5-Ga-old magmatic intrusion named the “North Pole Monzogranite.” The southwestern part of the North Pole Dome contains what the scientific community considers as the oldest ► [stromatolites](#) so far recognized on Earth, at the famous “Trendall locality” of the Strelley Pool Formation. Several Archean rock sequences were altered by Archean episodes of hydrothermal fluid circulation and ► [weathering](#); they have been used to test hyperspectral remote sensing instrumentation for detecting analog hydrothermal systems on ► [Mars](#).

Overview

Archean rock units at the North Pole Dome are arranged as follows (from base to top):

1. The North Pole Monzogranite (monzogranite is a biotite-rich granite) with an age between $3,459 \pm 18$ Ma (Thorpe et al. 1992), and $3,454 \pm 17$ Ma (Asanuma et al. 2018).
2. The $3,490 \pm 15$ -Ma-old North Star metabasalts that surrounds the North Pole Monzogranite at the core of the dome.
3. Five stromatolitic chert-barite horizons interbedded with pillowed basalts, collectively referred to as the $3,481 \pm 2$ -Ma-old Dresser Formation (previously called the Towers Formation).
4. Mafic rocks of the $3,469 \pm 3$ -Ma-old Mount Ada Basalt and a thin felsic volcanoclastic chert of the ca. 3,467-Ma-old Duffer Formation.
5. A 4-km-thick section of the Apex Basalt capped by up to 1.3 km of 3,459–3,452-Ma-old felsic volcanic and volcanoclastic rocks of the Panorama Formation.
6. The 3,430-Ma-old Strelley Pool Formation (formerly called Strelley Pool Chert), a 10–30 m thick succession of characteristically

white and gray layered cherts containing the distinctive conical stromatolites of the Trendall locality.

7. A thick (up to 9.4 km) succession of interbedded high-Mg and tholeiitic basalts and various cherts of the 3,395–3,346-Ma-old Euro Basalt Formation.

The rocks have been metamorphosed from prehnite-pumpellyite to lower greenschist facies, and a contact-metamorphic aureole is developed around the North Pole Monzogranite (Van Kranendonk et al. 2001).

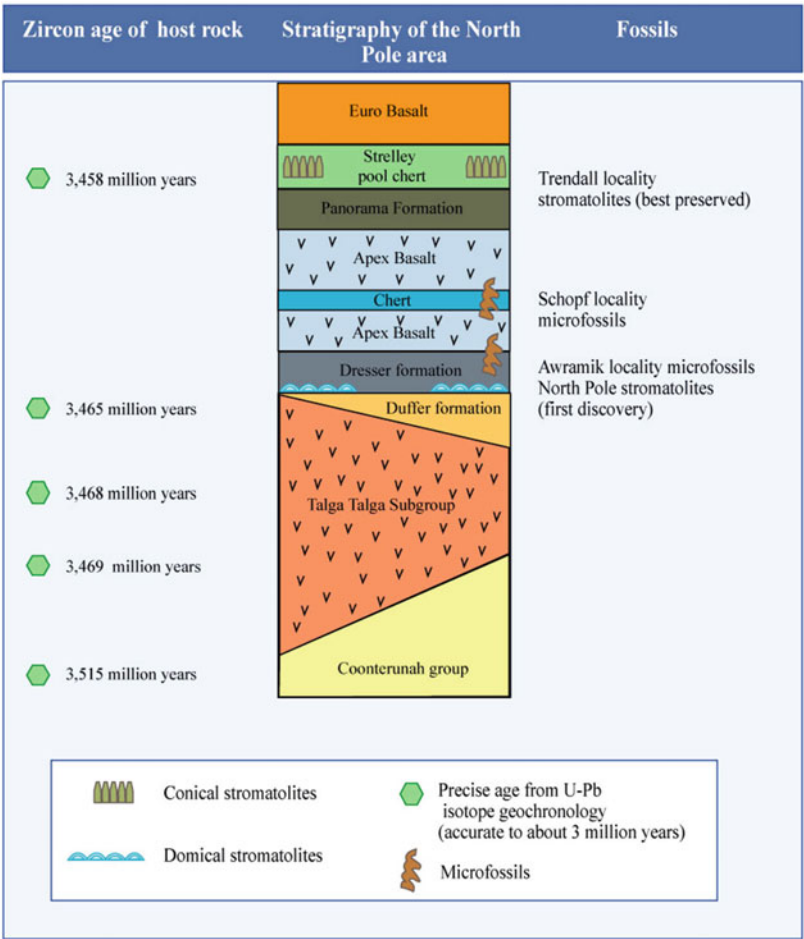
Although the North Pole Dome is a rather insignificant small granitoid among larger batholiths outcropping in the Eastern ► **Pilbara Craton**, this place has a particular interest for astrobiology and the search of ancient life. Indeed, the oldest

► **stromatolites** and MISS (microbially induced sedimentary structures) have been found within the 3,490-Ma-old Dresser Formation and the 3,430-Ma-old Strelley Pool Formation (e.g., Hofmann et al. 1999; Allwood et al. 2007; Noffke et al. 2013; Duda et al. 2016), at the so-called Trendall locality (named after its discoverer, in 1984, Australian geologist Alec Trendall).

The stratiform chert-barite units of the Dresser Formation are fed by a set of chert-barite dikes that were emplaced within, and immediately above, listric normal growth faults that were active during deposition of the cherts (Nijman et al. 1998). These thousands of dikes have been interpreted as remains of white and black smoker chimneys. The carbon (Ueno et al. 2004, 2006) and nitrogen (Pinti et al. 2001, 2009) isotopic composition of kerogen and carbon filaments

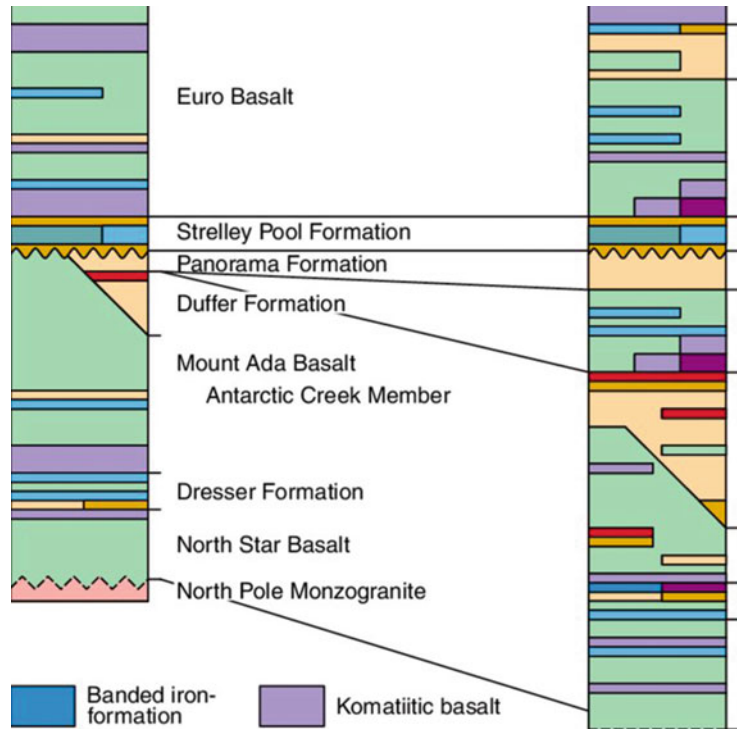
North Pole Dome (Pilbara, Western Australia),

Fig. 1 Schematic stratigraphic column of the North Pole area: the dated and fossiliferous layers are also indicated. (Figure by MIT OpenCourseWare)



North Pole Dome (Pilbara, Western Australia),

Fig. 2 Stratigraphy of the Pilbara Supergroup within the Panorama greenstone belt (left), compared to the stratigraphy of the entire East Pilbara Terrane (right). (Adapted from Hickman et al. 2011)



found in those cherts have been variably interpreted as representing the products of metabolic activity of methanogens and chemoautolithotrophs surviving around mid-Archean thermal ponds. Finally, airborne hyperspectral remote sensing surveys have been done on the hydrothermal altered rocks of the North Pole Dome, especially in relation with stromatolitic sites, to set instrumentation for detecting similar features on the surface of Mars (Brown et al. 2005) (Figs. 1 and 2).

Cross-References

- ▶ [Apex Basalt, Australia](#)
- ▶ [Biomarkers](#)
- ▶ [Chemolithoautotroph](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Mars Analogue Sites](#)
- ▶ [Metamorphic Rock](#)
- ▶ [Metamorphism](#)
- ▶ [Methanogens](#)
- ▶ [Microfossils](#)

- ▶ [Nitrogen Isotopes](#)
- ▶ [Origin of Life](#)
- ▶ [Pilbara Craton](#)
- ▶ [Stromatolites](#)

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star increases the pressure and temperature at the base of the H-layer (on top the carbon-oxygen white dwarf) up to the point where thermonuclear reactions (the so-called hot ► [CNO cycle](#)) ignite. The explosion is much weaker than that of a ► [supernova](#), it does not disrupt the white dwarf, and it may occur many times, on timescales from tens to thousands of years. The frequency of novae in the Milky Way is estimated to 40 novae per year.

Cross-References

- [CNO Cycle](#)
- [Supernova](#)
- [White Dwarf](#)

NS

- [Nitrogen Sulfide \(NS\)](#)

NSO, The Netherlands

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Netherlands Space Office](#)

Nova

Nikos Prantzos
Institut d’Astrophysique de Paris, Paris, France

Definition

A nova is a stellar eruption, resulting from explosive H-fusion on the surface of a ► [white dwarf](#) in a binary system. Accretion from the companion

Definition

Since July 1, 2009, the Netherlands Space Office (NSO) is acting as the space agency for the Netherlands. NSO concentrates Dutch space policy in one organization. NSO reports directly to a steering committee of involved ministries (Economic Affairs; Education, Culture and Science; Science and Education; Transport, Public Works and Water Management). It develops and carries out the space program for the Netherlands.

The Space Office represents the Netherlands in an international space context (to other space agencies, including ESA) and acts as the single point of contact for space policy and implementation in the space area. One of its roles is to strengthen communication about space activities to stakeholders, students and educators, and the general public. NSO counts around 25 permanent people.

Another organization, namely, the SRON (Netherlands Institute for Space Research) is the Dutch expertise institute for space research. The institute focuses on astrophysical research, earth science, and exoplanet research. More than 200 permanent and temporary employees are spread between the two laboratories based in Utrecht and in Groningen.

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<http://www.spaceoffice.nl/>

Nuclear Reaction

Alain Coc
 IJCLab (Laboratoire Irène Joliot-Curie),
 Université Paris-Saclay, Orsay, France

Keywords

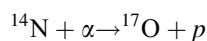
Energy · Nuclei · Nucleosynthesis

Definition

Nuclear reactions are processes that lead to the modification of the composition, structure, or internal energy of atomic nuclei.

History

The first laboratory experiment to demonstrate nuclear transmutation via a nuclear reaction was conducted by Rutherford in 1919, bombarding ^{14}N with α -particles, producing ^{17}O , and liberating a proton through the reaction:



Overview

Nuclear reactions play an important role in astrophysics as they are the source of energy of most stars and, through nucleosynthesis, are at the origin of the chemical elements. In general, a nuclear reaction results from the collision between two atomic nuclei producing one or more nuclei, possibly in excited states, together with the release or absorption of energy. One of its most important characteristics is its cross-section, which measures its probability to occur. The cross-section has the dimension of a surface and is given in units of barn (b) equivalent to 10^{-24} cm^2 . Some important reactions that involve electrons and neutrinos, like $p + p \rightarrow ^2\text{H} + e^+ + \nu_e$ in the Sun, are mediated by the weak interaction and are considerably slower than those involving the nuclear or even the electromagnetic interaction. Because of their higher cosmic abundances, nuclear reactions involving ^1H (i.e., protons), ^4He (i.e., α -particles) nuclei, or neutrons are of special interest in astrophysics. In particular, the triple-alpha reaction $3 \alpha \rightarrow ^{12}\text{C}$ is at the origin of Carbon in the Universe, thanks to the presence of a nuclear excited level in ^{12}C with favorable properties.

In astrophysics nuclear reactions take place in two distinct environments: a dense medium in thermodynamical equilibrium (typically a stellar interior) or a dilute medium crisscrossed by high-energy nuclei (e.g., interstellar medium). The latter is the site of ► [spallation reactions](#) whose cross-sections as a function of energy are the relevant quantities. The former is the site of thermonuclear reactions, characterized by their rates. Thermonuclear reaction rates are just the cross-sections, averaged over the Maxwell–Boltzmann distribution of the interacting nuclei, and are a function of temperature.

Spallation reactions, because of the energy involved, have high cross sections and hence can be obtained from laboratory measurements. For reactions taking place in stellar interior, thermal energy is usually low when compared with the Coulomb repulsive potential between nuclei.

Quantum tunneling is hence required for the fusion, leading to very low cross-sections. Laboratory measurements of these cross-sections are a challenge that can only be met for long-lived, light nuclei (i.e., low electric charge). For many reactions, in particular those involved in the r-process with extremely short-lived nuclei, experimental limitations require the extensive use of nuclear theory to estimate cross-sections.

Cross-References

- [Nucleosynthesis, Explosive](#)
- [Nucleosynthesis, Neutrino](#)
- [Nucleosynthesis, Stellar](#)
- [Radioactivity](#)
- [Spallation Reaction](#)

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Nuclear Stability

Alain Coc
IJCLab (Laboratoire Irène Joliot-Curie),
Université Paris-Saclay, Orsay, France

Definition

Nuclear stability means that the nucleus of an element is stable and thus it does not decay spontaneously emitting any kind of ► [radioactivity](#). Among the ≈ 9000 nuclei expected to exist, and the ≈ 3000 presently known, only 195 are stable against spontaneous decay, because of energy conservation. In the chart of nuclides, a two-dimensional graph in which one axis represents the number of neutrons and the other represents the number of protons in an atomic nucleus, the

stable nuclei are gathered in the valley of Nuclear Stability. This valley follows at first the line corresponding to nuclei with an equal number of protons and neutrons, and then bends toward the neutron-rich side at higher masses, due to Coulomb repulsion. Those nuclei with the highest ► [binding energy](#) per nucleon are the most stable with respect to destructive nuclear reactions. Note that a few radioactive atoms have lifetimes longer than the age of the Universe (e.g., ^{209}Bi), while others become stable when ionized (e.g., ^7Be).

Cross-References

- [Binding Energy](#)
- [Decay Constant](#)
- [Half-Life](#)
- [Radioactivity](#)

Nucleation of Dust Grains

Joseph Andrew Nuth III
Solar System Exploration Division, NASA's
Goddard Space Flight Center, Greenbelt, MD,
USA

Keywords

Circumstellar outflows · Condensation · Dust formation · Graphite · Silicates · Interstellar Dust

Definition

Nucleation refers to the dynamic change observed in a system initially consisting of a chemically uniform phase that occurs upon cooling (or heating) to produce a new chemical phase. Such changes occur when a gas, such as water vapor in air, forms liquid droplets upon cooling or an amorphous solid or viscous liquid, such as a glass, forms crystals due to thermal annealing. The water vapor “nucleates” from the gas leaving the air behind. Similarly, the newly formed

crystals may have a different chemical composition than the glass from which they formed.

Overview

Dust grains form in various environments: in circumstellar outflows, after energetic events in protostellar nebulae (such as collisions or lightning), and possibly after the passage of shocks in the ► [interstellar medium](#). Dust surfaces can catalyze a wide range of organic reactions, and the dust itself can control the thermal environment found in many dense astrophysical objects. For these reasons, it is important to understand the properties of freshly condensed dust grains as well as how such properties evolve in response to their environment.

Basic Methodology

The nucleation of dust grains in circumstellar outflows has been addressed both theoretically and via laboratory techniques. Both methods have severe limitations, yet both have produced some useful results. Most studies of grain nucleation focus on the processes that occur in circumstellar winds, though nucleation can occur in other locations (e.g., in nebulae around ► [protostars](#) as well as in many different terrestrial processes). However, the situation in circumstellar outflows is a much better-defined problem: a hot, dust-free gas expands at a measured rate away from a stellar photosphere and at some time afterward forms dust grains that continue to grow until virtually all of the condensable elements have been removed from the gas. Condensed grains might also undergo thermal processing to convert amorphous dust into crystalline material in some outflows. The dust grains in a particular outflow are the ultimate products of nucleation, growth, and annealing. However, this entry will focus exclusively on the nucleation of grains, that is, the transition from a dust-free gas to a two-phase system consisting of gas and the nuclei of liquid/solid material that has the potential to grow into observable dust grains.

For carbon-rich stars, nucleation can in principle be reduced to a problem in chemical kinetics, where a carbon atom or $\text{C}=\text{C}-\text{H}$ radical adds to a growing carbon chain that itself began as a $\text{C}=\text{C}-\text{H}$ radical. Many of the chemical reaction rates are taken from the rich literature on chemical combustion. The chemical pathway to grains in such models leads from ► [radicals](#) to polyaromatic molecules and finally to aggregate grains of cross-linked polyaromatic (or poorly graphitized) carbon. Nucleation in such cases refers only to the formation of the initial distribution of large, polycyclic aromatic hydrocarbon molecules. Models of this type were first suggested by Frenklach and Feigelson (1989) for circumstellar shells, while a variation of this model was suggested by Clayton et al. (1999) to account for the formation of carbonaceous grains in the shells of supernovae. The major problem with this approach is that there is no evidence that the chemical pathway proposed is the one actually taken in a carbon-rich astrophysical system. A minor problem is that not all of the chemical kinetic rate constants used in the model have been measured in the laboratory. The most popular way around these problems is to ignore the nucleation process altogether.

Tsuji (1964) first calculated the temperature-dependent composition of stellar atmospheres based on the assumption that the atoms, molecules, and solids in such systems would remain in chemical equilibrium. This model completely eliminates all of the uncertainties involved in the kinetic calculations discussed above and is based on a chemical thermodynamic database established by the chemical industry and the academic community and supported by government agencies. This model's greatest strength is also its greatest weakness since it always assumes the formation of the most stable chemical compounds and cannot account for observed species such as amorphous silicate or poorly graphitized carbon. Chemical species left out of the calculation simply "do not form." In addition, no information on the number density of particles or on their size distribution can be obtained from such models. In the most formal sense, when the model predicts that

half of the available aluminum is in corundum, this means that there is one and only one very large grain of corundum at equilibrium in the stellar atmosphere.

There is a compromise that combines elements of both thermodynamic and kinetic modeling that was formulated to calculate the rate of water droplet formation in a supersaturated atmosphere. Donn et al. (1968) first suggested the potential application of classical nucleation theory (Becker and Döring 1935) to the formation of grains in stellar outflows. Nucleation theory allows calculation of the rate of grain formation per unit volume and also allows calculation of the final grain-size distribution generated by a given trajectory in composition, density, and temperature (Gail and Sedlmayr 1999) if one is willing to make a few additional assumptions about the fraction of impinging atoms that stick to growing grains or the fraction that evaporate from a hot surface. The problem with nucleation theory is that the rate of grain formation strongly depends upon an ill-determined parameter known as surface energy.

Surface energy is the “force” that tends to make droplets round or that pulls two adjacent drops together to form a single drop with greatly reduced surface/volume ratio. An atom or molecule on a surface has a higher energy than one in the interior of a grain because it cannot be fully bonded with surrounding species. Nature tends to minimize the total energy of a system, so high surface/volume systems are unstable with respect to low surface/volume systems (e.g., small droplets will always grow into larger droplets by aggregation; it takes energy to break large droplets into smaller ones). It is difficult to measure the surface energies of important astrophysical compounds such as graphite, amorphous carbon, or amorphous silicates, and one can easily find differences in measurements reported in the literature ranging from factors of 10 up to factors of 20,000 for specific compounds. Unfortunately, the calculated rate of nucleation depends upon the exponential of the cube of the surface energy; therefore, a factor of 20 difference in the value of the surface energy used in a calculation leads to a factor of about 485 million difference in the

calculated nucleation rate. This difference is large, even by astrophysical standards.

In theory, it should be possible to carry out experimental studies of the nucleation of refractory vapors such as SiO in a hydrogen atmosphere from which one could derive the surface energy of the condensing grains. Indeed, such experiments have been carried out (Nuth and Donn 1982, 1983). However, there are problems. Astrophysical systems present an intriguing set of challenges for laboratory chemists. Most such chemistry occurs in atmospheric regions that would be considered an excellent vacuum by terrestrial laboratory standards and at temperatures that would quickly vaporize normal laboratory equipment. Timescales for changes in state variables such as temperature, pressure, and composition range from milliseconds to minutes for rapid events, like collisions or electric discharges. Outflows around asymptotic giant branch (AGB) stars have timescales ranging from seconds to weeks depending on the distance of the region of interest from the star, and on the way significant changes in the state variables are defined. “Steady-state” protostellar systems evolve on timescales ranging from centuries to millions of years, while the atmospheres in normal stars may only change significantly on several billion-year timescales. Needless to say, most laboratory experiments carried out to understand astrophysical processes are not carried out under conditions that perfectly match the natural suite of state variables or the timescales appropriate for changes under natural conditions. Experimenters must, of necessity make appropriate use of simple analog experiments that seek to place limits on the behavior of natural systems, often extrapolating the knowledge gained from such experiments to much lower pressure and/or significantly higher temperature environments.

Experimental studies of the nucleation of refractory materials, such as silicates, are rare. Most astrophysical studies of grain formation focus simply on the spectral properties of the grains produced in the experiment rather than on the mechanism of grain formation. Additional studies follow the spectral evolution of newly formed dust in response to environmental

parameters such as hydration or thermal annealing. Experimental studies of SiO nucleation have been published (Nuth et al. 2000), but the results of these studies are currently being revised in light of new vapor pressure data for SiO (Ferguson and Nuth 2008). The published studies did provide a measurement of the surface energy for SiO nuclei, and the reanalysis should provide a more accurate estimate of this quantity for use in model calculations based on nucleation theory.

Nucleation studies of single component refractory grains (SiO, Fe, Ag, Li, Na, K, Mg, and Ca) can be found in the literature; however, studies of the nucleation process in multielement systems cannot. Studies of the properties of grains formed from complex vapors are available, and these have presented some surprises: the smallest grains produced in the experiments are thermodynamically unstable but seem to form at metastable eutectic compositions (Rietmeijer et al. 1999). Many additional three condensate systems have been explored, and all seem to show such behavior, as do naturally occurring systems such as volcanic ash, or man-made particulates such as smoke from coal-fueled power generators (Rietmeijer et al. 2000). From an astrophysical perspective, the most important result of these studies is that mixed vapors of iron, magnesium, and SiO will nucleate amorphous magnesium silicates and iron silicates, but not mixed magnesium silicate-iron silicate grains. Mixed grains only form after coagulation and annealing of the primary condensates. The formation of separate populations of pure iron silicate and magnesium silicate grains could help explain observations of pure magnesium silicate minerals in some high mass outflow rate circumstellar winds.

Nucleation theory combines a quasi-steady-state thermodynamic cluster distribution with a simple kinetic model for both cluster growth and the growth of stable dust grains, the molecular “sticking” efficiency is frequently neglected in nucleation models. Most models simply assume that condensing atoms or molecules stick with near-unit efficiency whenever they strike a growing cluster or dust grain. In circumstellar outflows, the assumption of unit sticking efficiency makes

little difference for the pre-condensation cluster size distribution (Paquette and Nuth 2011); however, the value of the grain growth efficiency factor can make a huge difference (Nuth et al. 2020). An experimental study of the growth of zinc grains under microgravity conditions, where buoyancy-driven convection is not a factor, demonstrated that only three in $\sim 10^5$ zinc atoms that collided with a growing grain actually stuck (Michael et al. 2003). A study of the nucleation of iron grains in a sounding rocket experiment (Kimura et al. 2017) similarly determined that only a few atoms in every 10^5 that struck a growing iron grain were incorporated into the final dust particle. The difference between unit grain growth sticking efficiency and efficiencies closer to 10^{-5} makes a difference in the final grain size of many orders of magnitude and spread grain growth from a relatively concentrated area to a much larger fraction of the outflow.

Key Research Findings

Theory and modeling in this area have not produced reliable results, though experimental studies still leave much to be desired. There is a lot of work to do both experimentally and in the application of experimental data to astrophysical systems. Reliable surface energy data may soon be available for SiO condensation, while metastable eutectic condensation may limit the composition of the initial condensates in circumstellar outflows. Such compositions should be predictable based both on experimental studies and on available phase diagrams for multicomponent solids. The efficiency of grain growth from the vapor is a key parameter that requires additional study since this factor can have a large effect on the grain population ejected into the interstellar medium.

Applications

Understanding the nucleation process is essential for modeling the dust found in the outflows of dying stars as well as in evaluation of the potential

for surface-mediated processes to catalyze the formation of organic materials in ► [protoplanetary nebulae](#).

Future Directions

More experimental work is needed to understand the specific compositions of the grains that condense from vapors to confirm or refute the hypothesis that such condensates are NOT the thermodynamically predicted mineral species, but rather are metastable condensates that form at metastable eutectic compositions. The thermodynamically stable mineral species evolve from these materials following growth, aggregation, and thermal annealing that promotes diffusion, equilibration, and crystallization.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Polycyclic Aromatic Hydrocarbon](#)
- [Radical](#)
- [Silicate Minerals](#)

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Nucleic Acid Base

Michael P. Callahan

Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Adenine · Cytosine · Guanine · Purine base · Pyrimidine base · Thymine · Uracil

Definition

A nucleic acid base (or nucleobase) is a nitrogen heterocyclic compound, which serves as the informational monomer of ribonucleic acids (RNA) and deoxyribonucleic acids (DNA), the biopolymers responsible for the storage and transmission of genetic information. Structurally, nucleic acid bases are substituted purines and pyrimidines

(► [purine bases](#) and ► [pyrimidine bases](#)). The primary nucleic acid bases are adenine, cytosine, guanine, thymine, and uracil. Minor/modified nucleic acid bases are also found in RNA and DNA. Since nucleic acid bases are components of RNA, DNA, and coenzymes, they are broadly distributed in nature.

Overview

A nucleic acid base is a nitrogen heterocyclic compound found in nucleic acids – the most common nucleic acids being ribonucleic acids (RNA) and deoxyribonucleic acids (DNA). In RNA and DNA, nucleic acid bases take the form of substituted purines and pyrimidines and comprise one of the three characteristic components of nucleotides (the other two components being a five-carbon sugar and a phosphate group). In DNA, genetic information is encoded in the linear sequence of nucleotides. A single DNA strand may have millions of nucleotides.

Nucleic acid bases are weakly basic compounds. They are stabilized by resonance among atoms in the ring, which gives most of the bonds partial double bond character. Nucleic acid bases derived from pyrimidines are planar molecules. Nucleic acid bases derived from purines are nearly planar molecules with a slight ring pucker. Since they are aromatic in character, nucleic acid bases are characterized by strong UV absorption (~260 nm). Nucleic acid bases may exist in different tautomeric forms depending on the pH. At neutral pH, they are generally unionized, hydrophobic, and therefore relatively insoluble.

The primary nucleic acid bases are adenine, cytosine, guanine, thymine, and uracil. Two properties of nucleic acid bases important in maintaining the overall structure and stability of DNA (and RNA) are hydrogen bonding and base stacking interactions. A ► [base pair](#) usually involves hydrogen bonding between a purine and a pyrimidine (see Watson-Crick pairing). In DNA, guanine base pairs with cytosine, while adenine base pairs with thymine. In RNA, uracil replaces thymine and pairs with adenine. Other types of base-pairing configurations exist, such as

Hoogsteen base pairing. Usually purine-purine and pyrimidine-pyrimidine base pairs (also referred to as base-pair mismatches) are both energetically unfavorable. However, the wobble base pair of inosine-adenine is one example of a purine-purine base pair. When nucleic acid bases are aligned so that the faces of the aromatic rings are parallel to each other, they form non-covalent attractive π -stacking interactions. The sum of all stacking interactions within the nucleic acid creates a large stabilizing effect, which helps maintain the structure of the nucleic acid.

Different starting materials, catalysts, and reaction conditions have been used to synthesize nucleic acid bases under plausibly prebiotic conditions demonstrating that their synthesis was likely robust (see ► [purine bases](#) and pyrimidine bases for some examples). Two well-studied compounds for the synthesis of nucleic acid bases are hydrogen cyanide (HCN) and formamide (NH_2COH). At high concentrations ($\sim >0.01$ M), HCN forms heterogeneous polymers in water, which may have been an important source of both nucleic acid bases and amino acids. For example, a plethora of biological and nonstandard nucleic acid bases have been detected in frozen mixtures of HCN and NH_3 after acid and base ► [hydrolysis](#). When HCN concentration in water is low (without eutectic freezing), hydrolysis to formamide is favored over polymerization. While this pathway is unlikely to produce significant amounts of formamide, other sources of formamide may exist. Additionally, formamide can be concentrated by evaporation (such as in the drying lagoon model). One-pot syntheses of nucleic acid bases have been achieved using formamide in the presence of various catalysts such as alumina, calcium carbonate, iron sulfur and iron-copper sulfur minerals, kaolin, ► [montmorillonite](#), olivine, silica, titanium dioxide, and zeolites. Again, both standard and nonstandard nucleic acid bases are produced, which presents interesting scenarios for the origin of the first ► [genetic code](#).

Minor/modified nucleobases exist in DNA and RNA, and their existence has been suggested to be relics from the ► [RNA world](#) (hypothesis). The incorporation of modified nucleobases into

nucleic acids can alter properties such as charge, conformation, base pairing, base stacking, hydration, and/or coordination with metal ions. In the laboratory, enzymatic incorporation of alternative base pairs into duplex DNA and RNA has been demonstrated. Consequently, an expanded genetic alphabet could lead to greater functional diversity as well as the possibility of greater catalytic ability. It is plausible that the first genetic material contained alternative nucleobases, since they are also produced in the synthesis of the canonical nucleobases and have similar properties (e.g., stability, Watson-Crick base pairing, etc.).

Nucleic acid bases (in the free form and in the gas phase) are unlikely to form and survive in interstellar and circumstellar environments since they eventually decompose in the presence of intense UV radiation. However, nucleic acid bases may be able to survive if located in a dense ► [interstellar cloud](#), although no positive detection has been made yet. Additionally, nucleic acid bases may survive if offered protection from irradiation. For example, they may exist in some precursor form (perhaps bound in the macromolecular component of a meteorite) or protected by ices or grains.

Conversely, UV irradiation may also have played an important role in forming nucleic acid bases. UV photolysis of pyrimidine in pure water over the temperature range 20–120 K yielded uracil. It is worth mentioning that these products may have formed during warm-up since the organic residue is brought to room temperature and removed from the experimental apparatus for ex situ analysis. However, similar “warm-up” events may occur naturally on Earth, for example, by impact events. Also, these results indicate that pyrimidine mixed with water ice is more stable against UV photodegradation than isolated pyrimidine. The nucleic acid base adenine has been reportedly produced from ► [Titan](#) atmosphere analogues irradiated by soft X-rays. In this experiment, a gas mixture simulating the Titan atmosphere (95% N₂, 5% CH₄) was deposited on a cooled substrate (maintained at 14 K) and irradiated by soft X-rays. Adenine was detected in the acid-hydrolyzed organic residue (after warm-up)

and characterized by ¹H NMR spectroscopy and gas chromatography/mass spectrometry. Again warming is necessary to remove the organic residue for ex situ analysis. On the surface of Titan, warming may be similarly achieved during a comet impact or volcanism event.

Cryogenic conditions are not necessary for the formation of nucleic acid bases; therefore, nucleic acid base synthesis on the primitive Earth is also likely. Solar UV light would be one of the most abundant and readily accessible sources of energy on the primitive earth. For example, uracil was produced in the laboratory by UV irradiation of a mixture of urea and β-alanine in the presence of clay minerals. Uracil was also produced by the photochemical decarboxylation of orotic acid (a pyrimidine formed by hydrolysis of HCN oligomers) under plausible prebiotic conditions.

Photostability of nucleic acid bases is an often overlooked property that may have been important for ► [prebiotic chemistry](#), especially when considering the possible prebiotic environment on the early Earth. Nucleic acid bases are UV chromophores in RNA and DNA and the absorption of UV photons can result in photodamage of the nucleic acid. On the early Earth, the absence of an ozone layer allowed for increased exposure of short wavelength UV light. Thus, the genomic information encoded in DNA (i.e., the nucleic acid bases) would have been under constant photochemical attack. This vulnerability is compensated by means of enzymatic repair. It is conceivable that on the early Earth, such enzymatic repair mechanisms may not have existed yet. In addition, enzymatic repair is energetically costly. Fortunately, nucleic acid bases are intrinsically photostable. This is due to the existence of ultrafast pathways that remove the electronic energy of the nucleic acid base to the surrounding (solution) environment in the form of heat as demonstrated by femtosecond laser spectroscopy and theoretical modeling of the excited state dynamics. UV photostability may have been an important factor for the evolutionary selection of the biological nucleic acid bases in addition to their capability to base pair and base stack. Alternatively, avoiding photodamage may ultimately

constrain the environments in which nucleic acid bases can survive.

Finally, the tantalizing suggestion of meteorites and comets delivering nucleic acid bases should be mentioned. The pyrimidine uracil and the purines adenine, guanine, hypoxanthine, and xanthine have been detected in carbonaceous chondrites. More recently, purines not typically found in biochemistry have also been detected in meteorites, including 2,6- and 6,8-diaminopurine as well as purine itself. While still controversial, extraterrestrial signatures in the compound-specific carbon isotopic measurements of uracil and xanthine previously detected in the Murchison meteorite have been reported.

Cross-References

- Adenine
- Anticodon
- Base Pair
- Carbonaceous Chondrite
- Codon
- Coenzyme
- Cyanoacetylene
- Cytosine
- Deoxyribose
- Genetic Code
- Guanine
- HCN Polymer
- Hydrolysis
- Miller, Stanley
- Mutation
- Nucleoside
- Nucleotide
- PNA
- Prebiotic Chemistry
- Purine Bases
- Pyrimidine Base
- Ribonucleoside
- Ribonucleotide
- Ribose
- Spark Discharge
- Thymine (T)
- Uracil (Ura)
- Watson-Crick Pairing

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Nucleic Acid Duplication

► [Replication \(Genetics\)](#)

Nucleic Acid Pool of Random Sequence

► [Combinatorial Nucleic Acid Library](#)

Nucleic Acids

Jessica C. Bowman and Loren Dean Williams
School of Chemistry and Biochemistry, Georgia
Institute of Technology, Atlanta, GA, USA

Keywords

Adenine · Adenosine · Cytidine · Cytosine ·
Deoxyribose · DNA · Guanine · Guanosine ·
Phosphate · Purine · Pyrimidine · Ribose ·
RNA · Thymidine · Thymine · Uracil · Uridine

Synonyms

[Polydeoxyribonucleotide](#); [Polyribonucleotide](#)

Definition

Nucleic acids are long, unbranched polymers of nucleotides. Each nucleotide monomer consists of a nitrogenous base, a pentose sugar, plus a phosphate group. Nucleotides polymerize by chemically linking a phosphate group at the 5' position of one nucleotide to the hydroxyl group at the 3' position of the next nucleotide. The linkage creates a phosphodiester bond, releasing a water molecule. In its two principal forms, ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), nucleic acids store, transcribe, and translate genetic information into the diverse array of proteins needed for execution of almost every cellular process.

Overview

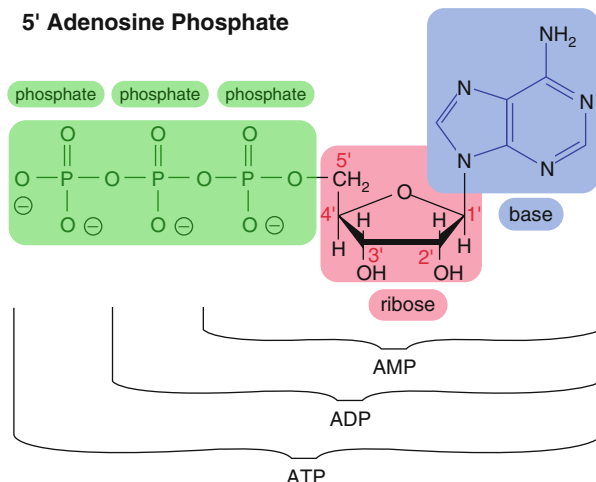
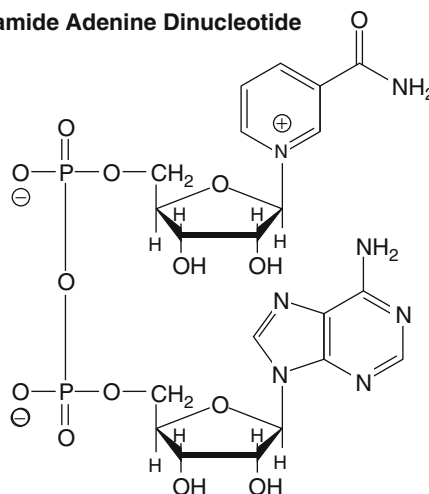
The large, complex molecules of life are carbon-based, and fall into four broad categories: carbohydrates, lipids, proteins, and nucleic acids. Carbohydrates, the simplest of which are sugars, provide energy and structure. Lipids include various steroids, isoprenoid compounds, fatty acids, and amphipathic phospholipids that make up cellular membranes. Proteins, which are composed of amino acids, are involved in almost every cellular process: catalysis, recognition, transport, regulation, and structure. The fourth major category is nucleic acids. Nucleic acids store, transcribe, and translate genetic information into a diverse and preprogrammed array of proteins.

The fundamental units (or monomers) that compose ► [DNA](#) and ► [RNA](#) are called ► [nucleotides](#) (Saenger 1984). A nucleotide contains a planar, nitrogen-containing heterocycle called a base. A base is either a single-ring pyrimidine or a double-ring purine. In addition to a base, each nucleotide contains a phosphate group and a five-carbon sugar, either ribose or deoxyribose (see Fig. 1a). Phosphate groups can be attached to either the 5' or the 3' positions of the sugar. Nucleotides can contain multiple phosphates as in adenosine triphosphate (ATP), which contains three phosphate groups in series, at the 5' position. When all phosphate groups are removed from a nucleotide, it is called a ► [nucleoside](#). ► [Nucleotides](#) are polymerized to form nucleic acids (DNA and RNA), but nucleic acid monomers and dimers also play critical roles in many cellular processes. ATP is the primary energy storage and transfer molecule of all living systems. Nicotinamide adenine dinucleotide (NAD^+ , Fig. 1b) contains adenosine 5' diphosphate, as does Flavin adenine dinucleotide (FAD^+). NAD^+ and FAD^+ are oxidizing agents (electron acceptors) in important biochemical processes (Voet and Voet 2003). cAMP (3', 5'-cyclic adenylic acid) is a signaling compound. It transmits signals that originate with hormones, such as glucagon and adrenaline, within cells. cAMP regulates protein kinase and Ca^{2+} levels (Voet and Voet 2003).

Nucleotides are polymerized in cells to form long linear chains (Fig. 2) used to encode genetic

Nucleic Acids, Fig. 1

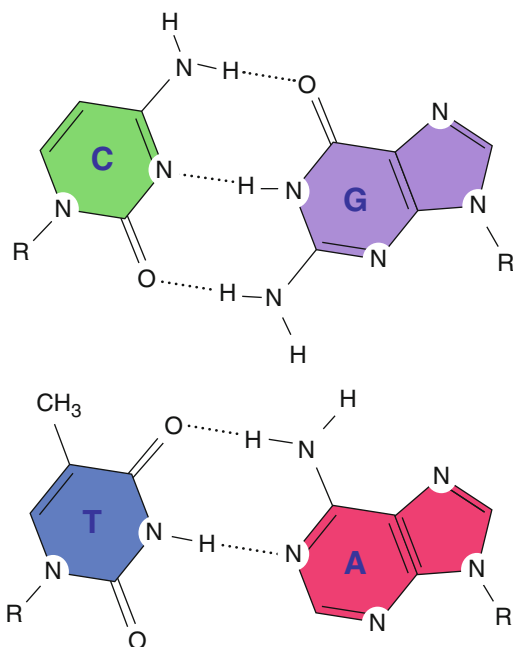
(a) The nucleotide adenosine triphosphate (ATP). Removal of one phosphate by the addition of water produces adenosine diphosphate (ADP). Removal of the second phosphate produces adenosine monophosphate (AMP). (b) The dinucleotide nicotinamide adenine dinucleotide (NAD⁺)

a 5' Adenosine Phosphate**b Nicotinamide Adenine Dinucleotide**

information in all living systems. Two types of five-carbon sugar are contained in nucleic acid polymers: 2'-deoxyribose is found in DNA, while ribose is found in RNA. In DNA's 2' deoxyribose, the 2' carbon is bonded to two hydrogen atoms. In RNA's ribose, one of those hydrogen atoms is replaced by a hydroxyl group. This difference in the sugars of DNA and RNA has a profound impact on the lability of the phosphodiester backbone. RNA hydrolyzes much more quickly than DNA, especially in the presence of magnesium ions. It is commonly said that RNA is less stable than DNA, although the 2' hydroxyl group of RNA reduces the *kinetic barrier* to backbone hydrolysis. The difference in

backbone hydrolysis of RNA and DNA is kinetic rather than thermodynamic.

One of the nitrogen-containing bases of DNA differs slightly from its RNA counterpart. The purines guanine (G) and adenine (A), and the pyrimidine cytosine (C), are common to DNA and RNA. The distinguishing base is thymine (T) in DNA and uracil (U) in RNA. A methyl group of T is replaced by a hydrogen atom in U. In both DNA and RNA, the bases are attached to the sugars at the 1' position through a B-N glycoside linkage. Polymerization of nucleotides, which creates the "phosphodiester backbone," is achieved through phosphate ester bonds, in which a phosphate group joins the 5' hydroxyl group of

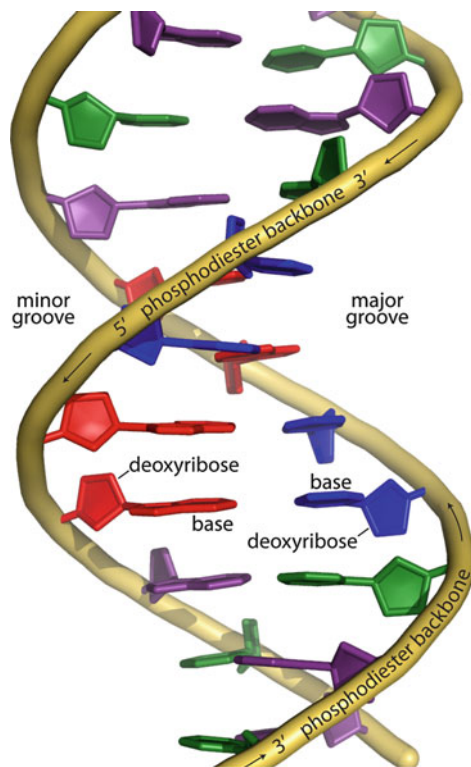


Nucleic Acids, Fig. 3 Watson-Crick base pairs, in which two hydrogen bonds (*dashes*) link T with A while three hydrogen bonds link C with G. The bases are colored by type: adenine (*red*), thymine (*blue*), cytosine (*green*), and guanine (*purple*). Note that in DNA, A pairs only with T and C pairs only with G

neutral; (iii) a nucleotide unit is longer, with more bonds and greater flexibility than an amino acid; (iv) the side chains of nucleic acids (the bases) are planar and uncharged, while the side chains of proteins vary in size, shape, flexibility, polarity, and charge; and (v) nucleic acids readily assemble by side chain-side chain interactions (base pairs), while proteins primarily assemble by backbone-backbone interactions (α -helices and β -sheets).

In cells, DNA codes for messenger RNA (mRNA) that in turn codes for protein. This direction of the flow of genetic information is known as the central dogma of biology (Crick 1970), which is almost universally employed by extant life.

There is support for abiotic synthesis (Oró and Kimball 1962) and extraterrestrial delivery (Schmitt-Kopplin et al. 2010) of nucleic acid precursors to Earth. Purine and ► **pyrimidine bases** have been identified, with supporting carbon isotope dating, in carbonaceous chondrites such as the Murchison meteorite that fell in Australia in 1969 (for a review see Schmitt-Kopplin et al. 2010).



Nucleic Acids, Fig. 4 The B-form DNA double helix shown in reduced form for simplicity. The phosphate groups are not shown. The bases are colored by type, as in Fig. 3

Deoxyribonucleic Acid (DNA)

Specific pairing of purine and pyrimidine bases in a double helix (Fig. 4) was first proposed by James D. Watson and Francis Crick in 1953. This “B-form” helical structure contains nucleic acid bases paired by hydrogen bonds. In the B-form, base pairs are centered on the helical axis, with the base pair normals coincident with the axis. DNA bases stack like pennies in a roll.

The sugar-phosphate backbones fall on the outside to form an antiparallel, right-handed helix. Base pair stacking, rather than hydrogen bonding, makes the greatest contribution to duplex stability (Devoe and Tinoco 1962). The B-form helix, with a repeat of around ~ 10.3 base pairs, contains a wide major groove and a narrow minor groove.

Elucidation of the base pairing scheme was aided by Erwin Chargaff’s observation that the ratios of

A to T and C to G are very close to 1:1 in a variety of species (Zamenhof et al. 1952). In addition, Watson and Crick's model incorporated results of DNA fiber diffraction experiments carried out by Rosalind Franklin (Franklin and Gosling 1953).

The importance of Watson and Crick's model, along with work by Linus Pauling and others on protein structure, is that it greatly facilitated a unification of chemical and biological sciences, leading to the creation of the fields of biochemistry and molecular biology. The structure of DNA allowed the incorporation of the basic concepts of chemistry – hydrogen bonding, van der Waals interactions (stacking), bond angles, and torsions – into the practice and understanding of biological sciences. As Watson and Crick noted, "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material."

The ease of manipulation of DNA has fostered its extensive use in the study of essentially all cellular components. Identification of specific DNA sequences (restriction sites) cleaved by restriction enzymes (Roberts 1976) led to the development of recombinant DNA technology, in which targeted DNA sequences are essentially cut, copied, and pasted into other DNA sequences. It was later found that DNA polymerases and oligodeoxyribonucleotide primers (short pieces of DNA) can be used to amplify essentially any target sequence from genomic DNA using what is called the ► [polymerase chain reaction](#) (PCR) (Mullis and Faloona 1987).

Ribonucleic Acid (RNA)

According to the ► [RNA world](#) hypothesis (Rich 1962), articulated in detail by Gilbert (1986), a single type of molecule served as both genetic information carrier and catalyst in primitive living systems. In this model for the origin of life, genetic RNA was replicated by catalytic RNA. A single polymer fulfilled essentially all of life's requirements, avoiding the chicken and egg dilemma presented by extant biochemistry – which came first, catalytic proteins or genetic nucleic acids? The RNA world hypothesis provides a reasonable answer: RNA came first, with both catalytic and genetic functions. A smooth and continuous evolutionary pathway from

catalytic RNA to protein enzymes was paved with mixed RNA/protein assemblies (Poole et al. 1998). Support for the RNA World hypothesis is found in observations that RNA performs catalytic functions in extant biology (Kruger et al. 1982; Guerrier-Takada et al. 1983).

RNA, like DNA, can form right-handed anti-parallel duplexes with stacked base pairs. RNA duplexes give A-form helices, in which the base pairs are displaced from the helical axis, and are rolled, so that their normals are not parallel to the helical axis. RNA's A-form helix is thicker and more compressed along the helical axis than DNA's B-form helix.

Unlike DNA, RNA forms complex three-dimensional structures dictated by combinations of secondary and tertiary interactions between bases, and by cation-mediated interactions between phosphate groups. The result is distinct folds, such as the L-shaped structure of transfer RNAs (tRNAs) (Fig. 5), or more complex structures such as ribosomal RNAs (rRNAs).

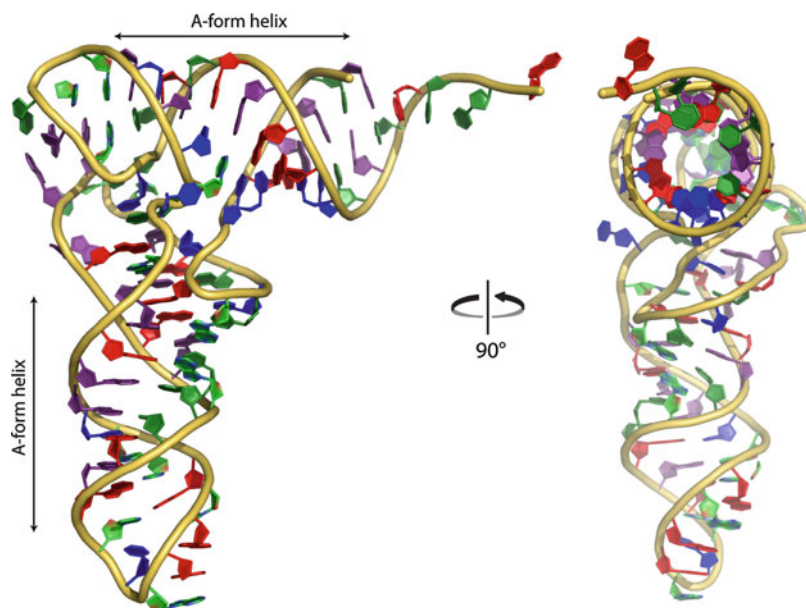
RNA polymerase transcribes DNA into mRNA, which carries sequence information to the ribosome (Kornberg 2007). The ► [ribosome](#) translates the mRNA into protein with the assistance of tRNAs specific to each amino acid.

Ribosomes are around 200 Å in diameter and are comprised of 65% rRNA and 35% ribosomal proteins. They can be either cytoplasmic or membrane bound, depending on the protein actively in synthesis. Ribosomes and their subunits are classified by their Svedberg unit (rate of sedimentation in centrifugation), which ranges from 35S to 100S. Prokaryotes, mitochondria, and ► [chloroplasts](#) have 70S ribosomes (comprised of a small 30S subunit and a large 50S subunit), and eukaryotes have 80S ribosomes (with a small 40S and large 60S subunit). The small 30S and 40S subunits have their own subunits consisting entirely of rRNA: the 16S or 18S subunit, respectively. It is believed that mitochondria and chloroplasts are relict bacterial endosymbionts.

Until 1977, the generally accepted evolutionary relationship among known species was represented by two kingdoms: prokaryotes (bacteria) and eukaryotes. Carl Woese and George Fox used sequences of 16S rRNA to support reclassification of a portion of the prokaryotes into a third kingdom,

Nucleic Acids,

Fig. 5 The L-shaped structure of transfer RNA (tRNA). The bases are colored by type as in Figs. 3 and 4. Here U is blue. Close inspection of the right panel reveals that the base pairs are shifted away from the helical axis, as expected for an A-form helix



later dubbed Archaea (Woese and Fox 1977). Woese and Fox found 16S rRNA genes to be among the most highly conserved in sequence over the phylogenetic tree. Their approach has been widely accepted and is a standard for phylogenetic classification, so that more than 10,000 16S rRNAs have been sequenced to date.

Other RNAs include miRNA and siRNA, responsible for defensive RNA degradation, and snoRNAs that guide ribonucleoproteins to target sites on rRNA for modification.

X-ray crystallography has been used to determine the three-dimensional structure of the atoms in molecules such as the ribosome. The 2010 Nobel Prize in chemistry was awarded to Ada Yonath, Tom Steitz, and Venki Ramakrishnan for ribosomal structure determination. Superimposition of the atomic coordinates of crystallized 50S subunits from *Haloarcula marismortui* and *Thermus thermophilus*, species representing disparate regions of the evolutionary tree, along with other information, suggests that the core of the ribosome is an ancient molecular fossil that predates coded protein (Hsiao et al. 2009). In part, these findings have led to the search for the ancestral peptidyl transferase center (or “ancestral PTC”) of the ribosome, the minimal rRNA necessary for folding and general condensation to produce proto-proteins.

Basic Methodology

- **Oligonucleotide** synthesis. Many DNA oligonucleotides are readily obtained by automated chemical synthesis (often on solid support, with synthesis occurring in the 3′–5′ direction) at lengths of up to 100 nucleotides. Chemical synthesis of RNA is more difficult but the technology has improved substantially over the last decade. Most labs outsource their synthesis to highly efficient commercial enterprises.
- **DNA sequencing** is the determination of the sequence of the nucleotides A, C, G, and T in a nucleic acid. DNA sequencing technology is highly mature. A modern, high-throughput method uses fluorescent dye labeled chain terminator dideoxynucleotide triphosphates in a single sequencing reaction.
- **Restriction**. DNA can be cut at defined positions in a sequence by commercially available restriction enzymes. Commonly utilized type II enzymes cleave DNA within a specific palindromic recognition sequence (compared to type I enzymes that cleave DNA far from the recognition sequence at random) producing DNA with blunt or dangling ends of known sequence.

- Ligation. DNA fragments can be linked by a ligase such as T4, which catalyzes the formation of a phosphodiester bond between a 3' terminal hydroxyl and 5' terminal phosphate in duplex DNA. Ligases are commercially available.
 - Polymerase Chain Reaction. PCR is the amplification of DNA sequences from short oligonucleotides or target regions of plasmid or genomic DNA. Target sequences are amplified with primers containing a short sequence complementary to the target sequence and extraneous specific sequences coding for restriction sites and/or promoters. One primer anneals to the sense strand and the other to the antisense strand of the DNA. A DNA polymerase performs the amplification work by creating new strands of DNA, with loose dNTPs added to the reaction. Amplification with primers containing specific restriction sites allows for subsequent ligation into a bacterial plasmid also containing those restriction sites.
 - ► [Electrophoresis](#). A basic technique used to separate nucleic acids by length, shape, or protein association in a fluid covered matrix (such as agar or polyacrylamide) by an external electric field.
 - RNA Transcription. DNA with a promoter region (such as T7) can be transcribed to produce single-stranded RNA in vitro with RNA polymerase.
 - Crystallography. The coordinates of atoms in molecules such as DNA, RNA, or protein complexes of either can be resolved in three dimensions using X-ray diffraction crystallography, the technique of growing crystals in solution by slowly lowering the solubility of component molecules, mounting the crystals on a loop, and irradiating them with a beam of monochromatic X-rays through a 180° rotation.
- [DNA](#)
 - [DNA Damage](#)
 - [DNA Repair](#)
 - [DNA Sequencing](#)
 - [Electrophoresis](#)
 - [Extraterrestrial Delivery of Organic Compounds](#)
 - [Genome](#)
 - [Guanine](#)
 - [Nucleic Acid Base](#)
 - [Nucleoside](#)
 - [Nucleotide](#)
 - [Oligonucleotide](#)
 - [Phylogenetic Tree](#)
 - [Phylogeny](#)
 - [Polymerase Chain Reaction](#)
 - [Prebiotic Chemistry](#)
 - [Purine Bases](#)
 - [Pyrimidine Base](#)
 - [Ribonucleoside](#)
 - [Ribonucleotide](#)
 - [Ribose](#)
 - [Ribosome](#)
 - [RNA](#)
 - [RNA World](#)
 - [Thymine \(T\)](#)
 - [Uracil \(Ura\)](#)
 - [Watson-Crick Pairing](#)

Cross-References

- [Adenine](#)
- [Chicken or Egg Problem](#)
- [Cytosine](#)

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Nucleoid

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

The nucleoid is the area of a prokaryotic cell in which the genetic material, the ► [chromosome](#), is localized.

Cross-References

- [Cell](#)
- [Chromosome](#)
- [Genome](#)

Nucleon

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry and physics, a nucleon is the collective name for the two subatomic particles, the neutron and the proton. Nucleons are constituents of the atomic nucleus. They are composed of still smaller subatomic particles, the quarks.

N

Nucleoside

John H. Chalmers
Scripps Institute of Oceanography Geosciences
Research Division, University of California, San
Diego, La Jolla, CA, USA

Keywords

Adenosine · Cytidine · Deoxyribose · DNA ·
Guanosine · Nucleic acid base · Purine ·
Pyrimidine · Ribose · RNA · Thymidine ·
Uridine

Synonyms

[Ribosylaminoadenine](#); [Ribosylaminocytosine](#);
[Ribosylaminoguanine](#); [Ribosylaminouracil](#)

Definition

Nucleosides are ribosides and deoxyribosides of purine and pyrimidine nucleic acid bases (nucleobases) formed via beta-glycoside linkage to ring nitrogen atoms. The canonical ribonucleosides in RNA are adenosine, cytidine, guanosine, and uridine. In DNA, deoxythymidine replaces uridine and deoxyribose replaces the ribose moieties of adenosine, cytidine, and guanosine. Chemically modified nucleosides are also found in RNA and DNA, where they play functional roles in regulation, translation, and protection from viral infection, as well as in tRNA (transfer RNA) and rRNA (ribosomal RNA) where they play structural roles. These species include methylated adenines and cytosines as well as hydroxymethylated, aminoacylated, and glucosylated species.

Overview

Plausible, robust prebiotic syntheses of the nucleosides in DNA and RNA are among the most pressing unsolved problems in origin of life research (Orgel 2004; Switzer 2009). The prebiotic synthesis of ► [adenine](#) was accomplished by Oró in 1960 from ammonium cyanide, and variations of the synthesis yielded guanine, xanthine, hypoxanthine, and diaminopurine (Orgel 2004). Similar mixtures of purines have also been made by Saladino and coworkers from formamide (Orgel 2004). Syntheses of uracil and ► [cytosine](#) from cyanoacetaldehyde, the hydration product of cyanoacetylene, and urea or guanidine are efficient and also produce small amounts of isocytosine and diaminopyrimidine (Robertson and Miller 1995a). Formaldehyde reacts readily with uracil to make 5-hydroxymethyluracil, which can be readily reduced to thymine with formate (Robertson and Miller 1995b).

The instability and low yields of ribose from the ► [formose reaction](#) have been considered serious barriers, but the addition of lead, borate, or silicate ions to the reaction increases the yield (Zubay 1998; Ricardo et al. 2004; Lambert et al.

2010). Deoxyribose is somewhat more stable and reactive than ribose (Larralde et al. 1995; Dworkin et al. 2003), but fewer studies have been done on this sugar.

Adenosine, guanosine, xanthosine, and inosine have been made in significant yields by heating dry ribose, Mg^{2+} , and sodium metaphosphate with adenine, guanine, xanthine, and ► [hypoxanthine](#), respectively (Orgel 2004; Switzer 2009). Unfortunately, analogous experiments with ► [pyrimidine bases](#) have been unsuccessful except with 2-pyrimidone, which readily forms zebularine (Bean et al. 2007). To get around this difficulty, attempts have been made to start with ribose and build up the pyrimidine ring de novo by Sanchez and Orgel (Orgel 2004; Switzer 2009). Alternatively, Sutherland and colleagues have reacted glycolaldehyde with cyanamide and constructed both the ribose and pyrimidine moieties together by sequential addition of glyceraldehyde, cyanoacetylene, urea, and pyrophosphate followed by UV irradiation (Powner et al. 2009). This procedure produces cytidine and uridine 2'-3'-cyclic phosphates. Progress is being made, but a great deal more research needs to be done to develop robust syntheses of nucleosides or ► [nucleotides](#).

Because of these difficulties, analogues in which either the sugars or the bases have been altered have been synthesized for origin of life research (Eschenmoser 1999; Dworkin et al. 2003), DNA sequencing, cancer and AIDS chemotherapy, and other applications (Sismour and Benner 2005). These compounds include C-glycosides like the naturally occurring pseudouridine.

Cross-References

- [Adenine](#)
- [Cytosine](#)
- [Deoxyribose](#)
- [Guanine](#)
- [Hypoxanthine](#)
- [Nucleic Acid Base](#)
- [Nucleotide](#)

- [Phosphates](#)
- [Purine Bases](#)
- [Pyrimidine Base](#)
- [Ribonucleoside](#)
- [Ribose](#)
- [Thymine \(T\)](#)
- [Uracil \(Ura\)](#)

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Nucleoside 5'-Monophosphorimidazolidine

- [Activated Nucleotide](#)

Nucleoside Phosphoimidazolidine

Kunio Kawamura

Department of Human Environmental Studies,
Hiroshima Shudo University, Hiroshima, Japan

Keywords

Chemical evolution · Nucleotide ·
Oligonucleotide · RNA

Synonyms

[Activated nucleotide](#)

Definition

In chemical evolution and related fields, a nucleoside phosphorimidazolidine is defined as “a nucleoside 5'-monophosphorimidazolidine,” where imidazole is a leaving group bound to the phosphate of a nucleoside 5'-monophosphate via an N-P bond. Nucleoside phosphorimidazolidines are a kind of ► [activated nucleotide](#). The leaving group supplies energy to form ► [oligonucleotides](#) from the nucleoside phosphorimidazolidine. Prebiotic experiments have showed that nucleoside 5'-phosphorimidazolidine monomers form ► [RNA](#) oligomers up to 50 nucleotide units in length in the presence of metal catalysts, clay mineral catalysts, or a polynucleotide template.

Overview

The accumulation of RNA molecules should have been an essential step for the emergence of life-like systems on the primitive earth. In modern organisms, polymerization of RNA monomers merely proceeds under the specific conditions, of which thermodynamics and kinetics allow the biochemical polymerization in organisms. Nucleoside 5'-triphosphate monomers are only used to

synthesize RNA polymers in organisms. The cleavage of phosphoester bonding within triphosphate moiety supplies energy for the formation of phosphodiester bonding of RNA oligomers. Furthermore, the polymerization of the nucleoside 5'-triphosphate is accelerated by an RNA polymerase and directed by a DNA template in organisms giving the 3'-5' isomers in a selective way. In the absence of an RNA polymerase or the absence of a DNA template, the polymerization of 5'-triphosphate does not proceed. In addition, it is known that RNA polymers are formed from nucleoside 5'-diphosphate in the presence of polynucleotide phosphorylase without a DNA template. The formation of DNA molecules also proceeds by similar mechanism. In these reactions using 5'-triphosphate or 5'-diphosphate, the phosphoester bonding within the 5'-triphosphate or 5'-diphosphate moieties provides sufficient energy for the formation of phosphodiester bonding of RNA polymers. This indicates that high-energy nucleotide monomers should have been essential for the formation of RNA polymers under the primitive earth conditions.

Thus, the pathways to form RNA polymers without an enzyme and a template molecule have been investigated under the simulated primitive earth conditions. Continuous investigations by Orgel and coworkers have identified nucleoside 5'-phosphorimidazolidine, a candidate primitive activated nucleotide monomer for the first time (Lohrmann and Orgel 1973; Orgel and Lohrmann 1974). The formation of nucleoside 5'-phosphorimidazolidine proceeds under the potential primitive earth conditions (Lohrmann 1977). The nucleoside 5'-phosphorimidazolidine and related compounds have been examined whether oligonucleotides could be formed from these materials under the primitive earth conditions. Successful studies including RNA oligomer formation in the presence of metal catalysts (Sawai 1976), clay mineral catalyst (Ferris and Ertem 1992; Ferris et al. 1996), and a polynucleotide template (Inoue and Orgel 1983) showed RNA oligomers up to 50 nucleotide units in length form under primitive earth conditions. The variations using different bases instead of imidazole also facilitate the formation of oligonucleotides (Huang and Ferris 2006).

Cross-References

- ▶ [Oligonucleotide](#)
- ▶ [RNA](#)
- ▶ [RNA World](#)

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Nucleosynthesis, Explosive

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Synonyms

[Explosive nucleosynthesis](#)

Definition

Explosive nucleosynthesis refers to nucleosynthetic processes occurring in stellar explosions (supernovae, novae, X- and γ -ray bursts, etc.). Because of the short timescale, important weak interactions (modifying the neutron/proton ratio

N/Z) have no time to occur. Several chemical elements, like iron (Fe), gold (Au) or uranium (U) are produced in such explosions. In particular, explosive Si-burning (fusion) in core collapse and thermonuclear supernovae produces mostly ^{56}Ni ($N = Z = 28$), which decays to stable ^{56}Fe ; the characteristic γ -ray lines of the decay were detected in ► [supernova](#) SN1987A and SN2014J, confirming the theoretical predictions. The so-called r-nuclides (heavier than iron and neutron-rich) are also produced by explosive nucleosynthesis, through the rapid capture of neutrons in the innermost regions of core collapse supernovae or neutron star collisions.

Cross-References

- [Nova](#)
- [Nucleosynthesis, Neutrino](#)
- [Nucleosynthesis, Stellar](#)
- [R-process](#)

Nucleosynthesis, Neutrino

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

Neutrino nucleosynthesis refers to the non-thermonuclear mode of nucleosynthesis occurring during the explosion of a massive star. A fraction of the 10^{58} neutrinos released by the supernova has energies comparable to the binding energies of the heavy nuclei (several MeV/nucleon) which are found in the various supernova layers. Neutrinos knock out one particle from abundant nuclei creating lighter and less abundant ones, e.g., ^{11}B from ^{12}C or ^{19}F from ^{20}Ne .

Cross-References

- [Nuclear Reaction](#)
- [Nucleosynthesis, Explosive](#)

- [Nucleosynthesis, Stellar](#)
- [Supernova](#)

Nucleosynthesis, Stellar

Nikos Prantzos¹ and Sylvia Ekström²
¹Institut d'Astrophysique de Paris, Paris, France
²Observatoire Astronomique de l'Université de Genève, Faculté des Sciences, Université de Genève, Genève, Switzerland

Keywords

Nuclear reactions · Stars · Stellar evolution · Supernovae

Definition

Stellar nucleosynthesis is the process involving ► [nuclear reactions](#) through which fresh atomic nuclei are synthesized from pre-existing nuclei or nucleons. The first stage of nucleosynthesis occurred in the hot, early Universe, with the production of H, He, and traces of Li-7 (*primordial nucleosynthesis*). In the present-day Universe nucleosynthesis occurs through: (1) thermonuclear reactions in stellar interiors and explosions (building nuclei up to the Fe-peak), (2) neutron captures in stellar interiors and explosions (building nuclei above the Fe-peak), and (3) ► [spallation reactions](#) in the interstellar medium, whereby light nuclei (Li, Be, and B) are produced by fragmentation of heavier ones (C, N, and O).

History

The theory of nucleosynthesis emerged around the middle of the twentieth century as a result of rapid progress in our understanding of three different fields: (1) the chemical composition of the Sun and the solar system, (2) the physical conditions prevailing in the interiors of ► [stars](#) during their various evolutionary stages, and (3) the systematic properties of nuclei and nuclear reactions.

Overview

The solar or cosmic abundances of the various nuclear species (Fig. 1, upper panel) constitute an important macroscopic property of (baryonic) matter. This property is rather closely related to a microscopic one, namely the “binding energy per nucleon” (BEN, lower panel in Fig. 1). The latter quantity represents the energy per nucleon required to break a nucleus into its constituent particles and is a measure of the ► [nuclear stability](#).

The key features of the BEN curve are obviously reflected in the cosmic abundance curve, albeit at a local level only: more stable nuclei are more abundant than their neighbors (e.g., nuclei built from alpha particles – ${}^4\text{He}$ – such as ${}^{12}\text{C}$, ${}^{16}\text{O}$, or ${}^{40}\text{Ca}$; or the Fe-peak nuclei), while the fragile Li, Be, and B isotopes are extremely under abundant. However, at a global level, the light H and He are overwhelmingly more abundant than the more strongly bound C, N, and O, which in turn

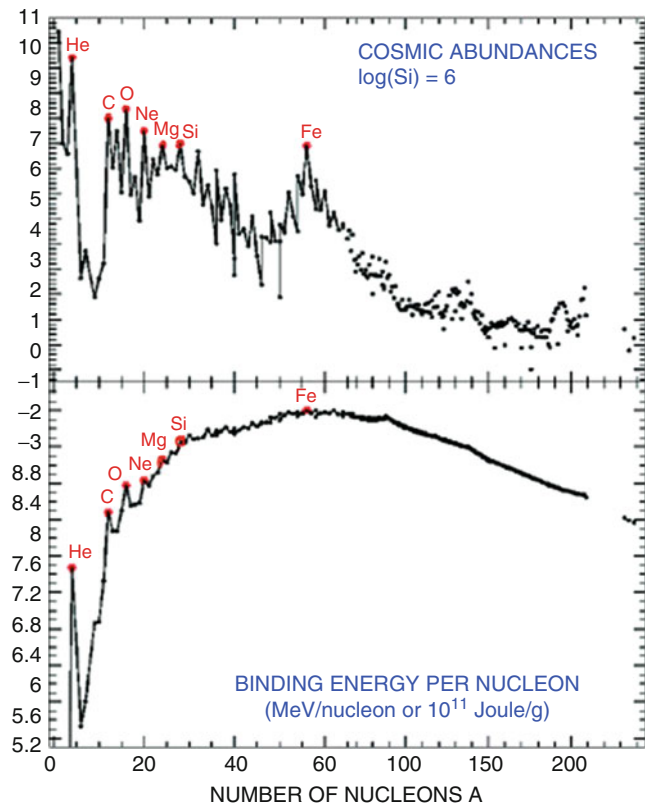
are more abundant than the even more stable Fe-peak nuclei. The (local) correlation between cosmic abundances and nuclear stability suggests that nuclear reactions have shaped the abundances of elements in the Universe. The fact that the correlation is only local and does not hold at a global level implies that nuclear processes have affected only a small fraction of the baryonic matter in the Universe (less than a few per cent).

Searching for the sites of nuclear reactions, which shaped the cosmic abundances, has been the main theme of nuclear astrophysics in the past half century. It is now well established that:

- The light isotopes of H and He, along with 10–30% of the fragile ${}^7\text{Li}$, have been produced in the hot early Universe by thermonuclear reactions between neutrons and protons.
- All the elements between C and the Fe-peak have been produced by thermonuclear reactions inside stars, either during their quiescent evolutionary stages or during the violent

Nucleosynthesis, Stellar,

Fig. 1 Solar abundances on a logarithmic scale of the stable nuclei (*top*), and corresponding binding energies of these nuclei (*bottom*) vs. mass number



explosions (supernovae) that mark the deaths of some stars.

- Elements heavier than those of the Fe-peak have been produced by neutron captures in stars, either in low neutron densities and long timescales (s- elements) or in high neutron densities and short timescales (r- elements); a minor fraction of those heavy elements has been produced by photodisintegration of the heavy isotopes in supernova explosions (p-isotopes).
- Finally, the light and fragile isotopes of Li, Be, and B are not produced in stellar interiors (they are rather destroyed in high temperatures), but by ► [spallation reactions](#), with high energy cosmic ray particles removing nucleons from the abundant C, N, and O nuclei of the interstellar medium.

In the following, we focus on the *stellar nucleosynthesis* of heavy nuclei, which are much more important than the light nuclei for the origin of terrestrial planets and of life. This topic is tightly linked to the properties of stellar interiors. In this review, we follow astronomical practice and refer to nuclear fusion reactions as “burning.” We likewise use nuclear physics notation, writing the reaction $X + b \rightarrow c + D$ as $X(b,c)D$ and using α and γ to denote an alpha particle (${}^4\text{He}$ nucleus) and gamma-ray, respectively. Moreover, we use A and Z to denote atomic weight (number of neutrons plus protons in the nucleus) and atomic number (nuclear electric charge), respectively.

Quiescent Nucleosynthesis

H-Burning in Main Sequence Stars

Most of the stars in the Universe shine by converting H to ${}^4\text{He}$. However, only $\sim 15\%$ of the cosmic abundance of ${}^4\text{He}$ is produced by stars (otherwise, the cosmic background of optical light would exceed by far the observed one): more than 80% of it has been produced in the Big Bang by the *primordial nucleosynthesis*. In stars of mass $< 1.2 M_{\odot}$ and central temperatures below 20 million K, most of the H-burning energy is released by the ► [p-p chains](#). In stars of higher

masses and temperatures, H-burning occurs through the ► [CNO cycle](#), where the C, N, and O isotopes (produced from previous stellar generations) act as catalysts. The sum of the abundances of CNO nuclei remains constant throughout H-burning, but there is an internal rearrangement: ${}^{12}\text{C}$ and ${}^{16}\text{O}$ turn into ${}^{14}\text{N}$ and, to a smaller extent, into ${}^{13}\text{C}$ and ${}^{17}\text{O}$; these are the main nuclei produced by the CNO cycle.

He-Burning in Red Giants

After H exhaustion, the stellar core contracts and releases gravitational energy, which brings the surrounding H-rich layers to temperatures high enough for H-burning reactions. At the same time, the envelope expands and cools and the star turns into a *red giant* (or super giant for the most massive of them, i.e., above $10 M_{\odot}$). The envelope of such a star is convective and brings to the surface products of the previous central H-burning phase. Enhanced abundances of ${}^4\text{He}$ and ${}^{14}\text{N}$, as well as modified isotopic ratios of, e.g., ${}^{13}\text{C}/{}^{12}\text{C}$ or ${}^{17}\text{O}/{}^{16}\text{O}$, are the marks of this “1st dredge-up” phase, which allows one to compare nucleosynthesis theory to observations.

When the H-exhausted core reaches temperatures of 100–200 millions K (with higher temperatures corresponding to higher stellar masses), He fusion begins. The process is known as the triple-alpha reaction and proceeds in two steps (${}^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be}$ and ${}^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}$) with the second one involving a resonant reaction; the final outcome is the formation of a ${}^{12}\text{C}$ nucleus from three alpha particles.

In the very beginning of He-burning, at temperatures of ~ 100 MK, ${}^{14}\text{N}$ turns into ${}^{18}\text{O}$ and later into ${}^{22}\text{Ne}$, through successive alpha-particle captures. Thus, He-burning constitutes the production mode of ${}^{18}\text{O}$ in the Universe, since some amount of it survives in the He-shell the subsequent reaction ${}^{18}\text{O}(\alpha, \gamma){}^{22}\text{Ne}$. In late He-burning, ${}^{12}\text{C}$ nuclei capture α particles to form ${}^{16}\text{O}$ nuclei; the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction is not resonant, however, so that at central He-exhaustion a considerable amount of ${}^{12}\text{C}$ is left over in the stellar core. ${}^{16}\text{O}$ is usually dominant at that stage, but the exact ${}^{16}\text{O}/{}^{12}\text{C}$ ratio depends on the rate of the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction, which is still uncertain.

Toward the end of core He-burning in massive stars, at temperatures of 250 MK, neutrons are released through $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$. As they lack an electric charge, those neutrons are easily captured by all nuclei in the star (in proportion to the corresponding neutron capture cross sections). A part of those nuclei is destroyed in subsequent stages of the evolution of massive stars, but those that survive are ejected by the final supernova explosion. This “weak $\blacktriangleright$ s-process” leads to the production of the light s-nuclei, with mass number A between 60 and 90. Heavier s-nuclei are produced during the AGB phase of shell He-burning in low and intermediate mass stars, where neutrons are released mainly through $^{13}\text{C}(\alpha, n)$.

In AGB stars, material from the He-burning layer is mixed first in the H-layer and finally in the convective stellar envelope (“3d dredge-up” phase). The enrichment of the latter with He-burning products leads to the appearance of “Carbon stars” and “s-stars.” Such late evolutionary stages provide important tests for theories of $\blacktriangleright$ stellar evolution and nucleosynthesis. This is also the case with the most massive stars (with initial masses above $30 M_{\odot}$), which develop strong stellar winds, due to the high radiation pressure on their envelopes. Losing more than $10^{-5} M_{\odot}$ per year, they finally reveal layers that have been affected by nucleosynthesis. The products of core H-burning (^4He and ^{14}N) and then of core He-burning (^{12}C , ^{16}O , and ^{22}Ne) appear thus with enhanced abundances on the stellar surface. Those stars are called *Wolf-Rayet stars*, and their spectroscopy offers another invaluable test of nucleosynthesis theories.

Advanced Nuclear Burning in Massive Stars

Despite their small number (less than 1% of a stellar generation), massive stars constitute the most important agents of galactic chemical evolution. Indeed, most of the elements heavier than helium in the Universe are synthesized in the hot interiors of massive stars and, in particular, during the final *supernova* explosion. Contrary to their lower mass counterparts, which stop evolving after burning He in a shell surrounding an inert

Carbon-Oxygen core, stars with mass $M > 10 M_{\odot}$ burn successively all the available nuclear fuels in their core, until its composition is dominated by nuclei of the iron peak. However, the duration of all stages subsequent to core He-burning is so short that no direct observational tests of the evolutionary status of the core (which is hidden inside a red supergiant envelope) are possible. Only “post-mortem” observations offer a possibility of (indirectly) validating the results of the models (Fig. 2).

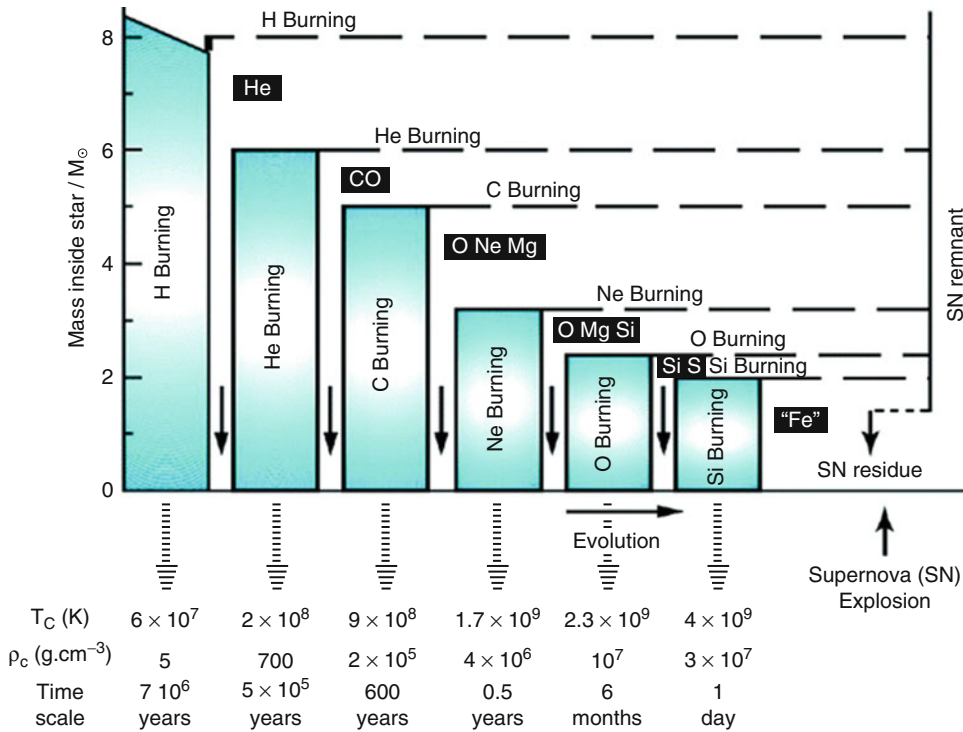
Neutrino Losses

One of the most important features of the advanced evolutionary stages of massive stars is the copious production of neutrinos, due to the high temperatures and densities reached in the stellar core after He-exhaustion ($T > 0.8$ GK, density $> 10^5 \text{ g cm}^{-3}$). Neutrino-antineutrino pairs are produced by: (1) *electron-positron annihilation*, the e^{-} 's and e^{+} 's being created by the hot thermal plasma; (2) *photo-neutrino process*, analogous to Compton scattering, with the outgoing photon replaced by a neutrino-antineutrino pair; and (3) *plasma process*, where a *plasmon* (an excitation of the plasma) decays into a neutrino-antineutrino pair.

Neutrinos interact only weakly with matter and escape easily from the stellar core, taking away most of the available thermal energy (produced by nuclear reactions and/or gravitational contraction). In order to compensate for that neutrino “hemorrhage,” the core has to increase its nuclear energy production, by contracting and increasing its temperature. As a result, the evolution of the star is greatly accelerated: the time between C-ignition and the final supernova explosion is less than 0.1% of the corresponding main sequence lifetime.

C, Ne, and O Burning

C-burning in massive stars occurs at temperature $T \sim 0.8$ GK and density $\sim 10^5 \text{ g cm}^{-3}$. The core composition at C-ignition is dominated by the ashes of He-burning, ^{12}C , and ^{16}O (more than 90% of the total) in a proportion that decreases with the stellar mass. The exact proportion of $^{12}\text{C}/^{16}\text{O}$ and the exact initial fraction of ^{12}C (which is crucial for the energetics of C-burning)



Nucleosynthesis, Stellar, Fig. 2 Schematic evolution of the interior composition of a massive star of $25 M_{\odot}$. The central temperatures (T_c) and densities (ρ_c), as well as the approximate durations of the various burning stages,

appear in the bottom. After the final supernova (SN) explosion, a neutron star or a black hole is left behind (SN residue), while the rest is ejected in the interstellar medium, forming the SN remnant

N

depend sensitively on the – still uncertain – value of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate and on the adopted criterion of convection during He-burning. The reason for the latter dependence is that every α particle brought in the convective core while He is almost exhausted (and the rate of the 3α reaction too low to produce new ^{12}C nuclei) converts a ^{12}C nucleus into ^{16}O .

The fusion of two ^{12}C nuclei produces a compound nuclear state of ^{24}Mg , which decays by emitting a proton or an alpha particle. Note that the neutron emission channel, i.e., $^{12}\text{C} + ^{12}\text{C} \rightarrow n + ^{23}\text{Mg}$, corresponds to an endothermic reaction with a small probability (0.1% at $T = 1$ GK) but it is nevertheless important because the decay of ^{23}Mg to ^{23}Na changes the *neutron excess* $\eta = \Sigma(N_i - Z_i)Y_i$, where N_i , Z_i , and $Y_i = X_i/A_i$ are the neutron number, the charge, and the number fraction of nucleus i , respectively. Moreover, neutron captures on heavy nuclei produce heavier than Fe nuclei, thus modifying the s-process composition resulting from the previous

He-burning phase. Also, protons and alphas released by the $^{12}\text{C} + ^{12}\text{C}$ fusion are captured on the ambient nuclei through dozens of (energetically unimportant) reactions; in particular, α captures on ^{20}Ne produce ^{24}Mg . Thus, the main products of C-burning are ^{20}Ne , ^{23}Na , and ^{24}Mg .

After C exhaustion, the composition of the stellar core is dominated by ^{16}O and ^{20}Ne (more than 90% of the total by mass). ^{23}Na and ^{24}Mg also exist at the few per cent level (in mass fraction). Despite its smaller Coulomb barrier, ^{16}O is not the next fuel to burn, since it is exceptionally stable (being a doubly magic nucleus with $Z = N = 8$). The photodisintegration of ^{20}Ne nuclei $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$ becomes energetically feasible at $T \sim 1.5$ GK, i.e., before the fusion temperature of ^{16}O nuclei ($T \sim 2$ GK) is reached. The released α particles are captured on both ^{16}O (to restore ^{20}Ne) and ^{20}Ne (to form ^{24}Mg). The net result of the operation is that this ^{20}Ne “melting” can be described by: $2 ^{20}\text{Ne} \rightarrow ^{16}\text{O} + ^{24}\text{Mg}$.

The photodisintegration of ^{20}Ne is endoergic, but the exoergic α captures on ^{16}O and ^{20}Ne more than compensate for the energy lost. ^{20}Ne burning produces 0.1 MeV/nucleon or 1.1×10^{17} erg/g, i.e., about one-fourth the specific energy released by C-burning. Several other energetically unimportant reactions, induced by p, n, and α particles occur during Ne burning; in particular, ^{23}Na (a product of C-burning) disappears through $^{23}\text{Na}(\text{p}, \alpha)^{20}\text{Ne}$ and $^{23}\text{Na}(\alpha, \text{p})^{26}\text{Mg}$.

After Ne burning, the stellar core consists mainly of ^{16}O , ^{24}Mg , and ^{28}Si . Also, ^{29}Si , ^{30}Si , and ^{32}S are present at the 10^{-2} level (in mass fraction).

The subsequent fusion of two ^{16}O nuclei produces a compound nucleus of ^{32}S which decays through the p, α , and n channels; the corresponding branching ratios and energy released are 58% (7.68 MeV), 36% (9.58 MeV), and 6% (1.45 MeV), respectively. The energy released by oxygen burning is 5×10^{17} erg/g or 0.5 MeV/nucleon. As in the previous stages, dozens of n, p, and α induced reactions occur. However, the increased temperature and density introduce two novel features:

1. Electron captures occur mainly on ^{31}S , ^{30}P , ^{33}S , ^{33}Cl , and ^{37}Ar . These weak interactions modify substantially the neutron excess, up to ~ 0.01 (especially in the lower mass and denser stars); the final neutron-rich composition is clearly non-solar and should be rarely ejected by the star.
2. Photodisintegration reactions become also important and destroy most of the heavier than Fe nuclei that have been built through n captures in the previous burning phases (mostly by s-process during He-burning). However, this happens only in the innermost and hottest regions of the stellar core; outside them, products of previous burning stages survive.

Si-Melting and Nuclear Statistical Equilibrium (NSE)

At O-exhaustion, the composition of the stellar core is dominated by ^{28}Si (30–40% by mass fraction) and, either ^{32}S and ^{38}Ar (in the more massive cores, where low densities do not favor electron

captures) or ^{30}Si and ^{34}S (in the lower mass stars, below $15 M_{\odot}$). ^{28}Si “burns” at temperature $T \sim 3.2$ GK and in a way that is reminiscent of the ^{20}Ne “burning.” The fusion of two ^{28}Si nuclei requires such high temperatures that photodisintegration of all nuclei would result. Instead, part of the ^{28}Si nuclei photodisintegrates, mainly through a sequence of reactions involving α particles: $^{28}\text{Si}(\gamma, \alpha)^{24}\text{Mg}(\gamma, \alpha)^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}(\gamma, \alpha)^{12}\text{C}(\gamma, 2\alpha)\alpha$.

Other photodisintegration reactions releasing p and n also occur, especially in material with neutron excess substantially different from 0 (due to previous electron captures, i.e., in high density stellar cores). The released α particles and nucleons are further captured by ^{28}Si and heavier nuclei, and equilibrium is established between direct and inverse reactions.

The mean atomic weight of the mixture progressively increases, since free nucleons and α particles are tied to heavier and more strongly bound nuclei; that is why the overall process is better described as *Si-“melting.”* In fact, local equilibrium between a few nuclear species is established already by the end of O-burning, but, as the temperature increases, the various quasi-equilibrium clusters merge. In early Si-melting, there are already two major quasi-equilibrium clusters established: one with nuclei with $A = 24$ –46 and another with Fe peak nuclei. Toward the end of Si-melting, the two clusters merge and the quasi-equilibrium group includes all nuclei above ^{16}O . Assuming that two ^{28}Si nuclei turn into one nucleus of the Fe-peak, one finds that the energy released by Si-melting is 0.2 MeV/nucleon or $\sim 2 \times 10^{17}$ erg/g.

Toward the end of Si-melting, all electromagnetic and strong nuclear interactions are in equilibrium with their inverses. Since neutrinos still escape freely from the stellar core, neutrino-producing weak interactions never come into equilibrium with their inverses and total equilibrium is not established. The last reactions to reach equilibrium are those linking ^{24}Mg – ^{20}Ne , ^{16}O – ^{12}C , and, finally, the reaction 3α – ^{12}C . When that happens, and assuming that all nuclides obey the statistics of an ideal Maxwell-Boltzman gas, Nuclear Statistical Equilibrium (NSE) is reached

and the composition is described as a function of three parameters: temperature T , density and electron fraction Y_e , or neutron excess η (in fact, Y_e and η are slowly modified under the action of weak interactions, specifically by electron captures).

In the conditions of NSE, for not too high temperatures ($T < 10$ GK), the most abundant nuclei are those with the largest binding energy for a given value of η . Thus, for $\eta \sim 0$, the most tightly bound nucleus is ^{56}Ni . Indeed, in *explosive nucleosynthesis*, ^{56}Ni is the dominant product of NSE; its radioactive decay has been (indirectly) observed in the case of the supernova SN1987A, brilliantly confirming the theory. However, in the quiescent burning conditions of late stellar evolution, weak interactions have time enough to modify η to values 0.06–0.08, corresponding to $Y_e \sim 0.46$ –0.47. In those conditions, the most tightly bound nucleus is the stable ^{56}Fe , while ^{52}Cr is also produced in substantial amounts (Fig. 3).

Explosive Nucleosynthesis in Supernovae

Explosive Nucleosynthesis in Core-Collapse Supernovae (CCSN)

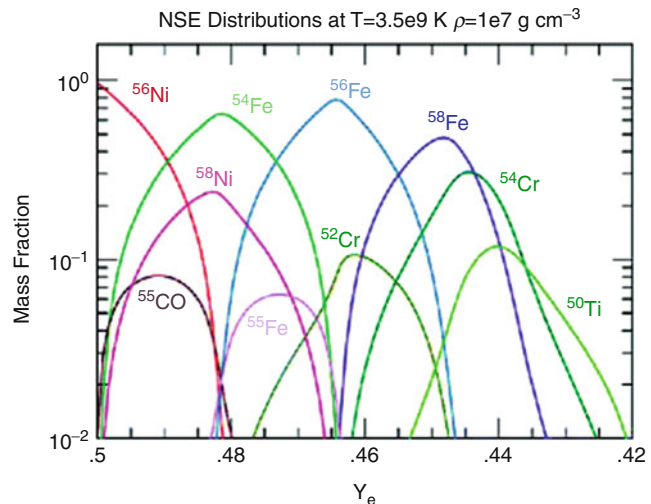
When the composition of the stellar core becomes dominated by the strongly bound nuclei of the Fe-peak, the star has arrived at the end of its

quiescent life. Further contraction of the core and increase of its temperature cannot release nuclear energy to sustain internal pressure: reactions involving stable nuclei at the peak of the binding energy curve are endothermic and constitute sinks of thermal energy. Moreover, electron captures proceed at even higher rates and continue removing electrons from the stellar plasma, weakening the main source of resistance against gravity, namely electron pressure. The iron core collapses and the star dies in a spectacular supernova explosion.

Iron core collapse proceeds on a timescale of milliseconds. Due to increasingly high temperatures, photodisintegrations tear down Fe nuclei to nucleons and alpha particles, while higher densities favor electron captures and conversion of protons to neutrons. When the density of nuclear matter is reached ($\sim 10^{14}$ g cm $^{-3}$), the repulsive component of the strong nuclear force brings the collapse of the inner core abruptly to a halt. At the boundary of the inner core a shock wave is formed, with an energy approximately equal to the kinetic energy of the core at the moment of the bounce ($\sim 5 \times 10^{51}$ erg, according to results of numerical simulations). As the shock wave propagates outwards, into the still infalling *outer core*, it photodisintegrates its Fe nuclei (tearing them down to nucleons) and consequently loses ~ 8.8 MeV/nucleon or 1.5×10^{51} erg per $0.1 M_{\odot}$.

Nucleosynthesis, Stellar,

Fig. 3 Abundances of major nuclides in nuclear statistical equilibrium (NSE), as a function of the electron mole number Y_e



If the mass of the infalling outer core is $M_{OC} = M_{Fe} - M_{IC} < 0.4 M_{\odot}$, the shock can reach the base of the envelope with enough energy to launch a successful explosion. As the shock wave propagates through the stellar envelope, it heats the various layers to temperatures higher than in the corresponding central burning stages. It can be shown that the peak temperature $T_p(r)$ at radius r as a function of the kinetic energy of the shock (KE) may be written as

$$T_p(r) \sim 1.33 \times 10^{10} \left(\frac{KE}{10^{51} \text{ erg}} \right)^{1/4} \left(\frac{r}{10^8 \text{ cm}} \right)^{-3/4} \text{ K}$$

Stellar material in the layers hit by the shock wave is heated to those temperatures for a time of the order of the local hydrodynamic timescale $\tau_{HD} \sim 0.446 \rho_6^{-1/2}$ s, where ρ_6 is the mean density interior to radius r in 10^6 g cm^{-3} . If the nuclear burning timescale at radius r is smaller than the hydrodynamical timescale $\tau_{HD}(r)$, then *explosive nucleosynthesis* will take place, modifying the composition left from the previous quiescent burning stage. Taking into account the relatively steep density profiles of pre-supernova stars, it turns out that peak temperatures are sufficient for vigorous explosive Si- and O-burning. The Ne and C layers are less affected, while the He and H layers are not affected at all by the explosion (envelope densities are too low for explosive burning to take place in those layers).

The major reactions in explosive burning for a given fuel are the same as those of the corresponding quiescent burning. However, the beta decay lifetimes of unstable nuclei are often larger than the timescales of explosive nucleosynthesis τ_{nuc} . This implies that the cross sections of nuclear reactions on those unstable nuclei are also required, a situation that is not usually encountered in quiescent burning.

In general, one may distinguish three classes of elements/isotopes coming out of the explosion:

1. The first set (N, C, O, Ne, Mg) results mainly from hydrostatic He and C/Ne burning (layers not affected by explosive nucleosynthesis). The *yields* (ejected mass) of those elements

increase with stellar mass, following the sizes of the corresponding He- and C- exhausted cores. A comparison of those yields to observations provides indirect tests of the physics of the pre-supernova models.

2. The second group (Al, Si, S, Ar, Ca) includes elements produced in both hydrostatic and explosive burning. Their yields vary less with progenitor mass than the ones of the previous group. Comparison to observations tests both pre-supernova models and explosion energy.
3. The third set involves elements of the Fe-peak, produced essentially by explosive Si-burning. Their yields are highly uncertain at present, since they depend on the mechanism of the explosion, i.e., the shock wave energy, the various mixing processes, and the “mass-cut” (the dividing line between the mass of the star finally ejected and the one that falls back to the compact object).

Explosive Nucleosynthesis in Thermonuclear Supernovae (SNIa)

Another type of supernovae is the thermonuclear explosion of white dwarfs (WD) in binary systems (SNIa). As the WD accretes matter from its companion and its mass increases, compressional heating raises the internal temperature to several hundreds of MK. The high density of the WD ($\sim 10^9 \text{ g/cm}^3$) leads to a very efficient *screening* of the nuclear reactions, whereby repulsive Coulomb barriers between positively charged nuclei are lowered by the presence of negatively charged electrons. $^{12}\text{C} + ^{12}\text{C}$ fusion occurs then at considerably lower temperatures and at much higher rates than in massive stars. Ignition occurs when the $^{12}\text{C} + ^{12}\text{C}$ reaction releases energy faster than neutrino losses (mostly by plasma process) can carry it away.

Contrary to the case of normal stars (where perfect gas dominates the internal pressure), WD are composed of degenerate gas: internal pressure depends only on density, not on temperature. Thus, heating of the medium (through the energy released by $^{12}\text{C} + ^{12}\text{C}$) is not accompanied by pressure increase, which would lead to gas expansion and cooling; instead, temperature increases

steadily, and so does the $^{12}\text{C} + ^{12}\text{C}$ reaction rate. In those conditions, a “carbon deflagration” burns explosively the material of the star, all the way toward Nuclear Statistical Equilibrium (NSE). The timescale of the explosion is too short to allow for important electron captures, and thus the final outcome is essentially ^{56}Ni : about $0.7 M_{\odot}$ are produced (about half of the WD mass), as required by the observed luminosity of SNIa. Only in the central regions, the high densities favor the production of ^{54}Fe and ^{58}Ni through electron captures. In the outer layers, NSE is not reached because of lower temperatures that lead to the production of intermediate mass nuclei, like Si, Ca, etc.

From the point of view of galactic chemical evolution, SNIa play a very important role, since they produce between 50% and 65% of the Fe-peak nuclei. Their smaller frequency (they are ~ 5 times less frequent than CCSN) is compensated by the larger amounts of ^{56}Ni and Fe-peak nuclei produced by their explosion ($\sim 0.7 M_{\odot}$ of ^{56}Ni compared to $\sim 0.1 M_{\odot}$ on average for CCSN).

The Heavier Than Iron Nuclei

Nuclei heavier than those of the Fe-peak (henceforth called “heavy nuclei”) cannot be produced by charged particle reactions: the temperatures needed to overcome the high Coulomb barriers are such that photodisintegrations would tear down all nuclei to their constituent particles. The heavy nuclei rely on another mechanism for their formation: neutron captures on pre-existing “seed” nuclei.

Already in the early works of nucleosynthesis (Burbidge et al. 1957), it was recognized that two different types of neutron capture processes have contributed to the formation of heavy nuclei: the so-called s- (for *slow*) process, responsible for the formation of nuclei in the valley of nuclear stability; and the r- (for *rapid*) process, responsible for the synthesis of the most neutron-rich isotopes of heavy elements. The majority of the heavy nuclei have contributions from both the s- and ► **r-process**.

The s-Process

In the s-process, low neutron densities ($\sim 10^8 \text{ cm}^{-3}$) and rather long timescales (> 1 year) are involved, so that when an unstable nucleus (A, Z) is encountered along the s-process path, it has the time to decay into a stable isobar ($A, Z + 1$). Indeed, the lifetimes of most of the unstable nuclei close to the valley of stability range from a few seconds to less than a year and are lower than their lifetimes with respect to neutron captures in the above conditions. The neutron captures are *slow* with respect to beta decay, and thus the s-process path closely follows the bottom of the nuclear stability valley. Note that the s-process, by its very nature, cannot reach the heaviest nuclei (the long lived Th and U isotopes), which are separated from the heaviest stable nucleus (^{209}Bi) by more than 20 mass units.

The relevant physical conditions for this mechanism are the following: neutron densities $n_n \sim 10^8 \text{ cm}^{-3}$, temperatures $T \sim 150\text{--}300 \text{ MK}$, densities $\sim 2\text{--}100 \text{ g cm}^{-3}$, and timescales $\sim 10\text{--}1000$ year. These conditions correspond to the phase of quiescent He-burning. Two relevant sites have been identified:

1. Central He-burning in massive stars, where the neutron source is $^{22}\text{Ne}(\alpha, n)$; this reaction operates toward the end of He-burning, at $T \sim 250 \text{ MK}$. The number of neutrons released allows the synthesis of only nuclei in the mass range $60 < A < 90$ (the so-called “weak” component of the s-process). Part of those nuclei survive the advanced evolutionary phases of massive stars and are ejected in the interstellar medium by the final supernova explosion. From the theoretical point of view, the He-core s-process is quite robust (despite the uncertainties in the $^{22}\text{Ne}(\alpha, n)$ rate), but it lacks direct observational support.
2. Double shell (H- and He-) burning in low mass stars, evolving in the Asymptotic Giant Branch (AGB, running very close and parallel to the Red Giant branch). During the thermal pulse phase, protons from the H-shell are mixed in regions rich in α and ^{12}C . The coexistence of p, α , and ^{12}C allows the production of abundant neutrons through the reaction series

$p + {}^{12}\text{C} \rightarrow {}^{13}\text{N}$, which decays to ${}^{13}\text{C}$, followed by ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$. The recurring pulses allow the production of a large number of neutrons per seed Fe-nucleus and the synthesis of the “main component” of the s-process, i.e., nuclei with $90 < A < 210$. Between thermal pulses, the convective stellar envelope penetrates deep in the star and “dredges-up” material from the s-processed region to the surface, from where the strong AGB wind expels s-nuclei to the interstellar medium. This rather complex scenario is supported by observations of enhanced s-abundances in the surfaces of low mass AGB stars. However, the mixing of protons with material from the He-zones, as well as the 3d dredge-up, is poorly understood at present.

The r-Process

Contrary to the s-process, the r-process involves huge neutron densities ($>10^{20} \text{ cm}^{-3}$) for time-scales of the order of 1 s (obviously corresponding to an explosive site): neutron captures are so *rapid* with respect to beta decays that the r-process path drives the stellar material far to the neutron-rich side of the stability valley. This continues until the inverse reactions balance the neutron capture reactions. In the simplest picture of the r-process, an equilibrium is reached in each isotopic chain. In these conditions, a large amount of material is accumulated in unstable neutron-rich nuclides with “magic” neutron numbers (i.e., $N = 20, 50, 82$, etc.). Material slowly shifts to higher Z values through beta decays, which govern the speed of the nuclear flow along the r-process path. At the end of the neutron irradiation, all unstable nuclei β -decay toward the nuclear stability valley. The peak abundances in the r-process elements are obtained from the beta decay of very neutron-rich material “stored” in nuclei with “magic” neutron numbers during the r-process.

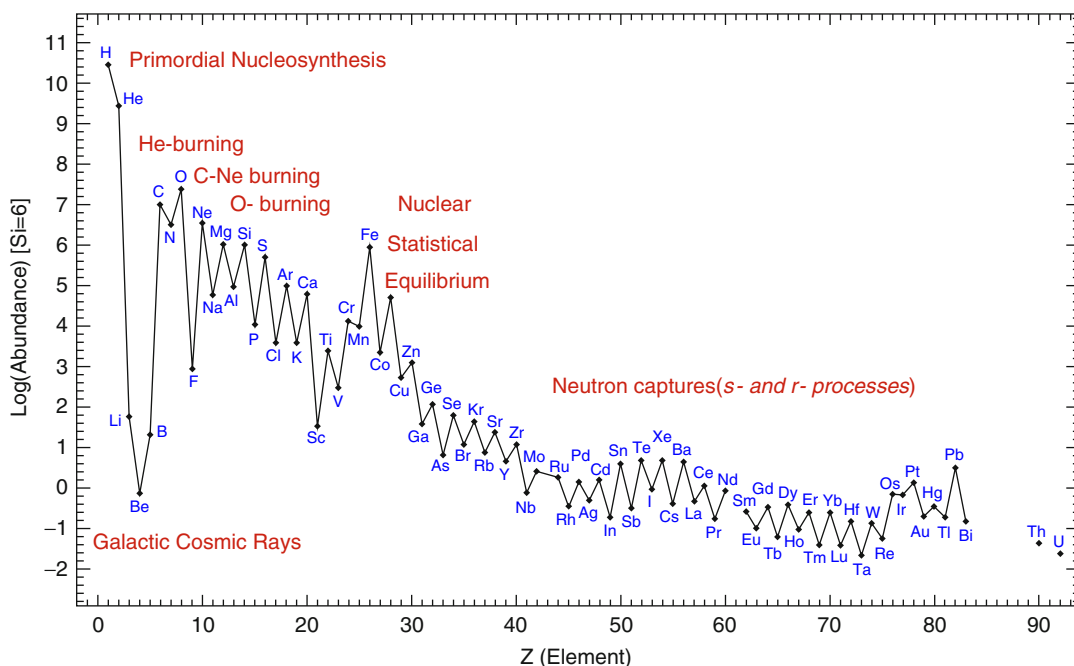
The site of the r-process is not yet identified, despite more than 30 years of intense investigation. Required neutron densities and timescales suggest an explosive event, while observations of the composition of the oldest stars in the Milky Way suggest that the r-nuclei were produced quite early on, i.e., that their source was short-lived. Core collapse SN satisfies both those

requirements, but neither the neutron source nor the relevant stellar layers have been identified yet. Neutron star collisions remain a plausible alternative.

Summary

The basic picture of stellar nucleosynthesis is well established nowadays, at least qualitatively. Massive stars ($M > 10 M_{\odot}$) synthesize in their various burning layers elements from C to Ca and eject them back to the interstellar medium in the final supernova explosion. During the explosion, a large fraction of Fe-peak isotopes (from Ti to Zn) is also produced. Intermediate mass stars ($2\text{--}10 M_{\odot}$) produce important amounts of He and CNO isotopes (except ${}^{16}\text{O}$, ${}^{18}\text{O}$, and ${}^{15}\text{N}$), as well as heavier than Fe-peak nuclei lying on the nuclear stability valley (s-nuclei, produced by neutron captures). All those nuclei are convected to the surface of the star and ejected into the interstellar medium through the stellar winds, mostly during the AGB and planetary nebula phases. The heavier than Fe-peak nuclei that are lying relatively away from the nuclear stability valley are thought to be produced during the explosions of massive stars, either in stellar layers exposed to large neutron fluxes (neutron-rich or r-nuclei) or in layers where photodisintegrations of already synthesized s-nuclei play an important role (proton rich or p-nuclei); the former process is also responsible for the formation of the heaviest stable nuclei, the Th and U isotopes. Finally, a large fraction of the Fe-peak nuclei ($>50\%$) is synthesized in thermonuclear supernovae (SNIa), white dwarfs in binary systems, that explode upon reaching the Chandrasekhar limit through accretion from a companion star (Fig. 4).

Taking into account the lifetimes (a few $10^6\text{--}10^7$ year for massive stars, a few $10^8\text{--}10^9$ year for intermediate mass stars and $>10^9$ year for the average SNIa), as well as the relative numbers of the various nucleosynthesis sites (the so-called Stellar Initial Mass Function, which favors the less massive stars), one may construct models of *Galactic chemical evolution* and compare their results to various observables.



Nucleosynthesis, Stellar, Fig. 4 Solar abundances and corresponding nucleosynthesis processes. The light elements are produced either in the Big Bang or through cosmic ray spallation reactions, while elements heavier

than B are produced in stars, either by fusion reactions (up to the Fe-peak) or by neutron captures (for heavier nuclei)

The success of this scenario lies mainly in its ability to reproduce (with reasonable assumptions) the solar distribution of intermediate mass elements (C to Fe-peak and s-elements). It also explains reasonably well most of the abundance ratios of such elements that are observed on the surfaces of stars of various ages in the Milky Way. Some important failures of our current understanding of stellar nucleosynthesis include the interpretation of observations of abundance ratios in the most metal poor stars of our Galaxy; this may point to significant variations from the “standard picture,” at least as far as the very first generations of massive stars are concerned (they could be more massive, on average, than today’s stars, or have larger rotation velocities). Progress is expected from continuous improvements in the fields of numerical simulations, nuclear data, and spectroscopic observations of abundances in all wavelengths.

The theory of stellar nucleosynthesis is certainly important to exobiology studies, to the extent that life (at least as we currently understand it) requires the presence of various heavy elements

(e.g., oxygen and carbon). However, a quantitative assessment of that requirement is difficult at present. Indeed, the absolute amount of heavy elements (i.e., their abundance with respect to H) that is required for the formation of telluric planets is very poorly constrained, either from theory or from observations. Observations of the [metallicity](#) distribution of stars with giant gaseous planets around them suggest that such stars are more Fe-rich on average than stars of the same spectral type not hosting planets. However, both observations and numerical simulations suggest that such a relation does not hold for telluric planets.

Cross-References

- [Abundances of Elements](#)
- [Asymptotic Giant Branch Star](#)
- [CNO Cycle](#)
- [Metallicity](#)
- [Nuclear Reaction](#)
- [Nuclear Stability](#)

- P-P Chains
- R-Process
- Spallation Reaction
- S-Process
- Stars
- Stellar Evolution
- Supernova

References and Further Reading

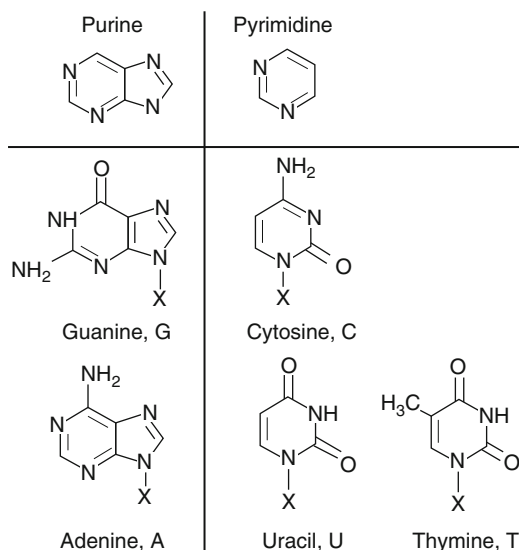
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Nucleotide

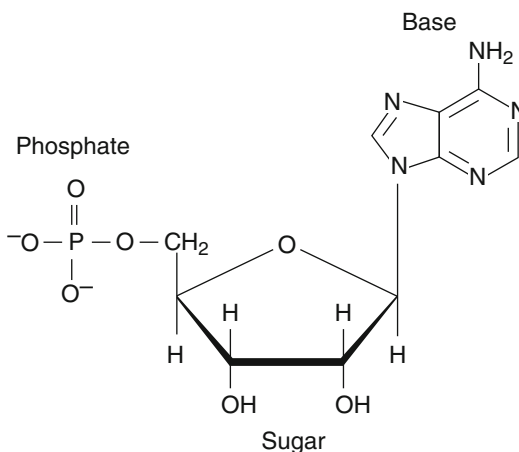
Samanta Pino
Department of Biology and Biotechnologies
“Charles Darwin”, University of Rome
“Sapienza”, Rome, Italy

Definition

Nucleotides are glycosylated derivatives of purine and pyrimidine heterocyclic bases. The purine derivatives are adenine and guanine; the pyrimidine derivatives are ► [cytosine](#), uracil, and thymine (acronyms A,G,C,U,T), as shown in Fig. 1. Thymine occurs only as a deoxyribonucleotide and uracil only as a ribonucleotide. The bases form compounds termed nucleosides, or deoxynucleosides, by linking to a carbohydrate, ► [ribose](#), or 2-deoxyribose, respectively. In the case of a link to D-ribose (or to its 2'-deoxy form), a β -N-glycosidic bond is formed between the N⁹ of a purine or the N¹ of a pyrimidine and the anomeric carbon of the sugar. Nucleosides can



Nucleotide, Fig. 1 The nucleic bases. X = H: base. X = ribose or deoxyribose: nucleoside. X = ribose phosphate: nucleotide



Nucleotide, Fig. 2 The nucleic base adenine bound to D-ribose yields the biologically predominant *anti*-adenosine conformer. In the *syn* conformation, the base is oppositely oriented about the N-glycosidic bond. The monophosphate nucleotide (5'AMP) is shown

be mono-, di-, or tri-phosphorylated yielding the corresponding nucleotides (Fig. 2).

Overview

Phosphorylation can occur at the 2', 3', or 5' positions and cyclic 2'–3' and 3'–5' nucleotides

may form, many of which play important biological functions. These compounds are commonly encountered in biological systems. Numerous alternatives and/or complex derivatives have been described both for the base and the sugar moieties, and for the number of phosphate groups.

Nucleotides are among the most important components of the cell and its metabolism, both in ► [anabolism](#) and catabolism. In addition to being the precursors of nucleic acids, nucleotides are allosteric effectors of enzyme activity, and thus exert numerous controls on enzymatic reactions. The major regulatory functions exerted often pertain to the pathways involved in the syntheses of the nucleotides themselves and to the reactions affording their precursors. Consequently, the pool of nucleotides in the cell is the result of strict anabolic equilibria.

The sophisticated compensatory mechanisms present at every level of the biological kingdoms are explained in evolutionary terms by their double role as providers of energy for phosphate transfer reactions and as genetic building blocks. In fact:

- Purine triphosphate nucleotides exert a particularly relevant role, GTP being an essential component of the translocation step in protein synthesis. (One GTP is used for the addition of one amino acid unit in protein polymerization from a tRNA-amino acid complex whose formation requires one ► [ATP](#).)
- The nucleotides ATP, GTP, CTP, TTP, and UTP are required in equilibrated concentrations for the polymerization of RNA and ► [DNA](#).
- ATP is the predominant energy store for phosphate transfer reactions.
- Nucleotides are constituents of key coenzymes (FAD, coenzyme A, NAD^+ , NADP^+) and are activated intermediates in important biosynthetic reactions, directly or in modified forms (such as S-adenosylmethionine and sugar-coupled nucleotides).
- Many nucleotide derivatives are metabolites which serve as alarmones, i.e., 3'–5' cyclic AMP (cAMP), ppGpp, pppGpp (guanosine tetra- and pentaphosphates), ApppA

(diadenosine tetraphosphate), and ZTP (5-amino 4-imidazole carboxamide riboside 5'-triphosphate). These compounds are in general formed under stress conditions such as the scarcity of a carbon source, amino acids, tRNA, or folate, or in the presence of oxidative stress, favoring alternative or escape metabolic responses.

Cross-References

- [Adenine](#)
- [Anabolism](#)
- [ATP](#)
- [Coenzyme](#)
- [Cytosine](#)
- [Deoxyribose](#)
- [DNA](#)
- [Guanine](#)
- [Heterocycle](#)
- [Nucleic Acid Base](#)
- [Nucleic Acids](#)
- [Nucleoside](#)
- [Pyrimidine Base](#)
- [Ribose](#)
- [RNA](#)
- [Thymine \(T\)](#)
- [Uracil \(Ura\)](#)

Nucleotide Oligomer

- [Oligonucleotide](#)

Nucleus

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

In biology, Nucleus is a double-► [membrane](#) limited space in the eukaryotic ► [cell](#) containing

► [chromosomes](#) and nucleoli. The double membrane is perforated by the nuclear pores that allow the metabolic and genetic connection with the ► [cytoplasm](#). The outermost envelope is continuous with the endoplasmic reticulum. A cell may contain more than one nucleus (e.g., as a result of fusion of several cells – syncytium – or by nuclear division without cell separation, coenocyte). Some protists have two types of nuclei (macro- and micronucleus), and in the arachniophyta, there is the remnant of an ancient nucleus from an engulfed alga (nucleomorph). Albeit the evolutionary origin of the nucleus remains unsolved, several authors suggest that the nucleocytoplasm is the result of an ancient symbiotic association between a bacterial cell and an archaeal cell.

Cross-References

- [Cell](#)
- [Chromosome](#)
- [Cytoplasm](#)
- [Membrane](#)

Nuclide

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Meguro-ku, Tokyo,
 Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry and physics, the term nuclide refers to an atom with a distinct number of protons and neutrons in its nucleus. Nuclides may be stable or unstable. Of the ~3,100 known nuclides, there are ~256 that are so stable that they have never been observed to decay. Unstable nuclides are radioactive and are called radionuclides. Their daughter

decay products are called radiogenic nuclides. Nuclides with the same number of protons (of the same chemical element), but differing numbers of neutrons, are called isotopes.

Cross-References

- [Isotope](#)

Nulling Interferometry

Daniel Rouan
 LESIA, Observatoire Paris-Site de Meudon,
 Meudon, France

Keywords

Coronagraphy · Exoplanet detection

Synonyms

[Dark fringe interferometry](#)

Definition

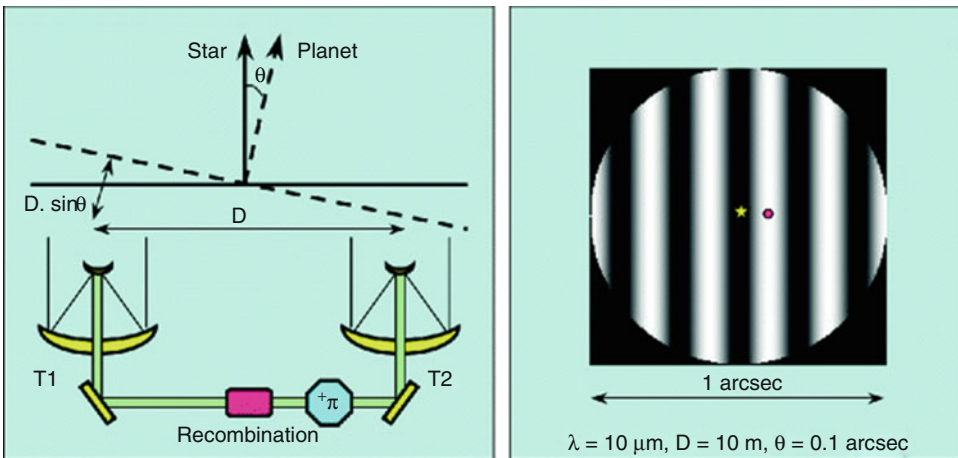
Nulling ► [interferometry](#) is the name given to an instrumental technique based on interferences between several telescopes and aiming at detecting directly exoplanets. The principle is to create a virtual “blind spot” at the exact location of a bright source, a star, in order to reveal the much fainter source, which is a planet orbiting it.

Overview

This technique is a variant of ► [coronagraphy](#) and aims at reducing the extreme contrast of intensity that may exist between two objects very close one to the other, as a star-planet system, but here the solution lies in the interferometric recombination of radiation from several telescopes. Coronagraphy is used primarily in the visible and near infrared: the angular

resolution of a large telescope of say 10 meter diameter corrected by adaptive optics is indeed ten times better than the angle subtended by a planetary orbit of 1 AU at a distance of 10 pc; however, the star-planet contrast is extremely high (typically 10^{10} for the Sun-Earth system). On the other hand, in the mid-infrared ($\lambda = 5\text{--}20\ \mu\text{m}$), this contrast is much more favorable since it is around $10^{6\text{--}5}$. Furthermore, a set of biosignatures, complementary to those potentially observable in the visible, is found in this domain wavelength range: ozone (band at $9.7\ \mu\text{m}$), carbon dioxide, and water vapor. It has been suggested that the simultaneous presence of these three signatures may constitute strong evidence of the presence of life. However, an angular resolution of 0.1 arcsec at $\lambda = 15\ \mu\text{m}$ would require a telescope with a diameter exceeding 30 m which is not presently conceivable in space. The issue of blocking the glare from the star using several small telescopes found a solution with the proposal by Ronald Bracewell of black fringe interferometry (or nulling interferometry). The first step, illustrated in Fig. 1, is to produce interference fringes projected onto the

sky by interferometric recombination of radiation from two telescopes separated by a distance D . The fringes alternatively transmit and block the light, so, if it is arranged that the star is put on a dark fringe and that half the inter-fringe spacing corresponds to the distance separating the star from the putative planet, then the contrast is optimal. In a conventional interferometer, only the bright central fringe, which corresponds to a zero path difference, is common to all wavelengths, while the fringe systems at different wavelengths overlap each other, leading to a global blurring and no actual dark fringe. On the other hand, it is unthinkable to operate a nulling interferometer at a unique wavelength to detect an exoplanet, because the planet's brightness is extremely low and, in addition, the needed spectral information is in a wide wavelength range ($5\text{--}17\ \mu\text{m}$). The powerful idea proposed by Bracewell was to insert an optical phase shift of π , not dependent on the wavelength and thus said to be achromatic, in one arm of the interferometer: the central fringe becomes a dark one but is still common to all wavelengths. Putting the star on this fringe then leads in



Nulling Interferometry, Fig. 1 The principle of nulling interferometry. *Left:* the optical scheme. The light collected by two telescopes pointing in the same direction is recombined after an optical device (in blue) has introduced a phase shift of π on one arm of the recombination path. The resulting interference pattern is characterized by a central fringe, which is dark and not bright as in a

conventional interferometer. *Right:* the fringe pattern. This is in fact a transmission map projected onto the sky. If the star (yellow) is put on the central dark fringe, it is masked, while the fringes' separation can be adjusted (by changing the telescopes separation), so as to correspond to a maximum of transmission at the location of the planet (red)

principle to an efficient rejection of its light without a limitation in spectral band.

Basic Methodology

Designing a nulling interferometer supposes that the beams from two or more large telescopes, separated by a distance of at least 50 m, are recombined coherently and that a special device, called an *achromatic phase shifter*, is introduced in one or several of the beams before recombination. In addition, since the expected brightness of the exoplanet is extremely low, the usually strong thermal background that characterizes observations in the infrared has to be maximally reduced: this means that the telescopes must be at a very low temperature, typically below 100 K. If we add that the atmosphere absorbs a large part of the useful wavelength range, one understands that the space environment is in practice mandatory. Finally, a very precise control of wavefront defects and a precise matching of the interferometer arms are required to achieve the required null depth of 10^{-5} . For all those reasons, it appears that detecting and characterizing exoplanets using nulling interferometry from space is an extremely ambitious goal and will not come to fruition before probably one or two decades.

Note that the measured signal is not only the sum of that from the planet(s) and some residual light from the star. There is also light corresponding to starlight scattered by the dusty disk of micron-sized particles, the remnants of the protoplanetary disk around the star. This disk is a powerful source of emission, the so-called *exozodi* light (derived from the name *zodiacal light* used for the solar system), which may be well above the emission from the planets. To distinguish the fraction of radiation specific to the planet, one can modulate its signal. Bracewell proposed to rotate the interferometer around the line of sight: the image of the planet then travels on the system of fringes projected onto the sky, becoming sometimes visible, sometimes extinct, so that only the signal modulated at the rotation frequency and consistent with the expected pattern reflects the contribution of the planet.

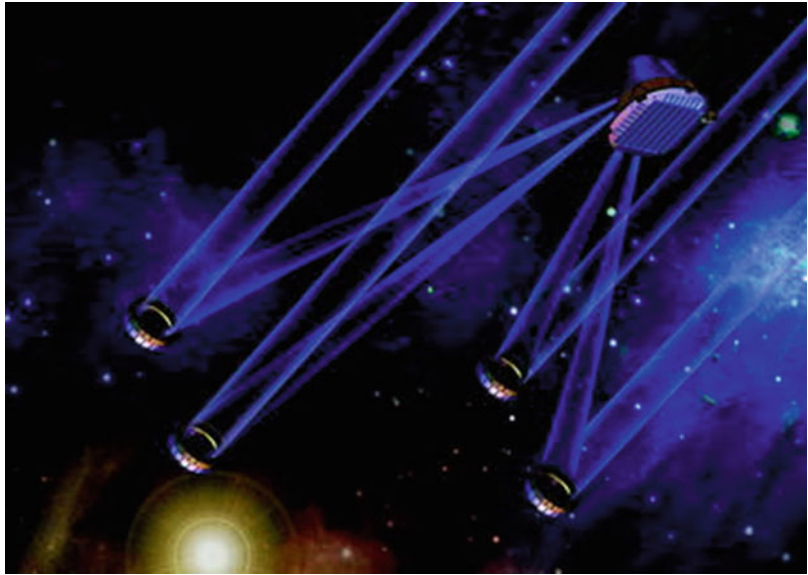
Key Research Findings

Several difficulties emerged when the study of nulling interferometers became more detailed.

- First, the angular size of the star is not infinitely small and photons at the edge of the stellar disk can escape the nulling. They represent only a tiny fraction of the starlight, but the contrast planet/star is so small that they are still predominant and the corresponding noise becomes a limitation. It may be shown that using more than two telescopes can overcome this limit.
- Second is how does one achieve the achromatic phase shift of π . Several solutions with good performances have been demonstrated in the laboratory: sets of transparent blades in each arm of the interferometer with proper materials and thicknesses, use of symmetrical pairs of periscopes, crossing of a focus in one arm, use of specific checkerboard mirrors, use of light dispersion on a deformable mirror, etc.
- Third, the signatures between a planet and the exozodi seen partly edge-on (appearing thus elliptic) must be separated: the modulation by a simple system of fringes would be undistinguishable. With a smart choice of interferometer configuration, one can, however, distinguish the modulated signal produced by a single object from the one due to a centrosymmetric structure such as the exozodi.
- Fourth, the cancelation of the stellar flux must have great temporal stability. This is, perhaps, the most serious difficulty: any deviation, even very small, from the π phase shift produces very large fluctuations in the starlight leakage, introducing an extra noise. This point is subject to particular attention in the laboratory experiments.
- Fifth, the free-flying interferometer concept should be evaluated. A nulling interferometer aiming at exoplanet detection is meaningful only in space, but the size of the baseline, larger than 30 m, makes unbelievable a system where telescopes would be physically connected. The concept which is being studied

Nulling Interferometry,

Fig. 2 Artist's view of the most recent concept of the Darwin project studied by ESA and NASA. The arrangement of the four telescopes in an X pattern allows modulation in a special way of the light from the planet, so that it may be distinguished from the light emitted by a cloud of small particles (the exozodiacal disk) in the plane of the planetary system; this cloud is believed to surpass the planet's brightness by a large factor



is one of several free-flying crafts, each carrying a telescope, plus one carrying the recombination station, with distances between them made constant through some servo-system using micro jet engines and micrometric distance measurement. The Darwin mission concept is based on this idea (Fig. 2).

Applications

The main goal of this technique, which will take many years to reach an appropriate technology readiness level, is the detection and characterization of objects analogous to the Earth, that is, small exoplanets in the ► [habitable zone](#), and ultimately to detect the presence of life. The Darwin mission (Fig. 2) is the emblematic project, submitted in 2009 to space agencies but not selected, which illustrates the best state of the art in terms of specific studies carried out over several years. The present concept relies on four cryogenic telescopes of 1 m diameter, arranged on an X-shaped pattern, and a recombining station which is at the common focus of the telescopes, avoiding thus the use of the complex delay lines usually found in interferometers. The distance between telescopes can be changed and a clever

phase modulation allows astronomers to distinguish the contribution of a planet from the one of exozodi.

Another goal that appeared more recently is the possibility to use a nulling interferometer from the ground to detect the exozodi in several stars, this knowledge being important for preparing future space missions. Several experiments have been developed in that direction at the Keck and the LBT telescopes in the USA.

Future Directions

During the previous decade, a vigorous program of research and development has been put in place, especially in the USA and in Europe, in order to find the most appropriate solutions to the various technical problems listed above. For several of them, the performance level reached in the laboratory proves that there should be no definitive technical blockade; however, it must be clear that the road will be a long one before a nulling interferometer mission can be actually launched; this may be the reason why today, nulling interferometry is no longer considered by space agencies as a potential mission for their midterm program.

Cross-References

- [Coronagraphy](#)
- [Darwin's Conception of the Origins of Life](#)
- [Exoplanet, Detection, and Characterization](#)
- [Exozodiacal Light](#)
- [Interferometry](#)
- [Space Environment](#)

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Numerical Ages of Rocks

- [Absolute and Relative Ages](#)

Numerical Taxonomy

- [Phenetics](#)

Nutrient Cycling

Silvia E. Newell¹, Steven W. Wilhelm² and Mark J. McCarthy¹

¹Wright State University, Dayton, OH, USA

²University of Tennessee Knoxville, Knoxville, TN, USA

Keywords

Carbon · Nitrogen · Phosphorus · Iron · Microbial loop · Biological pump · Viral shunt

Abbreviations

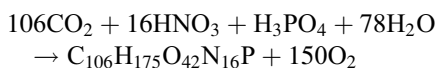
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DON	Dissolved organic nitrogen
POM	Particulate organic matter

Definition

Nutrients required for life (carbon, nitrogen, phosphorus, and certain trace metals, such as iron, zinc, and cobalt) are cycled throughout the ocean as they are incorporated into biomass, then released and recycled upon cell lysis through the microbial loop, or consumed and transferred to higher trophic levels, until delivered as fecal matter to the deep ocean through the biological pump.

Overview

Most biological production occurs in the surface ocean within the photic zone (where light reaches to about 100 m) and is limited by the availability of light and nutrients. Single-celled phytoplankton fix carbon through photosynthesis, forming the basis of the marine food web. In one commonly used example, photosynthesis and associated reactions can combine water, inorganic carbon (carbon dioxide; CO₂), nitrogen (nitrate; NO₃[−]), and phosphorus (phosphate; PO₄^{3−}) to form organic matter and release oxygen, in the following proportions (Sarmiento and Gruber 2006):



Mineralization (i.e., respiration, remineralization, oxidation of organic matter, etc.) is the opposite of this reaction, using oxygen in seawater as an electron acceptor to decompose organic matter and produce inorganic carbon (C), nitrogen (N), and phosphorus (P) while releasing energy. The stoichiometric relationship of C:N:P in phytoplankton of 106:16:1 is the “Redfield ratio” (Redfield 1958), but more recent research showed that this relationship varies based on phytoplankton community structure and available nutrients (Canfield et al. 2005).

Basic Methodology

Nutrients and trace metals in the ocean are studied from samples typically collected from research vessels, often using a rosette of bottles that trap water from specified depths. Concentrations are measured using nutrient analyzers and ICP-MS (inductively coupled plasma mass spectrometry). Productivity (carbon fixation rates) can be directly measured using CO_2/O_2 consumption or production. Rates of transfer from one form to another are typically determined using isotopic tracers (stable isotopes such as ^{13}C or ^{15}N or radioisotopes such as ^{14}C) or variation in natural abundance of stable isotopes measured using isotope ratio mass spectrometry (IRMS). Mathematical models are used to scale results. Biogeochemical transformation rate measurements are often paired with functional gene abundance or transcriptomes to link structure and function.

Key Research Findings

Carbon

The C in living biomass represents a small fraction of the total C inventory on Earth (0.002%; Canfield et al. 2005). The majority of C in the ocean is inorganic or within the DOM. Carbon enters the atmosphere as CO_2 and the ocean as HCO_3^- . Atmospheric CO_2 equilibrates with the

carbonate system of the ocean (Sarmiento and Gruber 2006), coupling these two pools.

The ocean is a net sink for atmospheric C ($\sim 2.6 \pm 0.5 \text{ GtC yr}^{-1}$; Le Quéré et al. 2015) through photosynthesis by phytoplankton. Abundant eukaryotic phytoplankton include diatoms (Bacillariophyceae) and coccolithophorids (Prymnesiophyceae), which often dominate coastal and upwelling areas. Diatoms are estimated to be responsible for $\sim 20\%$ of annual global CO_2 fixation (Matsuda et al. 2017). Prokaryotic picoplankton, specifically *Prochlorococcus* and *Synechococcus*, are the dominant primary producers in low-nutrient, open-ocean regimes (Moore et al. 2002). Zooplankton graze on phytoplankton, and their fecal pellets aggregate and fall to the ocean bottom. Viruses lyse phytoplankton and drive organic C from the particulate to dissolved pools via the *viral shunt* (Wilhelm and Suttle 1999). Heterotrophic bacteria remineralize fecal pellets, as well as other POM and DOM, to bioavailable inorganic nutrients (Ducklow et al. 2001). To complete the *biological pump*, respiration by consumers in surface waters converts organic C back to CO_2 and releases it to the atmosphere (Ducklow et al. 2001). Below 1000 m depth, dissolved organic C (DOC) is respired back to CO_2 and remains in the deep oceans, causing CO_2 enrichment. CO_2 can remain in the deep ocean for $>1,000$ years before it returns to the surface. Without biological production, atmospheric CO_2 would rise by >200 ppm (Sarmiento and Gruber 2006).

DOM is the largest constituent of the detritus pool in the ocean. Phytoplankton exudates are probably the most important DOM source in the photic zone (Canfield et al. 2005). Ogawa and Tanoue (2003) estimate that the marine DOC reservoir is 700 Gt, comprised of 650 Gt of refractory and 50 Gt of semi-labile DOC, roughly equivalent to the size of the atmospheric CO_2 pool (750 Gt). DOM dynamics are poorly understood due to the difficulty in characterizing complex organic compounds. Less than 20% of DOM has been grouped into major biological macromolecules, such as carbohydrates, amino acids, and lipids, while recalcitrant humic compounds comprise 15–25% of marine DOM (Canfield et al. 2005).

Heterotrophic microbes are the primary consumers of marine DOC and preferentially use specific components of the bulk DOC pool (Sarmiento et al. 2013). In the *microbial loop* (Azam et al. 1983), a large fraction of primary productivity is released as DOM and used by microbes; predatory protists consume bacteria and are then grazed by larger zooplankton or remineralize DOM to inorganic nutrients, which are assimilated by phytoplankton, then grazed by microzooplankton, and so on. However, microbes may alter the chemical composition of DOM, resulting in changing C:N:P ratios (and other elements), creating increasingly recalcitrant DOM via the *microbial C pump* (Jiao et al. 2011). The average turnover time for oceanic DOM is 30–300 years, but turnover time for labile DOM in the euphotic zone is <10 years, while recalcitrant DOM persists for 4000–8000 years in the deep ocean (Jiao et al. 2011; Canfield et al. 2005). Thus, production of recalcitrant DOM (within the microbial loop) is an important mechanism for long-term marine sequestration of fixed atmospheric C.

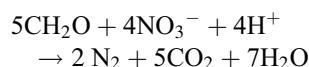
Nitrogen

Nitrogen is the limiting nutrient in much of the surface ocean, although lack of adequate iron (Martin and Fitzwater 1988) and light (Mitchell et al. 1991) also limits primary productivity in some regions. Nitrogen species with a range of oxidation states are found in the ocean, from +5 (NO_3^-) to −3 (NH_4^+). The most abundant species, dinitrogen (N_2) gas, saturates the water column and is not “fixed” or bioavailable, except to diazotrophs. Because bioavailable N usually limits oceanic primary production, N availability also controls CO_2 removal from the atmosphere. During diazotrophy (N fixation), N_2 is converted to NH_4^+ and incorporated into biomass, which can be remineralized to NH_4^+ during decomposition (Capone and Carpenter 1982). NH_4^+ may then be assimilated by primary producers or converted to NO_2^- , and then NO_3^- , via nitrification (Ward 2008). Dissimilatory NO_3^- reduction to NH_4^+ (DNRA) converts NO_3^- to NO_2^- , then to NH_4^+ (Tiedje 1988). Anammox (anaerobic NH_4^+ oxidation) transforms NH_4^+ and NO_2^- to N_2 gas

(Mulder et al. 1995). In canonical denitrification, NO_3^- is first converted to NO_2^- , then to NO and N_2O , and finally to N_2 gas (Zumft 1997). DNRA, anammox, and denitrification occur in anaerobic areas of water column oxygen minimum zones (OMZs) or anoxic sediments.

The nitrification pathway converts ammonia to NO_2^- and, subsequently, NO_3^- via two separate processes performed by mutually exclusive groups of organisms (ammonia oxidizers and NO_2^- oxidizers) or within a single organism (comammox; Pinto et al. 2016). The ammonia (NH_3)-oxidizing archaea (AOA) are the dominant group of NH_3 oxidizers in the ocean and are primarily comprised of *Crenarchaeota* or *Thaumarchaeota* (Ward 2008). Taxonomically, the NH_3 -oxidizing bacteria (AOB) fall into two proteobacterial classes, either the *Betaproteobacteria*, including the genera *Nitrosomonas*, *Nitrospira*, and *Nitrosovibrio*, or the *Gammaproteobacteria*, including the genera *Nitrosococcus* (Ward 2008). NO_2^- oxidizers are primarily *Nitrospinae* and *Nitrococcus* (Hofer 2017). At oxic-anoxic boundaries, coupled nitrification-denitrification is the “opposite” of N_2 fixation in that bioavailable N is removed as N_2 , and the balance between these pathways controls the inventory of fixed N in the ocean.

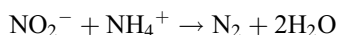
In the absence of oxygen, denitrifying bacteria use NO_3^- as an electron acceptor for the oxidation of organic matter:



Denitrification occurs in sediments and anoxic parts of the water column (Devol 2008), although a source of organic carbon is also required. Canonical denitrification is the heterotrophic, respiratory, stepwise reduction from NO_3^- to N_2 , in which the penultimate step is the production of N_2O , a potent greenhouse gas that can also be released. Denitrifiers encompass a wide diversity of organisms, from subgroups of proteobacteria to archaea (Zumft 1997) to foraminifera (Risgaard-Petersen et al. 2006).

Anammox, posited for decades, was confirmed in a Dutch wastewater treatment plant (Mulder

et al. 1995). Anammox is a useful pathway for wastewater treatment because it removes NO_2^- and NH_4^+ in equal proportions under anoxic conditions to produce N_2 :



Anammox bacteria belong only to the phylum *Planctomycetes*, and four genera have been identified: *Candidatus* Kuenenia, *Candidatus* Brocadia, *Candidatus* Anammoxoglobus, and *Candidatus* Scalindua (review by Harhangi et al. 2012). The anammox bacteria are slow-growing autotrophs, and recent measurements of anammox rates have shown it to be an important N loss pathway in the ocean (Devol 2008), contributing ~28% of total N loss (Babbin et al. 2014). The only clade of anammox bacteria identified in the Arabian Sea and many other marine environments, however, is *Scalindua* (Harhangi et al. 2012), suggesting that anammox diversity is limited in the marine environment.

Most water column N loss occurs in the three major OMZs, which together account for less than half of total fixed N loss in the ocean (Devol 2008). The three major OMZs are in the eastern tropical north Pacific off the coast of Mexico (the largest OMZ by area), the eastern tropical south Pacific off of the coasts of Peru and Chile, and the northern Arabian Sea (the largest OMZ by volume).

Phosphorus

Phosphorus is also a critical element for life, required for nucleic acids (DNA and RNA), energy storage and transfer (NADPH and ATP), and cell membranes (phospholipids). The P cycle differs from the N and C cycles in that it has no gaseous phase and is not involved in redox cycling. While P has four oxidation states (−3, 0, +3, +5), only the +5 state is stable under natural conditions in aqueous solutions. The main source of P to the oceans is riverine runoff from terrestrial weathering (Benitez-Nelson 2000), as dissolved PO_4^{3-} and organic forms. Upwelling, vertical advection, and eddy diffusion also supply P (and N) from the deep ocean and can fuel primary production in the euphotic zone. The only natural

P removal mechanism from the oceans is burial within marine sediments.

A deficit for N (compared to Redfield 16:1) is often observed in the subsurface supply of dissolved N and P, and cellular C:N is more constrained than the C:P (and hence N:P) ratio (Sarmiento and Gruber 2006). Thus, N is typically the limiting nutrient in the open ocean. However, P is generally considered the ultimate limiting nutrient for primary productivity on geological timescales (Poulton 2017), driven by permanent burial and terrestrial weathering rates. Under anoxic conditions, surface sediments can sequester P through binding to Fe(III), forming an “iron cap.” However, if weathering rates increase, thus increasing the oceanic P inventory, the N inventory could be increased via promotion of N fixation.

Low PO_4^{3-} (<0.1 μM) and elevated dissolved organic P (DOP; >0.2 μM) concentrations are typically observed in the euphotic zone, but below this depth, PO_4^{3-} and DOP concentrations reverse, with gradually increasing PO_4^{3-} and decreasing DOP to 1000 m (>3 μM DIP and <0.1 μM DOP; Loh and Bauer 2000). Phytoplankton uptake and assimilation in the photic zone, switching to respiration and remineralization with depth, drives this general pattern. When PO_4^{3-} concentrations are low, microbes exude extracellular enzymes to break down more complex, organically bound P to PO_4^{3-} (Goldammer et al. 2011). Typically, less than 10% of assimilated P is exported from the euphotic zone (Karl and Bjorkman 2002).

Trace Elements

Biological life requires a multitude of other elements at low concentrations (“trace” elements), including metals, such as zinc (Zn), cobalt (Co), and iron (Fe). Of these, Fe is of particular interest in that its chemistry results in free Fe becoming biologically unavailable in seawater, leading to Fe limitation of primary production for up to 25% of global ocean surface waters (de Baar et al. 2005). Observations and experiments have confirmed this observation on multiple scales (Martin and Fitzwater 1988; Boyd and Ellwood 2010). Although the requirement for Fe across

biological life remains constant, cellular quotas can vary by an order of magnitude, depending on Fe availability (Wilhelm et al. 2013).

The marine Fe cycle has been studied extensively for decades, focusing primarily on the role of Fe in limiting primary production (Boyd and Ellwood 2010) and the roles of microbial communities (Strzepek et al. 2005) and viruses (Poorvin et al. 2004) in Fe mineralization. Iron is commonly chelated to organic compounds (*ligands*) in seawater (de Baar et al. 2005), and this metal-ligand interaction may control the biological availability of Fe to the plankton community.

Future Directions

Understanding how marine organisms interact with their environment (i.e., nutrients) and in turn how competition for these nutrients drives different populations remains an overarching challenge for the marine community. All of this is couched within the background of changing climate – both temperature and oceanic pH are likely to alter the relationships nutrients and organisms have, and these remain a moving target.

Cross-References

- ▶ Anaerobic Respiration
- ▶ Archaea
- ▶ Bacteria
- ▶ Biogeochemical Cycles
- ▶ Carbon
- ▶ Carbon Cycle, Biological
- ▶ Carbon Dioxide
- ▶ Carbon Isotopes in the Solar System
- ▶ Carbon Source
- ▶ Cyanobacteria
- ▶ Cyanobacteria, Diversity and Evolution of
- ▶ Deep-Sea Microbiology
- ▶ Deep Subsurface Microbiology
- ▶ Denitrification
- ▶ Diazotrophy

- ▶ Dinitrogen
- ▶ Geomicrobiology
- ▶ Iron Cycle
- ▶ Iron Isotopes
- ▶ Iron Oxidation
- ▶ Iron Oxides, Hydroxides, and Oxyhydroxides
- ▶ Iron Reduction
- ▶ Metatranscriptome
- ▶ Metavirome
- ▶ Methane
- ▶ Methane Oxidation
- ▶ Methanogens
- ▶ Micronutrients
- ▶ Microorganism
- ▶ Nitrate Reduction
- ▶ Nitrification
- ▶ Nitrogen
- ▶ Nitrogen Cycle, Biological
- ▶ Nitrogen Fixation
- ▶ Nitrogen Isotopes
- ▶ Oceans, Chemical Evolution of
- ▶ Organic Refractory Matter
- ▶ Phosphates
- ▶ Prebiotic Chemistry
- ▶ Proteobacteria
- ▶ Respiration
- ▶ Sulfate Reducers
- ▶ Sulfate Reduction
- ▶ Sulfur Cycle
- ▶ Trace Elements
- ▶ Trace Metals

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Nutrients

► Macronutrient

Nuvvuagittuq Greenstone Belt

Jonathan O'Neil

University of Ottawa, Ottawa, Canada

Keywords

Greenstone belt · Hadean · Eoarchean · Primitive crust · early Earth · Volcanic rocks · Banded iron formation · Early life · Superior Province

Acronyms

NGB

Synonyms

Nuvvuagittuq Supracrustal Belt; Porpoise Cove Greenstone Belt

Definition

The Nuvvuagittuq greenstone belt is ~10 km² volcano-sedimentary sequence located in North-eastern Canada. The belt is mostly composed of mafic metavolcanic rocks comprising chemical sedimentary rocks that are interpreted to have recorded traces of early life. These supracrustal rocks are at least 3.8 billion years old, but deficit in ¹⁴²Nd compared to the modern terrestrial Nd standard in the metavolcanic rocks suggests they were formed 4.3 billion years ago. This would make them the oldest rocks known on the Earth and hosting the earliest evidence of life on our planet.

History

The NGB was first studied in the 1960s (Lee 1965), but it is only since the early 2000s that it

became a region of interest for early Earth and early life research, with the discovery of its ancient age. The first geochronological data showing that the belt is the oldest component of the Northeastern Superior Province was acquired during an MSc thesis focusing on the structural investigation of the Nuvvuagittuq area (Nadeau 2003), in collaboration with the Geological Survey of the Province of Quebec (Ministère de l'Énergie et des Ressources naturelles du Québec), conducting regional scale mapping of the Northeastern Superior Province of Canada (Simard et al. 2003; Simard 2008). Zircons from a thin felsic trondhjemitic band within the NGB supracrustal rocks yielded a U-Pb upper intercept age of 3825 ± 16 Ma (David et al. 2003; Simard et al. 2003). Similar Eoarchean U-Pb ages on zircons from the same lithology were subsequently obtained (Cates and Mojzsis 2007; David et al. 2009; Darling et al. 2013; O'Neil et al. 2013; Augland and David 2015), confirming the age of >3.75 Ga for the NGB. Because the NGB mostly includes mafic rocks that rarely contain the zircons used for conventional U-Pb ages, the age of the NGB supracrustal rocks was essentially constrained from the rare zircon-bearing trondhjemitic bands, providing a minimum age given their intrusive relationship to the mafic metavolcanic rocks of the NGB. The discovery of ¹⁴²Nd deficits compared to the modern terrestrial standard and the correlation between the ¹⁴²Nd/¹⁴⁴Nd and Sm/Nd ratios of the metavolcanic rocks and co-genetic ultramafic cumulates has subsequently been used to suggest an even older Hadean age of ~4.3 Ga for the NGB (O'Neil et al. 2008). This would make the NGB metavolcanic rocks the oldest rocks preserved on Earth. The interpretation of the ¹⁴²Nd isotopic composition of the NGB rocks and their Hadean age is not unanimously accepted in the scientific community, but all acknowledge that it is at least ~3.8 Ga. Given the existence of only a handful of areas containing rocks older than 3.7 Ga, and the possibility that the NGB represents the only known remnant of Hadean oceanic crust, it has become a region of high interest for early Earth

research and to study the origin of life on Earth. Dodd et al. (2017) have in fact proposed that the NGB banded iron formation hosts the earliest evidence of biological activity on Earth.

Overview

The Nuvvuagittuq greenstone belt (NGB) is located in the Northeastern Superior Province of Canada, approximately 35 km south of the Inuit municipality of Inukjuak on the east coast of Hudson Bay. The Nuvvuagittuq greenstone belt covers an area of ~10 km² and is composed of a volcano-sedimentary sequence at least Eoarchean in age (Cates and Mojzsis 2007), comprising rocks that may have been formed 4.3 billion years ago (Ga), which would make them the oldest rocks known on the Earth (O'Neil et al. 2008, 2012). The geochemistry of the Nuvvuagittuq metavolcanic rocks suggests that they represent a remnant of hydrothermally altered oceanic crust (O'Neil et al. 2019). Hematite structures found in the Nuvvuagittuq banded iron formations are interpreted to represent the oldest trace of biological activity of Earth (Dodd et al. 2017), pushing back the appearance of life to at least another 100 million years and perhaps more than 500 million years.

The Geology of the Nuvvuagittuq Greenstone Belt

The Nuvvuagittuq greenstone belt has experienced multiple phases of deformation and is now isoclinally folded into a north plunging synform and then refolded into an open south-plunging antiform (O'Neil et al. 2007; David et al. 2009). Most of the belt has been metamorphosed to at least upper amphibolite facies conditions (O'Neil et al. 2007; Cates and Mojzsis 2009), but greenschist facies metamorphic assemblages of the metavolcanic rocks in the southwestern and southeastern corners of the NGB suggest that some areas may not have reached the same high temperature as the rest of the NGB or that they represent retrogressive assemblages (O'Neil et al. 2011, 2019). These lower grade rocks locally preserve deformed pillow lava structures (O'Neil et al. 2011), consistent with their

formation in an oceanic environment. The NGB is directly surrounded and intruded by Eoarchean to Paleoproterozoic felsic rocks from the tonalite-trondhjemite-granodiorite (TTG) series and intruded by late Neoproterozoic granitic pegmatites (Cates and Mojzsis 2007, David et al. 2009; O'Neil et al. 2013).

The dominant lithology of the NGB is a heterogeneous amphibolite composed of variable proportions of cummingtonite + biotite + quartz, ± plagioclase ± garnet ± anthophyllite ± cordierite. Despite the mineralogical variations, these mafic metavolcanic rocks share recognizable petrological and geochemical characteristics and are grouped into a lithostratigraphic unit called the Ujaraaluk unit (O'Neil et al. 2011, 2019), formerly called “faux-amphibolite” (O'Neil et al. 2007). The proportion of cummingtonite and biotite in the Ujaraaluk unit varies widely, with lithologies ranging from amphibolite composed almost entirely of cummingtonite, to garnet-biotite schist. Variations in the proportions of cummingtonite and biotite also occur on a centimeter-scale. The amount of garnet is also highly variable ranging from garnet-free assemblages to rocks containing a significant proportion of garnet (up to ~15%). Locally, the Ujaraaluk unit is characterized by a Mg-rich and Ca-poor assemblage of cordierite, anthophyllite, and biotite. This cordierite-anthophyllite assemblage is interpreted to result from hydrothermal seawater alteration of oceanic crust (O'Neil et al. 2019).

The Ujaraaluk unit is generally basaltic to basaltic andesite in composition but can be divided into high-Ti and low-Ti units, following distinct fractionation trends for their incompatible trace elements. The low-Ti Ujaraaluk is further subdivided into depleted low-Ti Ujaraaluk and enriched low-Ti Ujaraaluk, according to relative concentrations in incompatible trace elements. The three Ujaraaluk groups display distinct Al/Ti ratios and characteristically different incompatible trace element profiles. They also follow a chemostratigraphy within the NGB with the high-Ti Ujaraaluk at the base of the sequence, the depleted low-Ti Ujaraaluk stratigraphically above the high-Ti group, and the enriched low-Ti Ujaraaluk group at the very top of the sequence (O'Neil et al. 2011).

The boundary between the high-Ti and a low-Ti Ujaraaluk unit is marked by the occurrence of a banded iron formation (BIF) 5–30 meters in width that can be traced continuously along the western limb of the belt and discontinuously along the eastern limb. The BIF is essentially a finely laminated quartz + magnetite + grunerite rock. A large silica-formation occurs in the eastern limb of the belt that reaches 100 meters in width. It is composed almost entirely of massive recrystallized quartz with minor disseminated pyrite. At the southern-most edge of this limb, the silica-formation grades into BIF, suggesting that it may be a silica-rich facies of the BIF. Within the lower metamorphic grade assemblages, the BIF occurs as a laminated jasper BIF sometimes associated with ferruginous carbonate rocks (Dodd et al. 2017). The jasper BIF and ferruginous carbonate rocks include microscopic structures such as concentric mineral rosettes, coarse-grained sub-millimeter granules and fine microscopic laminations, ribbons, tubes, and filaments of nanoscopic hematite in chert, which have been interpreted as likely derived from an ancient microbial ecosystem (Dodd et al. 2017). This would constitute one of the earliest, if not the earliest, evidence of biological activity on Earth.

Geochronology of the Nuvvuagittuq Greenstone Belt

The age of the NGB has been highly debated. The only scientific consensus is that the NGB is at least ~3.8 Ga, evidenced by U-Pb ages on zircons from thin trondhjemitic bands intruding the Ujaraaluk unit (Cates and Mojzsis 2007, David et al. 2009, Darling et al. 2013; O'Neil et al. 2013). A maximum age of 3780 Ma has been proposed for the NGB, based on U-Pb ages on a few zircons from rocks interpreted as detrital fuchsite-bearing quartzite, which would impose a maximum age of deposition for the volcano-sedimentary package (Cates et al. 2013). The fuchsitic quartzites have however been interpreted as highly metasomatized felsic intrusive rocks by Darling et al. (2013) which would thus place only a minimum age on the NGB mafic volcanic rocks.

Rocks from the Ujaraaluk unit display a wide variation in $^{142}\text{Nd}/^{144}\text{Nd}$ ratios (O'Neil et al. 2008, 2012). Given the half-life of 103 million years of ^{146}Sm , variations in ^{142}Nd can only be produced by Sm-Nd fractionation prior to ~4.0 Ga. The correlation between Sm/Nd and $^{142}\text{Nd}/^{144}\text{Nd}$ ratios measured in all geochemical groups of the Ujaraaluk unit and co-genetic ultramafic cumulates would be consistent with an age of ~4.3 Ga for these rocks (O'Neil et al. 2008, 2012, 2019), which would make them the oldest known rocks on the Earth. This interpretation for the variation in $^{142}\text{Nd}/^{144}\text{Nd}$ ratios has been challenged and rather attributed to mixing with an enriched Hadean source (Roth et al. 2013; Caro et al. 2017), but a ^{147}Sm - ^{143}Nd whole-rock isochron obtained on differentiated gabbroic sills intruding the Ujaraaluk unit and giving an age of 4.1 Ga would support an Hadean age for the NGB (O'Neil et al. 2012, 2019).

Significance for Early Earth Environments

Rocks from the Ujaraaluk unit generally have a mafic composition, and, prior to metamorphism, would range from basalt to andesite in terms of their silica contents ($\text{SiO}_2 = 42\text{--}67$ wt.%). The high-Ti Ujaraaluk unit at the base of the NGB has geochemical features that resemble those of tholeiitic volcanic suites, whereas the low-Ti Ujaraaluk rocks at the top of the sequence exhibits a wider range of composition from basalt to andesite and is characterized by a chemical composition similar to modern boninites and calc-alkaline volcanic suites (Turner et al. 2014; O'Neil et al. 2016). This succession of volcanic rocks displaying tholeiitic, to boninitic, to calc-alkaline affinities, is reminiscent of supra-subduction environments, which suggests that the NGB metavolcanic rocks may have been formed in subduction initiation settings in the Eoarchean or perhaps in the Hadean (Turner et al. 2014; O'Neil et al. 2016).

The geochemistry of the cordierite-anthophyllite assemblage of the Ujaraaluk unit, with high Mg and low Ca contents, is consistent with its protolith being basaltic to andesitic volcanic rocks hydrothermally altered by seawater, similar to volcanogenic massive sulfide deposits

hydrothermal environments (O'Neil et al. 2019). The presence of a potentially 4.3 Ga banded iron formation within the Nuvvuagittuq greenstone belt could have a significant impact on the study of the timing of the origin of life on Earth. Although the causes of Fe precipitation throughout geologic time are poorly understood, the BIF that occurs in Archean greenstone belts must have been precipitated under anoxic conditions. It has been suggested that Fe^{2+} can be directly oxidized by microbial activity under anaerobic conditions (Lovley et al. 1987; Widdel et al. 1993). Konhauser et al. (2002) have even proposed that Archean BIF could have been precipitated by the activity of anoxic bacteria. However, establishing the chemical sedimentary origin for a rock is a prerequisite to demonstrating potential biological activity involved in its formation. The trace element chemistry of the NGB BIF is consistent with a marine exhalite origin with a distinct seawater signature (O'Neil et al. 2007). The NGB BIF has heavier Fe isotopic compositions than the surrounding igneous lithologies (Dauphas et al. 2007; O'Neil et al. 2007), a feature that is consistent with an origin as a chemical precipitate. The sedimentary origin for the NGB BIF is also supported by the mass-independent fractionation of sulfur isotopes (Thomassot et al. 2015) and by their REE + Y geochemical compositions, displaying light rare earth element depletion relative to heavy rare earth element, with La and Eu positive anomalies (Mloszewska et al. 2012), typical of Archean BIF precipitated from seawater (Bolhar et al. 2004). High $\delta^{18}\text{O}$ (8–12‰) and $\Delta^{17}\text{O}$ (−0.02 to −0.05) values measured in the NGB metavolcanic rocks support the fact that they represent a section of ancient oceanic crust hydrothermally altered at low-temperature by seawater and perhaps accompanied by silicification between 50–150 °C (Bindeman and O'Neil 2022). The NGB BIF thus represents the ideal candidate to address the controversial question of the timing of the origin of life on Earth. The NGB jasper BIF includes micrometer-scale hematite tubes and filaments with morphologies and mineral assemblages similar to those formed by of microorganisms in modern hydrothermal vent precipitates (Dodd et al. 2017). The comparison between the features observed in the NGB BIF and analogous microfossils in younger rocks suggests that

biological activity in submarine-hydrothermal environments occurred at least at 3.8 Ga, and perhaps as early as 4.3 Ga.

Key Research Findings

The mafic metavolcanic rocks of the Nuvvuagittuq greenstone belt are interpreted to represent a remnant of hydrothermally altered oceanic crust, at least Eoarchean in age and possibly as old as 4.3 Ga, which would make them the oldest rocks discovered to date on Earth. The geochemistry of these rocks suggests they represent volcanic rocks formed in a subduction initiation setting. The geochemical and isotopic composition of the banded iron formation is consistent with sediments precipitated from seawater. The microscopic structures preserved in the jasper banded iron formation potentially suggest microbial activity in the Hadean.

Cross-References

- [Archaean Traces of Life](#)
- [Banded Iron Formation](#)
- [Continental Crust](#)
- [Earth, Formation, and Early Evolution](#)
- [Hadean](#)
- [Radioactivity](#)
- [Radiogenic Isotopes](#)

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Nuvvuagittuq Supracrustal Belt

► Nuvvuagittuq Greenstone Belt

O

O/OREOS

► [O/OREOS Nanosatellite](#)

O/OREOS Nanosatellite

Antonio J. Ricco¹ and Pascale Ehrenfreund²

¹NASA Ames Research Center, on Assignment from Stanford University, Moffett Field, CA, USA

²Space Policy Institute, George Washington University, Washington, DC, USA

Keywords

Nanosatellite · Cubesat · Space exposure experiment · Microgravity · Space radiation · *Bacillus subtilis* · Germination · UV-visible spectroscopy · Space biology · SEVO · SESLO · Photochemistry · Photodegradation of organics · Polycyclic aromatic hydrocarbon · Metalloporphyrin · Space microenvironment

Synonyms

[O/OREOS](#); [O/OREOS satellite](#)

Definition

The O/OREOS (Organism/Organic Exposure to Orbital Stresses) nanosatellite is a 5.5-kg,

10 × 10 × 34 cm free-flying autonomous spacecraft that comprises a control, power, and communications “bus” that supports two separate “1U” (10-cm cube) experimental astrobiology payloads. The 3U O/OREOS spacecraft launched as a secondary payload in November 2010 to a 650-km circular orbit and successfully completed its primary mission 6 months later; it continued to function in mid 2015. Data were telemetered to Earth throughout the mission from both its Space Environment Viability of Organics (SEVO) and Space Environment Survivability of Living Organisms (SESLO) payloads.

History

Development of the O/OREOS nanosatellite was initiated in August 2008 at the NASA Ames Research Center under the auspices of the NASA Astrobiology Small Payloads program as a demonstration mission. O/OREOS was successfully launched as a secondary payload on the US Air Force’s Space Test Program (STP) S26 Mission aboard a Minotaur IV rocket from Kodiak Island, Alaska, USA on November 19, 2010, to a 650-km, 72°-inclination circular orbit, with a period of 98 min. O/OREOS completed its primary 6-month mission successfully in May 2011. From November 2010 through August 2012, science data were telemetered to Earth from both of its experimental astrobiology payloads. Health-and-status data were also telemetered from the

spacecraft bus beginning in November 2010, continuing until the time of this writing (May 2015). On its outer surfaces, O/OREOS had received an estimated radiation exposure in excess of 15 kGy (15 kilogray) over the course of nearly 3 years in outer space; this is attenuated 100- to 1000-fold as a function of location within the satellite. Due in part to the additional drag provided by a novel “nanokite” deorbit mechanism, the O/OREOS nanosatellite is anticipated to re-enter Earth’s atmosphere and disintegrate in approximately 2032.

Overview

The O/OREOS experiments represent the first autonomous astrobiology and living biology studies conducted above the thermosphere in a cubesat/nanosatellite-class spacecraft.

The 1U SEVO payload incorporates a compact ultraviolet-visible-near-infrared (UV-vis-NIR) spectrometer, with the Sun as light source, and a 24-cell sample carousel housing four classes of vacuum-deposited organic thin film: ► [polycyclic aromatic hydrocarbon](#), ► [amino acid](#), metalloporphyrin, and quinone. These films are enclosed in hermetically sealed sample cells in one of four astrobiologically relevant microenvironments. The SEVO experiment spectroscopically monitored on a daily to biweekly basis the stability and changes in these organic films as they were exposed to solar far-UV, UV, visible, and near-infrared light (122–2600 nm), as well as trapped-particle and cosmic radiation (Mattioda et al. 2012). The SEVO payload successfully performed the first real-time in situ investigations of the photostability and dynamic changes of organic molecules and biomarkers in outer space, demonstrating a significant acceleration of photodegradation by photogenerated hydroxyl radicals in microenvironments that include water vapor. Spectral data sets from the 24 sample positions were typically downlinked within days of their acquisition, enabling rapid analysis and strategy modification of data collection parameters and timing in order to optimize science return.

The SESLO payload measured the long-term survival, germination, growth, and metabolic activity of *Bacillus subtilis* spores exposed for varying times to the microgravity, ionizing radiation, and heavy-ion bombardment environment (~1.7 Gy reached the cells over the course of 6 months). Multiple independent fluidic microwells containing wild-type (168) and radiation-sensitive mutant (WN1087) strains of dried *B. subtilis* spores were rehydrated with nutrients after 2 weeks, 3 months, and 6 months in orbit, causing the spores to germinate and grow. The growth medium included Alamar blue viability dye, which changes color as a result of cellular metabolism. Three-color transmitted intensity measurements of all microwells were telemetered to Earth for evaluation and interpretation (Nicholson et al. 2011) in comparison to delayed-synchronous laboratory ground control experiments. Data telemetered by SESLO showed that both *B. subtilis* strains of cells in microgravity generally grow and metabolize more slowly than those subjected to Earth’s gravitation.

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O/OREOS Satellite

- [O/OREOS Nanosatellite](#)

O₂

- [Dioxygen](#)

OB Association

Steven W. Stahler

Department of Astronomy, University of California, Berkeley, CA, USA

Definition

An OB association is a loose grouping of several thousand stars, a small fraction of which are of spectral type O and B. These latter are the most massive members of the group and also the most luminous, allowing identification of OB associations out to great distances. In external spiral galaxies, they trace the spiral arms. OB associations range in size, with diameters from tens of parsecs to about 100 pc. It is thought that all the stars formed together in a tighter configuration, and observations of stellar velocities reveal that the groups are in a state of expansion. The oldest recognizable OB associations have ages of order 10 Ma.

Cross-References

- [Elephant Trunks](#)
- [Stellar Cluster](#)
- [T Association](#)

Obduction

Nicholas Arndt

ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Obduction is the geological process which describes the thrusting of segments of ► [oceanic crust](#) and ► [mantle](#) onto ► [continental crust](#) at convergent plate margins. A slice of obducted oceanic crust is called an ophiolite. Commonly, high-pressure low-temperature metamorphic rocks belonging to the so-called blueschist-facies

are exposed in front of the obducted ► [ophiolite](#). During periods of enhanced ridge push, while most of the oceanic plate is subducted, slices of younger (and thus hotter and more buoyant) material are thrust onto small continental fragments or onto the margins of continents, particularly during the closure of ocean basins preceding continent-continent collision.

Cross-References

- [Oceanic Crust](#)
- [Ophiolite](#)
- [Plate Tectonics](#)
- [Subduction](#)

Oberon

Therese Encrenaz
Observatoire de Paris – Section de Meudon,
Meudon, France

Definition

Oberon, discovered by Herschel in 1787, is the outermost of the five big satellites of ► [Uranus](#). Its distance to Uranus is 583,500 km (or 23 Uranian radii), its diameter is 1520 km, and its density is 1.63 g/cm³. Oberon has been observed by the Voyager 2 spacecraft at the time of its ► [Uranus](#) flyby in January 1986. Its surface is heavily cratered; the largest crater, Hamlet, has a diameter of 206 km. It is considered as being differentiated into a silicate core surrounded by an icy mantle. The low albedo (0.14) of the surface suggests that it consists of a mixture of ice and organic matter, possibly irradiated by high-energy particles coming from Uranus’ magnetosphere.

Cross-References

- [Giant Planets](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)

Obliquity and Obliquity Variations

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, UMR 8539, Université
Paris, Paris, France

Synonyms

[Axial tilt](#)

Definition

In astronomy, the obliquity is the angle between an object’s (e.g., planet’s) axis of rotation and a line perpendicular to its ► [orbit](#) plane. The obliquity controls the variation of insolation with latitude and time, and thus influences the climate.

Overview

In the Solar System, the present-day obliquities of the planets are diverse Table 1.

Planetary obliquities vary with time because of the long-term gravitational perturbation by other planets (Laskar and Robutel 1993). This effect is small on the obliquity of the outer planets (► [Jupiter](#), ► [Saturn](#), ► [Uranus](#) and ► [Neptune](#)), which can be considered as primordial: They have roughly kept the value they had at the end of the

Obliquity and Obliquity Variations, Table 1 Obliquity of the eight planets of the Solar System and Pluto

Planet	Obliquity
Mercury	0.01°
Venus	177.4°
Earth	23.45°
Mars	25.19°
Jupiter	3.1°
Saturn	26.7°
Uranus	97.8°
Neptune	28.3°
Pluto	122.5°

formation of the ► [Solar System](#). In contrast, the very low obliquity of ► [Mercury](#) results from tidal interactions with the Sun. This is also the case for ► [Venus](#), although the effect was different because of its thick atmosphere (the Sun heats the atmosphere at the subsolar point, inducing a redistribution of the mass of the atmosphere, which also induces a torque). For the ► [Earth](#), the obliquity presents only small variations of about 1.3° around the mean value of 23.3° , with a dominating period of 42,000 years. In the absence of the Moon, theoretical calculations suggest that the situation would be very different, as multiple resonances then occur between the precession of the axis and the precession of the orbital plane. Earth's obliquity would then have varied widely between nearly 0° and 85° . In fact, this is the case for Mars, which may have varied between $\sim 0^\circ$ and up to more than 60° . In the past 5 Ma, the Martian obliquity varied (with a pseudo-period near 120,000 Earth years) between about 15° and 35° . Between 5 and 20 Ma ago, it oscillated between $\sim 25^\circ$ and 45° . Before that, it is impossible to reconstruct the details of the obliquity variations, because of the chaotic nature of the problem (Laskar et al. 2004).

On any planet, the obliquity controls the distribution of solar illumination with latitude, and the seasonal cycle. Increasing the obliquity enhances the seasonal variations (warmer summer, colder winter). The average annual insolation slightly decreases with obliquity equator ward of 45° latitude, and strongly increases with obliquity pole ward of 45° latitude. At the poles, it is proportional to the sine of the obliquity.

Cross-References

- [Earth](#)
- [Jupiter](#)
- [Mercury](#)
- [Moon, The](#)
- [Neptune](#)
- [Orbit](#)
- [Planet](#)
- [Rotation Planet](#)
- [Saturn](#)

- [Solar System, Inner](#)
- [Uranus](#)
- [Venus](#)

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Occultation

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

In astronomical usage, an occultation occurs when an object of larger angular size passes in front of an object of smaller angular size. A frequent example is the passage of the Moon between an observer on Earth and a star, producing an occultation of the star. The rarer occultations of stars by planets, satellites, or asteroids provide opportunities to probe the properties (atmosphere, size) of the occulting bodies. Such observations led to the discovery of the rings around the planets ► [Uranus](#) and ► [Neptune](#). When the Earth passes through the equatorial plane of ► [Jupiter](#) or ► [Saturn](#) (which correspond to the orbital planes of the major satellites of these planets), mutual occultations among these satellites can be observed. Occultation events have also been observed from unmanned space probes in the Jovian and Saturnian systems. The case when the foreground object has a smaller angular size than the more distant object is called a ► [transit](#).

Cross-References

- [Eclipse](#)
- [Transit](#)

Ocean

► Precambrian Oceans, Temperature of

Ocean Planet

Marc Ollivier¹ and Nader Haghighipour²

¹Institut d'Astrophysique Spatiale, CNRS, Université de Paris-Sud, Orsay, France

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Accretion · Exoplanet · Migration · Planetary formation · Snow line

Synonyms

Water planet; Water world

Definition

Ocean planets are hypothetical objects with masses ranging from 2 to 10 Earth-masses and primarily

made of water. The surface of an ocean planet is assumed to be completely covered by an ocean with a depth that can reach hundreds of kilometers (Fig. 1). Because of the massive presence of liquid water on their surfaces, ocean planets may be good candidates for the detection of life if they are in the Habitable Zone. No ocean planet has yet been detected; however, some recently discovered planetary bodies such as Kepler 22b may present potential candidates for an ocean planet.

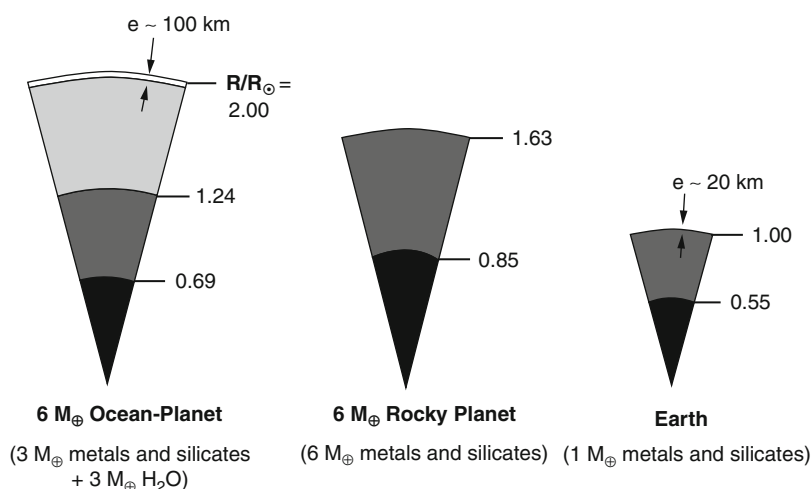
Cross-References

- [CoRoT Satellite](#)
- [Habitable Planet, Characterization](#)
- [Habitable Zone](#)
- [Kepler](#)
- [Radial Velocity](#)

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Ocean Planet, Fig. 1 A comparison between Earth, a rocky planet, and an ocean planet



Oceanic Crust

Nicholas Arndt

ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Oceanic crust is the outer solid layer of the Earth beneath the oceans. This type of crust is 6–9 km thick, it is essentially basaltic (mafic) in composition and denser of the continental crust. It comprises three main layers (from top to bottom): Layer 1, a thin layer (typically less than 500 m thick) of deep-water unconsolidated carbonate or siliceous sediment that thin towards mid-ocean ridges; Layer 2A consisting of ~0.5 km thick, glassy-to-finely crystalline basalt, usually in the form of pillow lava; Layer 2B, consisting of ~1.5 km thick sheeted vertical diabase (a rock essentially basaltic in composition but slightly metamorphosed) dykes; and Layer 3, ~5 km thick and of a density of 3.0 g cm^{-3} consists of gabbro (the intrusive form of basalt) and ultramafic cumulates (peridotite). The crust forms through partial melting of upwelling mantle beneath mid-ocean ridges; the layering results from differentiation of the basaltic magma produced by this melting. On Earth, the age of oceanic crust ranges from zero at oceanic spreading centers to a maximum of about 180 Ma in the northwestern Pacific.

Cross-References

- [Basalt](#)
- [Crust](#)
- [Mafic and Felsic](#)
- [Mid-ocean Ridge](#)
- [Obduction](#)
- [Ophiolite](#)

- [Peridotite](#)
- [Pillow Lava](#)
- [Plate Tectonics](#)

Oceans, Chemical Evolution of

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Carbonate · Chlorine · Fluid Inclusion · Major ions · Ocean chemistry · Oxygen levels · pH · Salinity · Sodium · Sulphur

Definition

The chemical composition of the ocean corresponds to the composition of its major and minor dissolved ions (Na^+ , Mg^{2+} , Ca^{2+} , K^+ , Sr^{2+} , Cl^- , SO_4^{2-} , HCO_3^- , Br^- , CO_3^{2-} , B^{3+} , F^-). The major ion content is considered relatively constant and defined as salinity, which is a measure of the total dissolved salts in seawater. The chemical evolution of the terrestrial oceans is controlled by complex interactions between the Earth system reservoirs, namely the geosphere (mantle and crusts), the biosphere, the atmosphere, and the hydrosphere itself.

Overview

Ocean Chemistry: The Result of Complex Interactions in the Earth System

Table 1 resume the average chemical composition of the Earth's modern oceans with the concentrations of the main ions dissolved in the seawater (in mol/g) and corresponding to an average salinity of 35 g/L (or ca 35,000 ppm, being the density of water equal to 1.025 kg/L). Salinity in the

Oceans, Chemical Evolution of, Table 1 Standard mean seawater chemical composition (Salinity = 35 g/L) reported as mol kg H₂O⁻¹ (DOE 1994). Boron is reported as sum of its hydroxides B(OH)₃ and B(OH)₄

Ion	Na ⁺	Mg ²⁺	Ca ²⁺	K ⁺	Sr ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Br ⁻	CO ₃ ²⁻	B ^{3+,4+}	F ⁻
mol/g	481.6	54.75	106.5	105.8	0.09	565.67	29.27	1.83	0.87	0.27	0.43	0.07

present oceans is relatively constant, between 31 and 38 g/L, yet several processes can cause the oceanic waters to be nonconservative. These processes include precipitation, dissolution, water-rock interactions, freezing, and oxidation processes (Millero 2003). For example, dilution from abundant monsoon-related rain or ice debacle can locally and substantially reduce the salinity, while marginal basins with restricted circulation and tropical temperatures (i.e., the Dead Sea) can increase dramatically the salinity by evaporation.

The chemical composition of the oceans is the result of complex interactions between all the reservoirs of the Earth. If the salinity of the oceans could be basically reduced to two main sources, namely the mantle which degases ► [halogens](#) both at the ► [mid-ocean ridges](#) and at the volcanic arcs (e.g., Schilling et al. 1978) and the continents which release cations and anions by rock ► [weathering](#) (hydrolysis, dissolution, etc.), all other reservoirs have played a role in modulating these sources through eons. For example, a CO₂-rich atmosphere that lasted for most of the Precambrian and part of the Phanerozoic certainly contributed to accelerate continental weathering through the Urey reaction (silicate weathering by CO₂ with precipitation of carbonates; Urey 1952), rendering the continents the main source of alkalinity eventually stored as carbonates (Albarede et al. 2020). On the other hand, the record of strontium isotopes (⁸⁷Sr/⁸⁶Sr) in Archean marine carbonates show values of 0.703–0.704 very close to those of the upper mantle (Veizer and Compston 1976) and far from the present-day ocean of 0.709, which reflect the dominant source of Sr and other elements from continental weathering (the ⁸⁷Sr/⁸⁶Sr ratio of the riverine input is 0.711). Following mass and isotopic balance calculations these numbers suggest that only 20% of the continental mass lands were present in

the Archean period. Similar numbers are obtained by Albarede et al. (2020) looking at the phosphorous contents in marine mudstone of different ages from Archean to the present-day. The only significant input of phosphorus in the ocean is continental runoff. Phosphorus concentration in mudstones expresses the ratio between chemical and mechanical erosion. As such, the phosphorus abundance in mudstones can be used to infer continental surface area. Based on compiled data and the progressive increase of phosphorous abundance in mudstone since earlier Archean, Albarede et al. (2020) suggest that at the time of the oxygenation of the earth (2.5 Ga ago), the continents were covering 7% of the Earth's surface against 30% of the present-day continental landmasses, making the Earth resembling an ► [Ocean-Planet](#) or aquaplanet.

Earlier little developed biosphere and smaller continental landmasses could have modulated the content of some halogen such as I and Br, which in modern ocean is uptake by plankton and removed from the ocean by burial of organic matter in sediments (Channer et al. 1997). Appearance and domination of C-fixation probably had a key role in producing and accumulating O₂ in the atmosphere and removing iron from Archean ferruginous oceans as ► [banded iron formation](#) (Catling 2015), while the absence of some metabolic pathway in earlier times, as sulfate-sulfide reaction could have contributed to maintain a low-sulfate ocean in the Archean (e.g., Crowe et al. 2014). More simply, the lack of oxygen in the pre-GOE atmosphere, SO₄²⁻ and NO₃⁻, which dominate the redox chemistry of modern seawater, were essentially absent in the Archean Ocean, while iron was overwhelmingly in its Fe²⁺ form (Albarede et al. 2020).

Tectonic processes shaping the geosphere have also a key role in ocean chemistry. There is a general accepted idea that Hadean and Archean

Ocean' salinity – prior of the onset of the modern plate tectonic somewhere around 3.0 Ga ago – was dominated by ions derived from mantle degassing (halogens, metals...) and from weathering of oceanic basaltic crust by intense hydrothermal fluid circulation (Pinti 2005). This would be a direct consequence of a much vigorous mantle convection favoring higher oceanic crust production at mid-ocean ridges (Bickle 1986) and the limited growth of continents (McCulloch and Bennett 1994). With the beginning of the plate tectonic and an effective way of recycling elements down the mantle through subduction, both halogens and other elements may have been constantly cycled between the surface and the interior of the Earth (Schilling et al. 1978) modifying the chemistry of seawater. Further, the rapid growth of continents should have progressively favored weathering and riverine transport of new elements to seawater. Continental landmass growth might have also locked important mass of salts in continental evaporitic settings decreasing at least of a factor 1.2 to $2\times$ the halite (NaCl) content of the primordial oceans (Knauth 2005). Several authors indicate the beginning of the Proterozoic era as the turning point in the dominance of salinity sources (hydrothermal cycling versus continental weathering; Veizer et al. 1989; de Ronde et al. 1997; Pinti 2005). There are also physical parameters to consider and which plays a role in the distribution of solute in the oceans. Presently on Earth the latitudinal distribution and the extent of continental landmasses control the global oceanic circulation and the formation of deep waters in what is known as the thermohaline circulation or the ocean conveyor belt (Broecker 1991). In an aquaplanet, oceanic circulation as known today is disrupted and the upwelling of cold current is stopped. This situation certainly plays a role in the redistribution of solutes in the ocean.

It is clear from these few, first order thoughts that modeling the evolution of the seawater chemistry is a hard task, because the multitude of physical, chemical, and biological variables that enter the general equation of the ocean chemistry. Yet, the geological record has left traces of the past chemistries of the oceans, some easy to be read and correctly interpreted, other ambiguous

because hampered by alteration and metamorphism. These include rare earth elements (REE) in chemical sediments precipitated in the oceans or isotopic signatures of biophile elements C, S, N (Thomazo et al. 2009) in these sediments. Here, below we report a general review of the knowledge around the early ocean chemistry evolution restricted to Hadean and Archean times, which is far to be exhaustive. Even after 37 years, the general work of Holland (1984) is still actual and to be read for understanding the numerous Earth system processes that could or have intervened in creating and modifying the oceanic chemistry through eons. Very recently Albarede and colleagues (Albarede et al. 2020) have dig potential processes affecting the Archean Ocean, presenting a fresher view of the element cycling in the oceans.

Halite: The Main Ingredient of Seawater' Salinity

Present-day ocean salinity is at 71% in mass (g/g) made of only two ions, namely sodium (Na^+) and chloride (Cl^-) which precipitation makes the most abundant evaporite mineral, halite (NaCl). This chemistry might have been dominant since the beginning. Chlorine is the most abundant halogen on Earth, followed by far by bromine, which is at least 3 orders of magnitude less abundant (Eggenkamp 2014). In the cosmochemical classification of the elements, halogens are volatile elements, as ► noble gases are, but differently from noble gases, they are highly reactive elements, displaying a preference for aqueous phases (Eggenkamp 2014; Clay et al. 2017). Therefore, they are mainly concentrated in the oceans ($\text{Cl} = 19,353$ ppm and $\text{Br} = 67$ ppm) and evaporites ($\text{Cl} = 607,000$ ppm and $\text{Br} = 151$ ppm) (Eggenkamp 2014). They were delivered to Earth, as other volatile elements (noble gases, N, C, H_2O), very early in the history of the Solar system during the first stage of the Earth' accretion (Clay et al. 2017). This is suggested by the close similarities in the Cl/Br ratio of chondrites and major Earth reservoirs (Clay et al. 2017) and the very close isotopic signature of chlorine ($\delta^{37}\text{Cl}$ in ‰ vs Standard Mean Oceanic Chloride or SMOC) in seawater (0‰ by definition),

chondrites ($+0.2 \pm 0.5\%$; Sharp et al. 2007) and the mantle (-1.6 to $+0.9\%$; e.g., Bonifacie et al. 2008; Pinti et al. 2020). Halogens were incorporated in the Earth and then degassed from the mantle, which is today mostly entirely depleted in halogens. However, halogens have not undergone the extreme early loss observed for other mantle volatiles, such as noble gases. The hydrophilic nature of halogens could have played a role in preserving them in surface aqueous phases, less affected by devolatilization processes during early accretionary events (Clay et al. 2017).

If chlorine and other halogens were present on Earth very early, sodium – the other element composing halite – was likely abundant on early Earth, locked in mineral phases such as plagioclases in the basaltic oceanic crust. Hadean ocean salinity was possibly controlled by high-temperature water-rock interactions between the condensing CO_2 – H_2O runaway greenhouse atmosphere and the primitive basaltic crust (Sleep et al. 2001). When condensing water started to penetrate deeper in the oceanic basaltic crust, dissolved chlorine (degassed from the mantle likely as HCl) reacted with Na-bearing minerals of basalt to produce halite (NaCl). Sleep et al. (2001) calculated that a global basaltic layer only 500-m thick could have accounted for the whole ocean NaCl budget. Initial salinity of the ocean is unknown, and values of 1.2–2 times the present value have been proposed only for the Archean ocean (Knauth 2005). This could be considered a minimum value for the Hadean.

The presence of halite in early oceans has been contested by some authors (i.e., Maisonneuve 1982) because it was believed that chlorine was sourced by weathering of continental evaporitic deposits. However, it is likely that the total budget of chlorine was available in oceans since the beginning, largely degassed from the mantle (Clay et al. 2017). An alternative model to a salty early ocean was proposed by Kempe and Degens (1985) which evoked the possibly to have an alkaline soda ocean, an environment similar to that observed in modern ► [soda lakes](#). The presence of high $p\text{CO}_2$ in the early atmosphere, 100–1000 times the present concentration, should

have brought to the acidification of the oceans but increased the amount of Ca^{2+} and bicarbonate in solution through silicate weathering. This in turn should have decreased the amount of $p\text{CO}_2$ with time, consumed by the Urey reaction. Although counterintuitive, in presence of relatively high $p\text{CO}_2$, hydration of Na–, K–, Ca–, and Mg-silicates produces alkaline solutions, which brought to precipitation of sodium carbonates (Na_2CO_3) (Kempe and Degens 1985). However, thermodynamic calculations indicated that the whole terrestrial available CO_2 budget (atmosphere-hydrosphere-mantle) is several orders of magnitude lower than the one needed to make a global soda ocean (Sleep et al. 2001).

If NaCl was since the beginning dominant in the early oceans, the total amount is still matter of speculation, but estimating it has important consequences on the early existence of a marine biosphere. Holland (1984) calculated an early NaCl salinity $1.2\times$ the present day, while Knauth (2005) taking into account all large evaporitic deposits on continental landmasses reaches a higher figure of $2\times$ the present-day amount. An ocean this saline would be a problem for most metazoans today, but its effect on prokaryote is not significant. Cyanobacteria, for example, have little problem with this enhanced salinity and extremophiles (Archaea halophiles) are known to live in highly concentrated brines with salinities ranging from 4.7% to 30% (against 3.5% of modern seawater).

There are other suggestions that chlorinity was higher in the pre-GOE seawater based on seawater chemistry (Albarede et al. 2020). In present-day seawater alkalinity of the ocean is locked into carbonates. With smaller landmasses affected by weathering, the main source of carbonates and mudstone was drastically reduced and consequently the flux of alkalinity to the ocean was much weaker than today. The control of seawater alkalinity, which today is exerted by the Ca^{2+} – CaCO_3 couple, was likely exerted by dissolved Fe^{2+} –magnetite or Fe^{2+} –ferrihydrite which buffered the atmosphere by reducing CO_2 to CH_4 and thus exerting an indirect control on the alkalinity of the ocean (Thibon et al. 2019). The

reduced alkalinity flux implicitly reduces the capacity of runoff to neutralize the high-temperature acidic hydrothermal fluids, with causes lower seawater pH and higher chlorinity.

Fluid Inclusions in Chemical Sediments and Ocean Chemistry

Direct measurements of past salinity have been tempted by analyzing fluid inclusions in chemical sediments of Archean age, amid the pristine nature of those inclusions (Appel et al. 2001; Foriel et al. 2004; de Ronde et al. 1997; Weiershauser and Spooner 2005; Marty et al. 2018; Burgess et al. 2020). The 3.8 Ga Isua meta-sedimentary sequences of West Greenland contain chemical sediments deposited in an oceanic environment without a significant silicic (i.e., composed of rocks rich in silica and alumina) detrital component (Holland 2003), in other words without continental inputs of ionic species. Compelling evidence for the existence of an ocean during deposition of Isua rocks are clastics that have been interpreted as marine turbidites and iron formations (IFs). These iron-rich layers are magnetite-quartz IFs, and the molar ratio $\text{Fe}_2\text{O}_3/\text{FeO}$ is less than 1.0, which suggests that [magnetite](#) was the dominant iron oxide and that [hematite](#) was absent or very minor in these IFs (Holland 2003). This in turn suggests that magnetite is not a replacement of oxyhydroxide precursors but a primary precipitating phase, thus that the oxygen level in the oceans was significantly low. The oxidation of Fe^{2+} to Fe^{3+} was possibly produced by UV-induced reactions between iron and H_2O (Cairns-Smith 1978). The chemistry of Isua seawater is unknown. Appel et al. (2001) observed fluid inclusions in quartz globules from pillow breccia at Isua. The chemistry of the highly saline aqueous fluids (about 25 wt.% NaCl equivalent) bears a strong resemblance to present-day seafloor hydrothermal fluids that likely provoked the alteration of the pillow breccia and the precipitation of quartz. Occurrence of fluid inclusions in Archean metasedimentary rocks (see [Fluid Inclusions](#)) has been signaled in several terrains of ages spanning from 3.5 to 2.7 Ga (De Ronde et al. 1997; Channer et al. 1997; Foriel et al. 2004;

Weiershauser and Spooner 2005). They have been interpreted as a pristine record of the chemical composition of Archean seawater. The chemistry of these inclusions pointed out to the mixing between at least two fluids, a saline fluid of Na–Ca–Cl composition (seawater) and a hydrothermal effluent often richer in Ba and Fe (de Ronde et al. 1997; Foriel et al. 2004). The Na:Cl ratio is the same as present-day seawater, but NaCl concentration ranges from 4% to 25% equivalent (against 3.5% equivalent in modern seawater). The salt enrichment and the chemistry (Na–Ca–Cl) points out to an evaporate seawater residue rather than genuine seawater (Martin et al. 2006). Marty et al. (2018) pointed out that the Archean inclusions contain fluids which are a mixture of a low salinity endmember, regarded as the Archean oceanic water, and several hydrothermal end-members rich in Cl, K, N, and radiogenic parentless ^{40}Ar . They concluded that the salinity of the Archean seawater endmember is basically the same than modern ocean. Among the notable differences with modern seawater, Burgess et al. (2020) measured Br/Cl ratios about 30% higher than both modern seawater and contemporary seafloor hydrothermal systems, perhaps indicating a stronger mantle buffering of seawater halogens during the Archean.

Basic Methodology

The complexity of the task of reconstructing the ocean chemistry through eons require to use numerous methods, from detecting and interpreting traces of the ocean lefts in the geological record to geochemical modelling. The first methodology required to find either pristine fluid inclusions in early chemical sediments precipitated directly from oceanic aqueous solutions and to measure [Rare Earth Elements](#) (REE) geochemistry and rock mineralogy of those mineral precipitates. This method faces two serious problems: (1) find appropriate rocks of Archean time having preserved original features and not heavily metamorphosed and (2) chemical marine sediments directly precipitated into oceans, when

the majority of the Archean geological record is made of magmatic and metamorphosed rocks. Indeed a few sedimentary sequences are older than 3.0 Ga and often marine sediments are overprinted by hydrothermal silicification which bring into elements from mantle-derived environments which partially masked those from the Earth's surface reservoirs. Often these sediments are simply chert deposits, which origin is still debated: either hydrothermal silica gel deposits around vents (analogue of modern white smokers; e.g., Orberger et al. 2006) or directly precipitated from an Archean ocean oversaturated of silica (Holland 1984; Knauth 2005). The analysis of REE generally allow to determine the sources of sediments and the real influence of the ocean on the sediment deposition, helping in unravel chemical-physical properties (pH, redox) of the seawater. Isotopes of biophile elements such as C, N, S and bio-mediated metals (Fe) were also helpful because their isotopic fractionation is related to some redox conditions of the oceans (e.g., Thomazo et al. 2009 for a review).

Key Research Findings

1. Although resulting from complex interactions among all the Earth's reservoirs, the ocean's chemistry is mainly regulated by two sources: (1) the mantle, through degassing of halogens and metals (Fe, Mn, etc.) at mid ocean ridge and release of ions (e.g., Na^+ , Mg^{2+} , Ca^{2+} , Sr^{2+}) during hydrothermal alteration of oceanic basaltic and gabbroic crust (e.g., Staudigel 2003); (2) silicate weathering of continental landmasses with riverine transport to the sea of ions removed from rocks.
2. Salinity of oceans has been likely always dominated by NaCl, with chlorine brought on Earth during waning stages of accretion and likely before the Moon-forming impact, and sodium extracted by basaltic protocrust.
3. Pristine Archean fluid inclusions indicate a Na/Cl ratio constant and similar to modern seawater, though chlorine concentration in the Archean Ocean is still matter of debate.

Applications

A complete picture of the seawater geological history on Earth could be extremely useful in determining the existence of past oceans on other telluric planets such as Mars, through the study of "sedimentary" rocks and chemical precipitates of "marine" origin.

Future Directions

The geological record of the seawater is still much incomplete and spotty. Bringing new evidence that pristine seawater fluid inclusions could have been preserved through eons and finding fluid inclusions containing nonevaporated seawater are the most challenging research to carry out in the next decade to clearly assess the chemical evolution of the oceans.

Cross-References

- ▶ Archean Eon
- ▶ Banded Iron Formation
- ▶ Chert
- ▶ Earth, Formation, and Early Evolution
- ▶ Fluid Inclusions
- ▶ Fractionation, Mass Independent and Dependent
- ▶ Hadean
- ▶ Hematite
- ▶ Hydrothermal Alteration
- ▶ Iron Cycle
- ▶ Iron Isotopes
- ▶ Iron Oxides, Hydroxides, and Oxyhydroxides
- ▶ Isua Supracrustal Belt
- ▶ Magnetite
- ▶ Mid-ocean Ridge
- ▶ Natron
- ▶ Nitrogen Isotopes
- ▶ Noble Gases
- ▶ Oceans, Origin of
- ▶ Oxygenation of the Earth's Atmosphere
- ▶ Rare Earth Elements
- ▶ Siderite
- ▶ Soda Lake

- Sulfidic Oceans
- Sulfur Isotopes
- White Smoker

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Oceans, Origin of

Daniele L. Pinti¹ and Nicholas Arndt²

¹GEOTOP Research Center for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

²Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Keywords

Carbonaceous chondrites · Enstatite chondrites · Comets · Cool early Earth · D/H · Isua · Jack Hills · Late Veneer · $^7\text{Li}/^6\text{Li}$ · Micrometeorites · $^{18}\text{O}/^{16}\text{O}$ · Terrestrial oceans · Zircon · Water carrier

Definition

The term “ocean” applies to the entire body of saltwater covering more than 70% of the Earth's

surface. From a planetary point of view, the term can be extended to the layer of liquid that partially or totally covers the surface or pervades the sub-surface of a planet or a moon. Examples of sub-surface oceans are those predicted beneath the icy surface of satellites orbiting giant planets (e.g., Titan, Europa, and Enceladus). In addition to water, the term includes other substances such as ethane, methane, or ammonia that are in a liquid state at the temperature and pressure conditions of the planetary surface. The liquid body at the planetary surface can be in thermodynamic equilibrium with an atmosphere or may be separated from it by another layer such as solid water ice.

Overview

This overview focuses on the formation of the Earth's oceans. There are geological evidences that the oceans were present on the ► [Earth](#) in the early Archean (3.8 Ga ago) after the ► [Late Heavy Bombardment](#) and plausible evidence that liquid water was stable on the Earth's surface in the ► [Hadean](#) (Mojzsis et al. 2001; Wilde et al. 2001). The geological evidence comes from the two oldest areas of volcanic and sedimentary rocks – the Isua Supracrustal Belt, West Greenland, and the Nuvvuagittuq Greenstone Belt, Québec, Canada. Radiometric dating of metasedimentary rocks in both areas have been established at about 3.8–3.7 Ga (Cates and Mojzsis 2007; Augland and David 2015; Bennett and Nutman 2013). In the Isua Supracrustal Belt, pillow basalts provide evidence of subaqueous eruption, and in both belts, metasedimentary rocks – ► [banded iron formations](#), metapelite, and ferruginous quartzite – are possibly the result of subaqueous deposition. Although the original depositional setting of some of the precursor sediments may have been lakes or shallow seas, it is far more probable that these strata were deposited in ocean basins.

The evidence for Hadean oceans is less direct, because the geological record has been mostly erased by the intense tectonic activity of the young Earth. Most evidence comes from 4.4 to 4.2 Ga-old detrital zircons (ZrSiO_4) from the Mt. Narryer quartzite and from Jack Hills

metaconglomerate, Western Australia (Mojzsis et al. 2001; Wilde et al. 2001). ► **Zircon** is a common U-rich trace mineral in felsic magmas formed by the melting of a hydrous source. Parental rocks of the Jack Hills zircons possibly formed from melting of subducted hydrated oceanic crust. The presence of such a crust requires interaction between basaltic lava and seawater as is suggested by the $^{18}\text{O}/^{16}\text{O}$ ratio (denoted as $\delta^{18}\text{O}$) of the Jack Hills zircons which extend to $+7.4 \pm 0.7\%$. This value can be explained only by mixing between the mantle source of the zircons ($\delta^{18}\text{O}_{\text{Oca.}} +5.0\%$; Valley 2003) and a source enriched in ^{18}O compared to the mantle value, derived from low-temperature ► **weathering** of oceanic crust. The $\delta^{18}\text{O}$ values of Hadean, Archaean, and Proterozoic zircons show a secular increase in values up to 12%. This can be explained by an increase in the amount of crustal, high- $\delta^{18}\text{O}$ material available for melting and assimilation, as the “wet” continental crust evolved and matured during the Precambrian. The presence of $\delta^{18}\text{O}$ of $+7.4 \pm 0.7\%$ in a 4.4 Ga-old detrital zircon of Jack Hills could thus be the indirect and oldest record of interaction of a magmatic source with liquid water at the surface of the Earth (Peck et al. 2001; Valley et al. 2005). A similar result was obtained by measuring the lithium (Li) isotopic ratio ($^7\text{Li}/^6\text{Li}$ or $\delta^7\text{Li}$) in Jack Hills zircons (Bouvier et al. 2012). Fresh igneous rocks have $\delta^7\text{Li}$ of $3.8 \pm 1.5\%$, whereas seawater has very high $\delta^7\text{Li}$ of $+31\%$. Fluid–rock interaction causes fractionation of Li with products of subaerial weathering as low as -20% . Two $\delta^7\text{Li}$ populations of zircons were identified by Bouvier et al. (2012). The first showed $\delta^7\text{Li}$ values similar to TTG and sanukitoids indicating growth from a differentiated magma source. A subset of Jack Hills zircons has extremely low $\delta^7\text{Li}$ (-18 to -4%), reflecting melting of extensively weathered crust.

The combination of geological observations together with geochemical and isotopic analyses –contributing in determining the climate and surface conditions of the Hadean Earth – led to the ► **“Cool Early Earth”** hypothesis according to which temperatures were clement, and oceans existed on the surface of the Earth as early as 4.4 Ga (Valley et al. 2002).

The source of the oceanic water is debated. It is commonly accepted that any primitive solar-type atmosphere surrounding the Earth was rapidly blown away by UV and X-rays produced by the Sun during its proto-(T-Tauri)-star stage. It is assumed that the Earth probably did not contain water, because it accreted very close to the Sun and largely composed of “dry” raw material, possibly enstatite chondrite (EC) ► **meteorites** (Javoy 1997). Previous measurements of water in EC indicated amounts close to 0.01 wt%, but in a very recent study (Piani et al. 2020), the amount and isotopic composition of water were measured again. It resulted that H_2O content could be as high as 0.5 wt% and the D/H (or δD) ratio ranges between -103 and -127% , less than that of the terrestrial oceans but within that of the Bulk Silicate Earth (-130 to -75%), Suggesting that EC could have participated to the ocean formation. Thus EC could be a complementary carrier of water to Earth, a hypothesis that needs to be further explored.

The present hydrosphere was probably acquired from meteoritic and cometary material that was added during repeated episodes of bombardment, which have been historically regrouped in the concept of “Late Veneer” (e.g., Wänke and Gold 1981). Late Vener is a term defined by geochemists to explain the observed abundance patterns of siderophile (iron-loving) elements in the silicate Earth. In particular, the elements of the group of Platinum (Pt) called HSE (High Siderophile Elements: Re, Os, Ir, Ru, Pt, Rh, Pd, Au) are anomalously enriched in the mantle, while after Earth differentiation, these iron-loving elements have been sequestered entirely into the metallic core of the Earth. This excess is explained by the late addition of chondritic material, which is known to contain high concentrations of HSE. It is still unclear how the “Late Veneer” precisely “fits” in the currently accepted, complex scenario of Earth’s accretion, involving both planetesimal bombardment and giant impacts from chondritic and differentiated projectiles (Morbidelli and Wood 2015). This issue is complicated by the fact that modern core-formation theories suggest that differentiation occurred in several steps, and consequently, several episodes of “Late Venner” could have taken place. Moreover, Earth

formation modeler's recently introduced the new concept of "Late accretion," which corresponds to the tail of the accretion history of a planet due to the planetesimal bombardment that happens after the last giant impact has occurred (the Moon-forming one in case of Earth, Morbidelli and Wood 2015). Here, it is assumed — in accordance with recent Earth's formation models that water was added very early in the accretion history of the planet (Morbidelli et al. 2000), and that this episode is distinguished from those of Late Veneer, which likely took place afterward.

The main question, which currently constitutes a hot debate among the scientific community, is the type of the impactor, which brought the main body of water to form these terrestrial oceans. Similarities between the hydrogen isotopic ratio D/H of the whole Earth ($149\text{--}153 \times 10^{-6}$), ocean water (155.7×10^{-6}), and the average D/H ratios of hydrated ► carbonaceous chondrites ($149 \pm 6 \times 10^{-6}$), and Antarctic micrometeorites ($154 \pm 16 \times 10^{-6}$) indicates that ► asteroids or asteroidal dust constitute the most likely water-carrier candidates (Maurette et al. 2000; Marty and Yokochi 2006). ► Comets apparently exhibit heavier D/H ratios of $290\text{--}320 \times 10^{-6}$ (as measured in Oort Cloud's long-period comets ► Hyakutake, ► Hale-Bopp, and P/► Halley) that are incompatible with oceanic water. However, mass and isotopic balance calculations suggested that eventually a few percent of cometary water contributed to the terrestrial water budget. The sustainers of the "cometary" origin of the Earth's water disagree with these results because the exact D/H signature of water in comets from the Oort Cloud is still unknown. Moreover, when the Solar System formed another family of comets, the Jupiter family formed in the region of the ► Kuiper belt, and those comets may have delivered ocean-like water to the inner Solar System. This is still controversial. Indeed, recent measurements of the D/H ratio in the Jupiter family comet 103P/► Hartley 2 by infrared spectrometry (Hartogh et al. 2011) showed a D/H ratio of $161 \pm 24 \times 10^{-6}$ supporting the view that this family of comets brought water to Earth. However, the ► 67P/Churyumov–Gerasimenko comet, supposed to have a similar origin to 103P/► Hartley 2,

yielded a $D/H = 530 \times 10^{-6}$, a value not compatible with the hypothesis of water delivery from this type of comets (Altwegg et al. 2015). Future measurements on carbon and water-rich asteroidal bodies, such as type-b asteroid Bennu targeted by NASA mission OSIRIS-REx, may definitely answer those questions.

The total amount of water delivered to Earth was certainly higher than the mass of the present-day oceans (1.4×10^{21} kg) because the losses of volatiles to space were important on the Early Earth. Pepin (1991) proposed that at least 50% of the water delivered to Earth could have dissociated to hydrogen and oxygen by the strong early UV radiation. Further losses were due to atmosphere erosion by impacts owing to collision with planetary bodies. Geophysical and high-pressure mineralogy experiments show that the modern mantle contains two to five times the ocean volume of water (Abe et al. 2000). Earth volatile bulk concentration (noble gases, halogens, and water) indicates that an addition of no more than 4% of carbonaceous chondrite "wet" material is enough to furnish the present-day volatile budget of our planet (Albarede et al. 2013). This amount of extra-chondritic material added the equivalent of 10–25 times the present-day ocean budget to Earth. Regardless of whether these figures will change with new studies, it appears that the amount of water added to the newly born Earth was much higher than that is preserved in the oceans.

Theories of how the ocean formed and stabilized on the surface of the Earth are based on geophysical models and speculation. Water, together with CO₂ (now trapped at the Earth's surface as carbonates), was initially a vapor phase in the secondary (outgassed) atmosphere. Water gas did not condense until the surface of the planet cooled down to less than 647 K, the critical point of water. Assuming that all oceanic water was present as a gas, the atmospheric pressure was about 270 bars of H₂O plus 40–60 bars of CO₂ (Sleep et al. 2001; Pinti 2005). This runaway greenhouse atmosphere, refurbished by a high heat flow from the still molten and highly dynamic interior of the Earth, kept the planet's surface sufficiently hot for several million years to prevent

water from condensing on its surface. When a primordial crust formed, it reduced the heat flux from the interior, and the surface of the Earth cooled down, allowing the condensation of water. It is difficult to assess exactly when this occurred. Geophysical models developed by Sleep et al. (2001) suggest that the oceans rained out a few million years or less after the Moon-forming impact, depending on the parameters chosen. If the geochemistry of the Jack Hills zircons does indeed reveal the presence of liquid water at the surface, oceans should already present between 4.4 and 4.3 Ga or, at least, liquid water was stable at the surface conditions of Earth. In such a scenario, the oceans cooled down quickly enough to render both prebiotic chemistry and the survival of the first living organisms possible between ~4.3 Ga and the end of the late heavy bombardment at ~3.85 Ga.

The chemistry of seawater in the early Hadean was likely controlled by high-temperature fluid-rock reactions between the hot CO₂-H₂O-rich atmosphere and oceans, and primitive basaltic crust (see ► “Oceans, Chemical Evolution of”). Weathering of Na-rich basalt reacting with chlorine saturated the seawater with NaCl. The acidity of water was possibly as high as pH = 5 because the ocean was in thermodynamic equilibrium with a CO₂-rich atmosphere (Pinti 2005), though alternative models of alkaline oceans saturated with ► *thermonatrite* formed by weathering of the basaltic proto-crust have been proposed (Kempé and Degens 1985).

Basic Methodology

The origin of oceans is a long-standing question, both geological, and before that, philosophical, since Ancient Greece. American geologist William W. Rubey wrote in 1951, a seminal paper entitled “Geological History of Seawater. An attempt to state the problem,” in which he tried to resolve the origin of the atmosphere and the oceans, based on geological observations and mass balance calculations. This first “modern” attempt was based on the hypothesis of an internal

source: gases and water accumulated during accretion from colliding planetesimals, then degassed from the mantle via the volcanism, or released from rocks by surface weathering, formed the secondary atmosphere of our planet and the oceans. Only with the development of isotope cosmochemistry and the theory of the “Late Veneer,” that is, an episode of bombardment of asteroidal and cometary matter to the accreting Earth, an external origin of water “theory took place.” Since then, the main methodology is to compare the isotopic signature of water in terrestrial oceans and the bulk silicate Earth with those measured in other celestial bodies, from lunar rocks (e.g., Greenwood et al. 2011) to meteorites and comets (see below). The development of *in situ* measurements on small celestial objects (e.g., Rosetta mission) or sample return missions (Hayabusa 1 and 2 and OSIRIS-REx) now gives the chance to measure the isotopic signature of water on potential extraterrestrial candidates, as possible water carriers to Earth. Parallel to this, field geologists and geochemists on Earth seek traces of ancient water trapped in the oldest minerals and rocks to determine a minimum age of existence of water in the geological record (e.g., Wilde et al. 2001).

Key Research Findings

To help understand the origin of the oceans requires the integration of information from the Earth, where the ocean still exists and where a fragmentary record of its early state is preserved in the geological record, with information from other planetary bodies. Studies of the Martian surface have already provided evidence of the small shallow oceans that existed there early in the planet’s history; also, the cold icy satellites provide a record of very different oceans. This information can potentially be exported to models for the formation of oceans on exoplanets. Léger et al. (2004), for example, have proposed the existence of a hypothetical family of ► “ocean planets” that are entirely covered by an ocean hundreds of kilometers deep.

Future Directions

Two main questions need to be addressed: (1) When did oceans form on Earth? (2) What is the ultimate source of the water? The first question is difficult to answer because the answers must be sought from a period from which virtually no geological record exists. Two decades ago, this task seemed hopeless, but the remarkable results emerging from the Jack Hills zircons and other relicts of the oldest crust have radically changed our knowledge of this period. The search for and precisely date and analyze other minerals or rocks may provide complementary evidence of interaction with liquid water. To answer the second question, it is imperative on one side to remeasure at high precision, with new instrumentation such as ion microprobe, the collections of different meteorite classes to correctly establish the amount of hydrate minerals and water isotopic signature; from the other side, analyses of pristine material brought back by recent space missions on asteroids, such as Hayabusa 2 and OSIRIS-Rex, should be able to establish to what extent and which asteroidal material could have contributed to the terrestrial water budget.

Cross-References

- ▶ [67P/Churyumov–Gerasimenko](#)
- ▶ [Archean Environmental Conditions](#)
- ▶ [Archean Eon](#)
- ▶ [Banded Iron Formation](#)
- ▶ [Carbonaceous Chondrite](#)
- ▶ [Chondrite](#)
- ▶ [Comet](#)
- ▶ [Comet Hale–Bopp](#)
- ▶ [Comet Halley](#)
- ▶ [Comet Hartley 2](#)
- ▶ [Cool Early Earth](#)
- ▶ [Degassing](#)
- ▶ [Deuterium/Hydrogen Ratio](#)
- ▶ [Earth, Formation, and Early Evolution](#)
- ▶ [Hadean](#)
- ▶ [Impact Degassing](#)

- ▶ [Late Heavy Bombardment](#)
- ▶ [Meteorite, Murchison](#)
- ▶ [Oceans, Chemical Evolution of](#)
- ▶ [Ocean Planet](#)
- ▶ [Oxygen Isotopes](#)
- ▶ [Porpoise Cove Greenstone Belt](#)
- ▶ [Precambrian Oceans, Temperature of](#)
- ▶ [Rosetta Spacecraft](#)
- ▶ [Sanukitoid](#)
- ▶ [Soda Lake](#)
- ▶ [Thermonatrite](#)
- ▶ [Water, Delivery to Earth](#)
- ▶ [Zircon](#)

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Oceanus Borealis

- [Mars, Paleo Ocean](#)

Oceanus, Oceani

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Definition

The term Oceanus refers to a large low-albedo feature – Oceanus Procellarum – on the Moon. Oceanus Procellarum (ocean of storms) is the only surface feature to which the term Oceanus is applied. It denotes the largest Mare area on the Moon. Oceanus Procellarum extends approximately 2500 km across and covers a surface area of 4 Mio. km². It is composed of extensive flood basalts but is not confined to an isolated impact crater or basin as it connects several Mare-type features. Oceanus Procellarum was sampled during the Luna and Surveyor missions and was visited by the Apollo 12 astronauts in late 1969.

Cross-References

- [Albedo Feature](#)
 ► [Apollo Mission](#)
 ► [Basalt](#)
 ► [Crater, Impact](#)
 ► [Impact Basin](#)
 ► [Mare, Maria](#)
 ► [Moon, The](#)
 ► [Palus, Paludes](#)

Odin

Ake Hjalmarson

Chalmers University of Technology, Gothenburg,
Sweden

Definition

Odin is a Swedish-led submillimeter wave spectroscopy satellite for astronomy and atmospheric research, supported by scientists and space agencies in Canada, Finland, France, and Sweden (>51%). The satellite is equipped with a 1.1 m antenna, four tunable submillimeter wave mixer receivers, a fixed-tuned receiver at 119 GHz dedicated to deep searches for molecular oxygen, O₂, and an optical/near-infrared receiver for aeronomy purposes. Odin was launched from far eastern Russia on 20 February 2001 and still is in full operation in 2013. The central aeronomy program consists of global, long-term temporal monitoring of the distributions of ozone and connected species such as ClO. The astronomy program was mainly dedicated to observations H₂O, NH₃, and O₂ in comets, planetary atmospheres, star formation regions, and circumstellar envelopes around late-type stars. For the last years the mission is focusing on atmospheric research. Odin and NASA's SWAS (launched 2 years earlier) have both provided important pilot studies for the larger and much more sensitive Herschel Space Observatory.

Odin publications: Search on http://adsabs.harvard.edu/abstract_service.html in the Astronomy and Physics databases for title word "Odin."

Cross-References

- [Circumstellar Chemistry](#)
- [Interstellar Medium](#)
- [Molecules in Space](#)

References and Further Reading

http://adsabs.harvard.edu/abstract_service.html

OGLE

- [Optical Gravitational Lensing Experiment](#)

OGLE-2005-BLG-390Lb

David W. Latham¹, B. Scott Gaudi² and Nader Haghighipour³

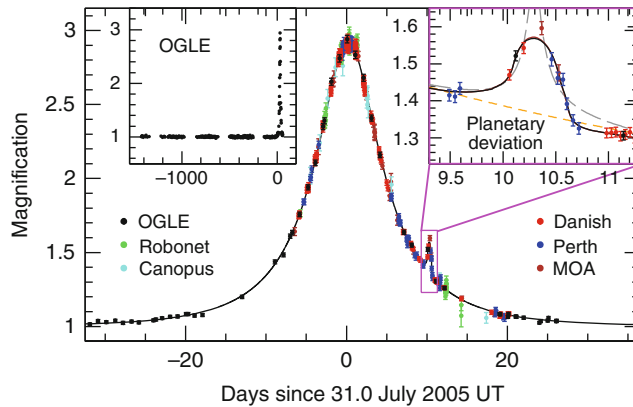
¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

²Department of Astronomy, Ohio State
University, Columbus, OH, USA

³Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Definition

OGLE-2005-BLG-390Lb is a cool ► [super-Earth](#) that was discovered with the gravitational microlensing technique by the Probing Lensing Anomalies NETwork/Robotic Telescope Network (PLANET/Robonet), ► [Optical Gravitational Lensing Experiment](#) (OGLE), and ► [Microlensing Observations in Astrophysics](#) (MOA) collaborations. The mass and orbital separation of the planet are uncertain, as is the mass and distance of the host star from the Sun, but the most likely values are a mass of ~5.5 Earth masses and projected separation of 2.6 AU for the planet and a mass of 0.22 solar masses and a distance of 6.6 kpc for the host star. With an equilibrium temperature of ~50 K, this low-mass planet is located in the cool, outer reaches of its planetary system; it is the first such planet discovered by any technique. Studies by Ehrenreich et al. (2006) suggest that the surface of the planet should be entirely frozen. However, depending on the rock-



OGLE-2005-BLG-390Lb, Fig. 1 The figure shows the observed light curve for the OGLE-2005-BLG-390 microlensing event, including data from the PLANET Danish, Perth, and Canopus telescopes, RoboNet Faulkes North

telescope, OGLE telescope, and MOA telescope. The OGLE data over a wider span of time is shown in the *top left inset*, whereas the planetary deviation is highlighted in the *top right inset* (Beaulieu et al. 2006)

to-ice mass ratio in the planet, the radiogenic heating could be sufficient to allow subsurface water to exist.

The figure shows the observed light curve for the OGLE-2005-BLG-390 microlensing event, including data from the PLANET Danish, Perth, and Canopus telescopes, RoboNet Faulkes North telescope, OGLE telescope, and MOA telescope. The OGLE data over a wider span of time is shown in the top left inset, whereas the planetary deviation is highlighted in the top right inset (Beaulieu et al. 2006) (Fig. 1).

Ehrenreich D, Lecavelier des Etangs A, Beaulieu J-P (2006) On the possible properties of small and cold extrasolar planets: is OGLE 2005-BLG-390Lb entirely frozen? *Astrophys J* 651:535–543

OGLE-2006-BLG-109Lb,c

David W. Latham¹, B. Scott Gaudi² and Nader Haghighipour³

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Department of Astronomy, Ohio State University, Columbus, OH, USA

³Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Cross-References

- [Exoplanets, Discovery](#)
- [Microlensing Observations in Astrophysics](#)
- [Optical Gravitational Lensing Experiment](#)
- [Probing Lensing Anomalies Network](#)

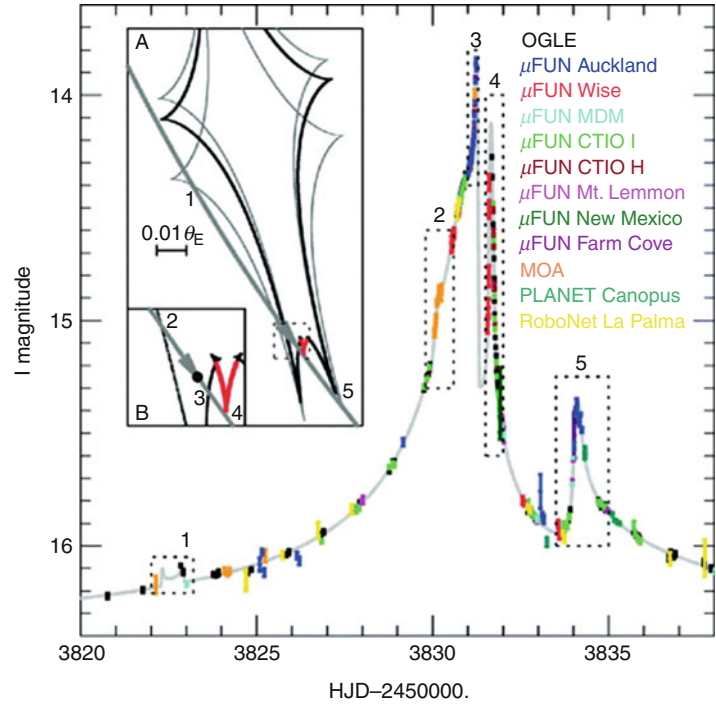
References and Further Reading

Beaulieu J-P et al (2006) Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing. *Nature* 439:437–440

Definition

OGLE-2006-BLG-109Lb,c is the first multi-planet system discovered with the gravitational microlensing technique (Gaudi et al. 2008). This system was discovered by the ► [Microlensing Follow-Up NETwork](#) (MicroFUN) collaboration, in conjunction with the ► [Optical](#)

OGLE-2006-BLG-109Lb,c,
Fig. 1 The light curve for the OGLE-2006-BLG-109 microlensing event. The inset shows the path of the source through the caustic, with the locations of the source which give rise to the five features labelled



Gravitational Lensing Experiment (OGLE),
 ► [Microlensing Observations in Astrophysics](#) (MOA), and Probing Lensing Anomalies Network/Robotic Telescope Network (PLANET/Robonet) collaborations. OGLE-2006-BLG-109Lb,c consists of two planets with masses similar to Jupiter and Saturn orbiting a star with roughly half the mass of the Sun located roughly 1.5 kPc from the Earth. This system is analogous to our Jupiter/Saturn system in that the two planets have the same mass ratios as Jupiter and Saturn as well as the same ratio of orbital radii, and the same (inferred) equilibrium temperatures (Gaudi et al. 2008; Bennett et al. 2010).

Figure 1 shows the observed light curve for the OGLE-2006-BLG-109 microlensing event, including data from OGLE, various MicroFUN telescopes, MOA, PLANET, and RoboNet. Five features are labeled. Four of these are due to the Saturn-mass planet, whereas the fifth can only be explained by a second, Jupiter-mass planet. The inset shows the path of the source through the caustic, with the locations of the source which give rise to the five features labeled.

Cross-References

- [Exoplanets, Discovery](#)
- [Microlensing Follow-Up Network](#)
- [Microlensing Observations in Astrophysics](#)
- [Optical Gravitational Lensing Experiment](#)
- [Probing Lensing Anomalies Network](#)

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OH

- [Hydroxyl Radical \(OH\)](#)
- [Water, Related Interstellar Radicals and Ions](#)

OH⁺

► [Water, Related Interstellar Radicals and Ions](#)

Oligarchic Growth

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

Oligarchic growth is the second-to-last stage in the formation of ► [terrestrial planets](#) and ► [giant planet cores](#). During this stage, the largest ► [planetary embryos](#) grow quickly while the smallest grow slowly, leading to a bifurcated mass distribution with a number of lunar- to Mars-mass embryos embedded in a swarm of smaller planetesimals. Oligarchic growth transitions to chaotic growth when the planetary embryos become large enough to overcome eccentricity damping due to ► [dynamical friction](#) from smaller planetesimals. This leads to embryo–embryo collisions and signals the last stage of accretion of terrestrial planets and giant planet cores.

Cross-References

- [Late-Stage Accretion](#)
- [Magnetic Fields and Planetary Systems Formation](#)
- [Planetesimals](#)
- [Runaway Growth](#)

Oligomer

Gözen Ertem

National Institutes of Health, Bethesda, MD, USA

Definition

The term oligomer is derived from the Greek “oligos,” meaning “a few.” In chemistry, an

oligomer is a short polymer consisting of approximately five monomer units, although agreement as to the strict length cutoff is debated and varies between four and one hundred. Oligomers are formed by oligomerization, which involves linking the monomer units together in a chemical reaction. Unlike a ► [polymer](#), if one of the repeating units of oligomer is removed, its chemical properties may be significantly altered.

In biochemistry, the term oligomer is commonly used for short, single-stranded DNA fragments, used in ► [hybridization](#) experiments as ► [primers](#). It can also indicate a short protein made of two or more subunits.

Cross-References

- [Hybridization](#)
- [Nucleic Acids](#)
- [Polymer](#)
- [Primer](#)
- [Protein](#)

Oligomerization

Shin Miyakawa

6-1-7 Minami Hatsutomi, Kamagaya, Chiba,
Japan

Definition

Oligomerization is a chemical process that links monomeric compounds (e.g., amino acids, nucleotides, or monosaccharides) to form dimers, trimers, tetramers, or longer chain molecules (oligomers). Examples are the conversion of nucleotides to oligonucleotides and amino acids to peptides. The boundary between what is considered an oligomer and a ► [polymer](#) is unclear, but it is usually accepted to be in the range of 10–100 monomer units. Prebiotic experiments have shown that ► [activated nucleotides](#) can be oligomerized using ► [clay](#) minerals as catalyst.

Cross-References

- ▶ [Activated Nucleotide](#)
- ▶ [Amino Acid](#)
- ▶ [Clay](#)
- ▶ [Mineral](#)
- ▶ [Monosaccharide](#)
- ▶ [Nucleotide](#)
- ▶ [Oligonucleotide](#)
- ▶ [Oligopeptide](#)
- ▶ [Polymer](#)
- ▶ [Prebiotic Chemistry](#)

Oligonucleotide

Kunio Kawamura

Department of Human Environmental Studies,
Hiroshima Shudo University, Hiroshima, Japan

Keywords

Chemical evolution · Nucleotide ·
Oligonucleotide · RNA

Synonyms

[DNA](#); [Nucleotide oligomer](#); [RNA](#)

Definition

An oligonucleotide is a relatively short RNA or DNA polymer linked via phosphodiester bonds. Under prebiotic conditions, oligonucleotides of RNA can be formed from ▶ [activated nucleotide](#) monomers including different kinds of nucleotide bases: ▶ [guanine](#), ▶ [adenine](#), uracil, ▶ [cytosine](#), and ▶ [hypoxanthine](#). The oligonucleotides of RNA formed under the primitive earth conditions normally contain both 2', 5'- or 3', 5'- linkages and often contain a 5'-residue linked by a diphosphate linkage.

Overview

The formation of oligonucleotides would have been an essential step for the emergence of life on the

primitive earth. In modern organisms, polymerization of RNA or DNA monomers merely proceeds from nucleoside 5'-triphosphate monomers in the presence of DNA template and specific enzymes. On the contrary, the prebiotic formation of RNA with 50 nucleotide units in length proceeds from nucleoside 5'-phosphorimidazolides under simulated primitive earth conditions. However, the prebiotic formation of DNA does not proceed from such activated nucleotide monomers.

Although the usage of condensation reagents is possible to form oligonucleotides from nucleotide monomers, the activated nucleotides are more effectively used to form long oligonucleotides with high yield. Continuous investigations have been carried out to identify the pathways for prebiotic formation of RNA oligonucleotide. Successful examples include the oligonucleotide formation from the activated nucleotide monomers in the presence of metal ions (Sawai [1976](#)), that in the presence of montmorillonite clay catalyst (Ferris and Ertem [1992](#); Huang and Ferris [2006](#)), that in the presence of a polynucleotide template (Inoue and Orgel [1983](#)). Normally, the condensation of the activated nucleotide monomers provides oligonucleotides with an average length of ten units in the presence of metal ion catalyst or clay mineral catalyst. Besides, spontaneous condensation of the activated nucleotide by continuous addition of the activated nucleotide in the presence of ▶ [montmorillonite](#) clay results in the formation of oligonucleotides up to 50-mer in length (Ferris et al. [1996](#)). On the other hand, oligoguanylates up to 40-mer in length form by the condensation of guanosine 5'-phosphorimidazolid on a polycytidylate template with Zn^{2+} ion, where the Watson-Crick hydrogen bonding directs the activated monomers of guanosine nucleotide on the template polynucleotide. However, this template-directed reaction is not efficient for the condensation of adenosine, uridine, or cytidine 5'-phosphorimidazolid on the complementary polynucleotide template. This is probably due to the fact that the template-directed formation of oligonucleotides is mainly supported by the stacking interactions between the activated nucleotide monomers rather than the Watson-Crick hydrogen bonding between the

activated nucleotide and the complementary template. At the same time, it has been confirmed that the replication of oligonucleotides partially proceeds from the mixture of four types of activated nucleotide monomers in the presence of mixed base template polynucleotides. Although the formation of oligonucleotide in the absence of the activated nucleotide is not considered to be successful, the possible pathway for the formation of oligonucleotide from nucleoside 3', 5'-cyclic monophosphate has been suggested recently (Costanzo et al. 2009).

Cross-References

- ▶ [Activated Nucleotide](#)
- ▶ [Montmorillonite](#)
- ▶ [Nucleic Acids](#)
- ▶ [Nucleoside Phosphoimidazolid](#)
- ▶ [RNA World](#)
- ▶ [Self-Replication](#)
- ▶ [Template-Directed Polymerization](#)

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Oligonucleotide Library

- ▶ [Combinatorial Nucleic Acid Library](#)

Oligopeptide

Jean-François Lambert

Laboratoire de Réactivité de Surface, Université Pierre et Marie Curie, Paris, France

Keywords

Activation · Amino acids · Peptides · Proteins

Synonyms

[Peptide](#)

Definition

An oligopeptide is a short-chain peptide, i.e., a polymer of ▶ [amino acids](#) (AAs) connected by amide, or more precisely peptide, linkages. The term is usually limited to peptides with less than 20–25 amino acid residues.

Overview

In “peptides-first” scenarios for the emergence of biomacromolecules, oligopeptides capable of specific catalysis of some biological reactions (primitive metabolism) are suggested to have appeared without the previous existence of genetic material. For instance, in his protometabolic model, de Duve (1991) calls these short peptides “multimers.”

Chemically, the emergence of oligopeptides from preexisting amino acids poses several problems. The first two are consequences of chemical thermodynamics. The condensation of an amide bond between two AAs is thermodynamically unfavorable in solution, thus the amount of oligopeptide in an amino acid solution at equilibrium falls quickly with the peptide chain length: for instance, a glycine solution with a total AA concentration of 0.5 M, at equilibrium, would contain only one molecule of 18-m per 100 km³.

In addition, the formation of oligomers from a mixture of different amino acids would likely

show little selectivity, i.e., all possible sequences would be randomly formed. Since the number of sequences increases exponentially with the peptide length, the probability of forming significant amounts of a specific oligomer is vanishingly low.

The last problem concerns the slow kinetics of oligomerization: at room temperature and moderate pH, completion of the reaction would take several centuries due to high activation energy barriers.

Several solutions have been proposed to allow the prebiotic emergence of oligopeptides with a reasonable probability:

- They could have formed in submarine hydrothermal vents: thermodynamic equilibria are displaced toward AA oligomerization in hydrothermal conditions, although probably not enough to give high peptide yields.
- Oligomerization could have been coupled to a thermodynamically downhill chemical process. This would involve the input of “high-energy molecules” (more properly, molecules with high free enthalpies of formation) such as nitrogen oxides.
- Alternatively, it may have occurred in the “adsorbed state,” i.e., after adsorption of the AAs on mineral surfaces (“polymerisation on the rocks,” Orgel 1998). This hypothesis connects well to “surface metabolism” scenarios (e.g., those of Wächtershäuser) and may solve the kinetic as well as the thermodynamic problem, since catalysis by surface groups is likely.

The last two scenarios have been shown empirically to result in the formation of oligopeptides up to the pentamers at least, even though molecular details remain sketchy. It is noteworthy that they are only successful in fluctuating environments, i.e., when coupled with variations of the macroscopic conditions such as wetting and drying cycles.

Cross-References

- [Amino Acid](#)
- [Oligonucleotide](#)

- [Peptide](#)
- [Polypeptide](#)

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Olivine

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Mars · The Moon · Stardust mission · Comet Wild 2 · Chondrites · Meteorites · Moderately refractory elements

Synonyms

[Peridot](#)

Chemical Formula

Mg_2SiO_4 (forsterite), Fe_2SiO_4 (fayalite)

Definition

Olivine is a magnesium-iron silicate mineral of the orthorhombic crystal system and belonging to the *nesosilicates* (i.e., composed of a single silica tetrahedra; see ► [Geological data](#)). The ratio of magnesium and iron varies between two endmembers of the solid solution series: forsterite (Mg-endmember) and fayalite (Fe-endmember). Olivine is a common mineral in mafic (basalt) and ultramafic (peridotite) magmatic rocks on Earth and ubiquitous in chondrites. At pressures corresponding to 400 km in the Earth, olivine transforms into its wadsleyite polymorph, which defines the roof of the transition zone.

Overview

Being composed of moderately refractory elements (Fe, Mg, Si), olivine is one of the silicate minerals that first condensed from the cooling Solar nebula. The pure forsterite endmember melting point is 1890 °C and the pure fayalite one has a melting point of ca. 1200 °C. The spectral signature of olivine has been detected in the dust disks around young stars (Draine 2003). Olivine is omnipresent in meteorites except for enstatite chondrites (dominated by pyroxene) and a few carbonaceous chondrites (Mason 1963). In chondrites and pallasites, polymorphs (minerals with the same chemical composition but different crystal structures) of the forsterite, such as wadsleyite and ringwoodite, can be commonly found.

Olivine occurs in Moon mare basalts (Meyer 2003). Spectra of the Martian surface from the Mars Global Surveyor Thermal Emission Spectrometer (TES) showed the occurrence of several outcrops of olivine-bearing rock in a 30,000-square-kilometer area located in the *Nili Fossae* region, northeast of *Syrtis Major* (Hoefen et al. 2003).

Analysis of Comet 81P/Wild 2 particles returned by the Stardust mission has revealed

abundant silicate grains that appear to have formed in the inner regions of the solar nebula (Brownlee et al. 2006). Particles similar to amoeboid olivine aggregates (AOAs) were discovered (Brownlee et al. 2006) together with CAIs (Simon et al. 2008). AOAs are lumpy, olivine-rich inclusions up to a few millimeters across, found in CV3 meteorites such as Efremovka, Leoville, and Vigarano (Ruzicka et al. 2012). The findings in Comet Wild 2 were very surprising because it is expected that comets form in the outer Solar system, where refractory elements such as Ca and Fe are depleted. The abundance of high-temperature nebular solids at the edge of the Solar system is strong evidence for massive outward transport of inner Solar system materials by a variety of nebular processes (Bockelee-Morvan et al. 2002). An alternative view is that the high-temperature components originated in the outer Solar system, perhaps inside transient Jupiter-mass objects that formed in the outer Solar system but were disrupted (Bridges et al. 2012).

Cross-References

- [Basalt](#)
- [Chondrite](#)
- [Comet Wild 2](#)
- [Mafic and Felsic](#)
- [Mars](#)
- [Meteorites](#)
- [Moon, The](#)
- [Peridotite](#)
- [Stardust Mission](#)
- [Ultramafic Rocks](#)

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- [Solar System, Inner](#)
- [Tharsis](#)

‘Omics Technologies

Alexander J. Probst

Department of Chemistry, Institute for Environmental Microbiology and Biotechnology, University of Duisburg-Essen, Essen, Germany

Keywords

Genomics · Transcriptomics · Proteomics · Metabolomics

Olympus Mons

Ernst Hauber

Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Definition

Olympus Mons is the largest known ► [volcano](#) on ► [Mars](#) and in the entire ► [Solar System](#) (height above the Martian topographic datum: 22 km; height above surrounding plains: ~20 km; basal diameter: ~640 km). The flanks are covered by tube-fed and channel-fed lava flows and have slopes of typically ~3–5°, except for a steeper, up to 6 km-high basal scarp. The morphological analogy to terrestrial volcanoes (e.g., Hawaii, Galapagos) suggests that Olympus Mons is a basaltic shield volcano. A summit caldera has ~80 km diameter and developed in multiple stages over the last several hundred million years (Ma). Some lava flows are probably even younger (~10 Ma), indicating possible ongoing volcanism on Mars.

Cross-References

- [Basalt](#)
- [Mars](#)

Definition

The term ‘omics technologies summarizes all shotgun-based molecular methods for studying biological molecules of cellular organisms and includes the technologies *genomics*, *transcriptomics*, *proteomics*, and *metabolomics*. It furthermore encompasses also subcategories of each of the aforementioned technologies like lipidomics as a subcategory for metabolomics.

History

The term ‘omics was coined fairly late (1990s) compared to the actual development of the different technologies themselves that it encompasses. For instance, the field of genomics began to attract interest of researchers already in the 1960s. In 2004 the term *metagenomics* was introduced to the literature (Tyson et al. 2004), followed by other meta’*omics* technologies in the years after. Meta’omics techniques such as metagenomics or metatranscriptomics do not focus on studying biological molecules of one organism rather of a community of organisms from, e.g., an environmental sample. Novel technologies developed around studying microorganisms have also led to many neologisms that include the term ‘omics, such as *culturomics* (Kambouris et al. 2018), but do not reflect the original meaning of the

terminology and are sometimes misleading due to ambiguity arising from overlaps with other areas of sciences.

Overview

Genomics as the first of all 'omics technologies deals with the analysis of genomic sequences, ideally a whole genome of a target organism (Blattner et al. 1997). Genomics includes the reconstruction of the sequence, gene prediction, and functional gene annotation. Transcriptomics in contrast is set out with the aim of analyzing the entire transcriptional pool of an organism culture including ribosomal RNA, transfer RNA, messenger RNA, and small RNA and is thus also termed genome-wide expression profiling. Comparative transcriptomics can, for instance, lead to important conclusions about the different genes that are expressed by cells under different conditions, for instance, comparing regular cells to cancerous cells (Rhodes and Chinnaiyan 2005). Proteomics deals with the analysis of the protein pool of cultured cells (Patterson and Aebersold 2003), enabling the conclusion which genes were expressed during the cultivation conditions. The basis for proteomics is genomics as the derived protein sequences are fragmented and need to be matched to a genomic database. For metabolomics all substrates and products (metabolites) of biochemical reactions from a cellular culture are measured and related to the metabolic pathways predicted from other 'omics technologies (Wu et al. 2005).

The basic methodological approach of all 'omics technologies is a shotgun approach, i.e., not a single gene, gene product, or metabolite is analyzed regarding its composition or relative abundance but the entire cellular pool of the respective molecules. Consequently, the initial step of each 'omic technology is extracting DNA, RNA, proteins, or metabolites from a cellular culture. In the next steps, the respective molecules are fragmented and/or chemically analyzed. The subsequent steps involve heavy computational lifting by assembling the fragments and/or comparing the derived information to

comprehensive databases, a research field termed bioinformatics.

In Astrobiology, genomics and transcriptomics have been applied to a variety of scientific tasks, mainly geared toward the understanding of genomic capacities of microorganisms or their responses to stress conditions. For instance, the analysis of the genome of *Bacillus pumilus* strain SAFR-032, an extremely resistant spore former, shed light onto its encoded DNA repair mechanism (Gioia et al. 2007). Another example is the genome-wide transcriptomic response of *Serratia liquefaciens* after exposure to simulated Mars conditions, which revealed an upregulation on many transporters, DNA repair mechanisms, and the translation machinery compared to regular cultivation conditions (Fajardo-Cavazos et al. 2018).

Cross-References

- [Deep-Sea Microbiology](#)
- [Deep Subsurface Microbiology](#)
- [Genomics](#)
- [Geomicrobiology](#)
- [Hot Spring Microbiology](#)
- [Hot Vent Microbiology](#)
- [Microbiome of the International Space Station](#)
- [Proteome, Proteomics](#)

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Onverwacht Group

Gary R. Byerly

Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA, USA

Keywords

Archean stratigraphy · Komatiitic volcanism · Large asteroidal impacts · Early life

Definition

The Onverwacht Group in the ► [Barberton Greenstone Belt](#) is a major stratigraphic unit comprising the lower part of the ► [Barberton Supergroup](#) (formerly Swaziland Supergroup) in South Africa and Swaziland. The Onverwacht Group is a predominantly volcanic sequence bounded by a number of major faults, and thus only minimum thicknesses and ages are known. Composite sections of the Onverwacht Group are 10–12 km in thickness and range in age from 3,550 to 3,270 Ma. Microfossils and stromatolites in carbonaceous cherts occur as sedimentary interbeds. Komatiitic volcanism was first documented in the Onverwacht Group. Eight large asteroidal impact layers have been found.

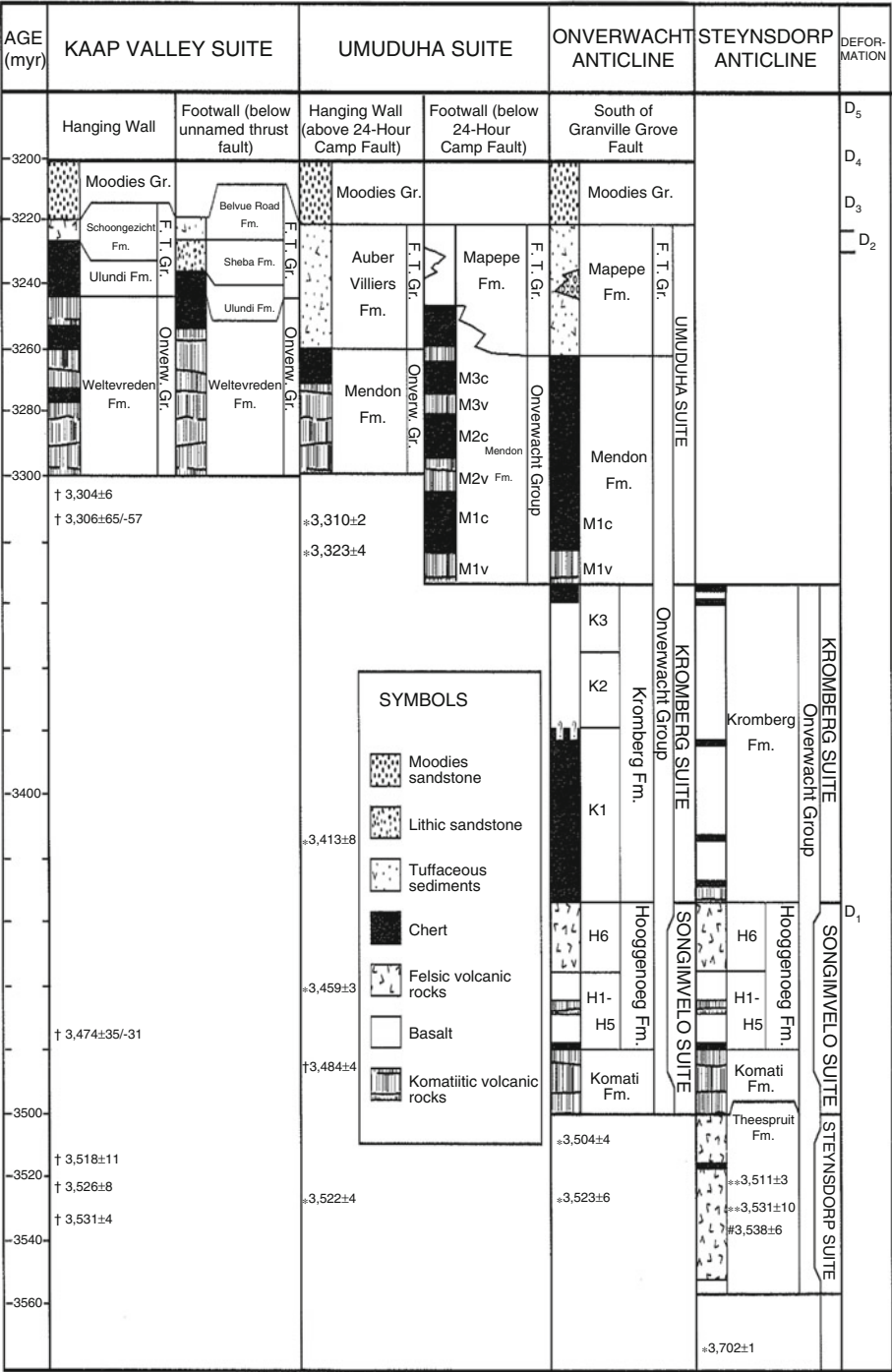
Overview

The Onverwacht Group in the Barberton Greenstone Belt is a major stratigraphic unit comprising

the lower part of the Barberton Supergroup (formerly Swaziland Supergroup) in South Africa and Swaziland (Viljoen and Viljoen 1969). The Onverwacht is a predominantly volcanic sequence bounded by a number of major faults, and thus only minimum thicknesses and ages are known. A generalized map of the greenstone belt, including the areal distribution of the Onverwacht, is found in Anhaeusser and others (1981), and a detailed map, revised stratigraphic nomenclature, and structural cross sections of the central greenstone belt are found in Lowe et al. (2012). Composite sections of the Onverwacht are 10–12 km in thickness and range in age from about 3,550 to about 3,270 Ma (Lowe and Byerly 2007) (Fig. 1).

As summarized in Lowe and Byerly (2007), the Onverwacht Group likely formed during three to four major tectonic cycles each of which resulted in major basaltic to komatiitic platforms followed by local development of dacitic volcanism linked to contemporaneous TTG plutonism along the southern, western, and northern margins of the greenstone belt. These tectonic cycles include progressively younger units from south to north. Four to five structural domains make up the Barberton Greenstone Belt. Each contains recognizable units of the Onverwacht Group but often with distinctive facies changes across the bounding faults.

The Onverwacht Group was likely assembled by a combination of tectonic and magmatic accretion. The southeastern most domains of the Onverwacht contain the oldest units, the Sandspruit Formation, consisting dominantly of komatiitic lavas, and the overlying Theespruit Formation, which includes komatiitic, basaltic, and dacitic lavas, the latter dated at 3,511–3,538 Ma. The overlying Komati Formation (Viljoen and Viljoen 1969), at 3,482 Ma (Dann 2000), is largely comprised of komatiites in the lower several kilometers but contains much more basalt and basaltic komatiite in the upper several kilometers. The 3.5 km-thick composite section of the Komati Formation contains no chert units and only a single thin dacitic ash bed. The Komati-Theespruit contact is everywhere represented by a major fault. Overlying the Komati Formation are the classic “upper Onverwacht formations” of



Onverwacht Group, Fig. 1 Stratigraphic and tectonic summary of the major units of the Barberton Supergroup (Lowe and Byerly 2007)

Viljoen and Viljoen (1969) – the Hooggenoeg and Kromberg Formations, each about 2 km in thickness. The Hooggenoeg is dominated by basalt and basaltic komatiite but contains five major chert units and is capped by a thick pile of dacitic volcanics (ca. 3,445 Ma). The Kromberg Formation along the west limb of the Onverwacht Anticline has a basal member of silicified volcanoclastics and carbonaceous and ferruginous banded cherts that are up to 400 m thick. These cherts contain what is arguably the best evidence for life in the Onverwacht Group. The basal unit of the Kromberg, K1e, has been dated at 3,416 Ma; the uppermost unit, K3c, at 3,330 Ma. Lowe and Byerly (1999) introduced two formations to the Onverwacht Group: In the south-central areas of the greenstone belt, the youngest unit of the Onverwacht Group is represented by the Mendon Formation, about 1 km thick, subdivided into six formal members, each with a chert unit capping a series of komatiitic flows. Each member of the Mendon Formation has a distinctive chemical composition (representing the most extreme komatiitic compositions found in the greenstone belt, with Al/Ti ranging from 5 to 100), and each chert has distinctive and correlative features, including volcanic ash beds, impact layers, and stromatolitic beds. In the northern areas of the greenstone belt, the 1–2 km thick Weltevreden Formation appears to be comparable in age to the Mendon Formation but is very different in its stratigraphy. Strata of the 2–3 km thick Weltevreden Formation have a very narrow range of komatiitic composition and nearly chondritic to slightly superchondritic Al/Ti. They contain remarkably fresh komatiites with fresh olivine and fresh glassy melt inclusions and thick deposits of komatiitic ash (Stiegler-Thompson et al. 2010). Several internal ages from the Mendon and Weltevreden Formations range from 3,300 to 3,270 Ma (Puchtel et al. 2013). De Wit and others (2011) offer a number of opposing perspectives on the geology of the Onverwacht Group.

Diagenesis, Archean weathering, metamorphism, metasomatism, and modern weathering have significantly modified the original igneous and sedimentary rocks of the Onverwacht. There

is nearly ubiquitous silicification of sediment in the Onverwacht. Carbonaceous matter, volcanic ash, ferruginous matter, and evaporitic materials are all subject to very early diagenetic or metasomatic silicification. Komatiitic lavas are in places highly silicified, likely by processes similar to those that act on sediment and likely at the Archean seawater-rock interface (Hanor and Duchac 1990). Metamorphism is rather uniform at lower greenschist facies for interior sections of the greenstone belt (Xie et al. 1997), although the lowest formations are only found in close contact with younger TTG plutons and typically display amphibolite facies metamorphic grade (Moyen et al. 2006).

Microfossils and microbial mats (Walsh 2010), organic matter (Tice and Lowe 2006), and stromatolites (Byerly et al. 1986) in Onverwacht Group sedimentary interbeds represent some of the most compelling evidence for early life on Earth. Microfossils include a variety of morphologies and sizes, suggesting a considerable diversity of early life in these early shallow-marine environments. Banerjee and others (2006) report the preservation of microbial biomarkers in pillow lavas from the Onverwacht. Recent studies have added isotopic and chemical analyses of individual microfossils (van Zuilen et al. 2007).

Komatiitic volcanism was first documented in the Onverwacht Group (Viljoen and Viljoen 1969). The discovery section and Komati-type section occur just north of the Komati River in the BGB. The Viljoen brothers studied both the lower and upper formations of the Onverwacht Group, but their work in demonstrating that komatiites represent lava flows is particularly important. Dann (2000) re-examined the Komati Formation, adding new detail to the volcanic architecture of this unit. Stiegler-Thompson and others (2010) further documented the widespread distribution of explosive komatiitic volcanism in the Onverwacht Group. The origins of komatiites, and particularly those of the Onverwacht Group, are debated in a series of publications using a variety of mineralogical, isotopic, and chemical information to support a wet-low temperature-subduction origin versus a dry-high temperature-plume origin (Parman et al. 1997; Robin Popieul et al. 2012; Puchtel et al. 2013).

Eight large asteroidal impact layers have been found in the Onverwacht Group (Lowe et al. 2003, 2014). Cr-isotope evidence has provided strong confirmation of the impact hypothesis. Each of these impacts was likely larger than the K/T impact, and several were likely comparable to other late-heavy bombardment impacts of the inner solar system that gave rise to the lunar maria. The impact layer in Hooggenoeg member H4c, the S1 impact layer, has been dated at 3,472 Ma and correlated with an impact layer of the same age in the Pilbara of western Australia (Byerly et al. 2002). A new impact layer has been identified in the lower Kromberg Formation and two other impact layers in the Mendon Formation.

Surface environments have been examined based on sedimentary cherts found within the Onverwacht Group (Tice and Lowe 2006). The lavas and sediments appear to have been deposited on a marine platform, with environments ranging from subwavebase to supratidal. Explosive volcanism resulted in significant deposits of airborne and wind-transported materials. Except for the latest stage of the Hooggenoeg Formation, when a large dacitic volcanic center evolved, topographic relief was low and resulted in the widespread distribution of units with only minor changes in thickness. At the end of Hooggenoeg time, enough relief was present that turbidites flanked the main volcanic center.

Cross-References

- [Archean Drilling Projects](#)
- [Archean Environmental Conditions](#)
- [Archean Eon](#)
- [Archean Mantle](#)
- [Archean Tectonics](#)
- [Archean Traces of Life](#)
- [Barberton Greenstone Belt](#)
- [Barberton Greenstone Belt, Sedimentology](#)
- [Barberton Greenstone Belt, Traces of Early Life](#)
- [Barberton Supergroup](#)
- [Greenstone Belt](#)
- [Komatiite](#)
- [Microfossils](#)
- [Serpentinization](#)

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Oort Cloud

Jacques Crovisier
Observatoire de Paris, LESIA, Meudon, France

Keywords

Comets · Small bodies

Definition

The Oort cloud is a spherical cloud of ► [comets](#) surrounding the Solar System and extending out to heliocentric distances greater than 100,000 AU.

Overview

The idea of a distant reservoir of ► [comets](#), extending to the verge of the ► [Solar System](#), was already discussed by Giovanni Schiaparelli (1910) and Ernst Öpik (1932). The Dutch astronomer Jan Oort (1900–1992) pointed out in 1950 the need of such a reservoir to explain the continuous input of new long-period comets. He showed, from the data gathered by Van Woerkom (1948), that many long-period comets have their aphelia at more than 20,000 AU. This reservoir is now known as the “Oort cloud.”

The Oort cloud is supposed to be spherical, extending from 20,000 AU from the Sun to 200,000 AU (the limit of the gravitational influence of the Sun). It could comprise as many as 10^{12} comets.

These comets cannot be directly observed in the Oort cloud, being too far from the Sun to manifest any activity. Following perturbations by a nearby star (or by a hypothetical distant planet), they may be transferred to orbits bringing them close to the Sun, where they become active. Such “Oort-cloud comets” have random inclination over the ecliptic and belong to the family of “nearly isotropic comets.” The most famous of them is 1P/Halley.

Comets stored in the Oort cloud were not formed there. They were formed further inward in the Solar System (presumably in the Jupiter – Uranus region) and subsequently ejected to the outer Solar System following gravitational perturbations by the giant planets.

The Oort cloud contrasts with the alternate reservoir of comets, the ► [Kuiper belt](#), which is at the origin of Jupiter-family comets.

Cross-References

- [Comet](#)
- [Kuiper Belt](#)
- [Trans-Neptunian Object](#)

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Opacity

Sylvia Ekström
Observatoire Astronomique de l'Université de Genève, Faculté des Sciences, Université de Genève, Versoix, Switzerland

Definition

Opacity measures the property of a medium to attenuate light. The opacity depends on the composition of the medium, its density, and temperature, but also on the wavelength considered. The *absorption coefficient* a_v (with units $[\text{cm}^{-1}]$) enters into the definition of the ► [optical depth](#). More often in astronomy, it is the mass absorption coefficient $\kappa_v = a_v/\rho$ (with units $[\text{cm}^2 \text{g}^{-1}]$) which is used.

The main sources of opacity in an astronomical context are:

- Electron scattering (at temperatures of the order one billion K).
- Electronic transitions (free-free, bound-free, or bound-bound at temperature of the order 10,000 K).
- Molecular or dust absorption (around or below 3000 K).

The opacity plays an essential role in radiative transfer, and thus in the energetic equilibrium of stars.

Cross-References

- [Mean Free Path](#)
- [Optical Depth](#)
- [Radiative Transfer](#)

Opaline Silica on Mars

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Institut für Planetenforschung, Berlin, Germany

Definition

Opaline silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) occurs at several locations on ► [Mars](#), although the definitive identification is contentious. The confirmed finding would indicate past aqueous activity. Aqueous free silica is a product of ► [basalt](#) weathering, when the interaction of water with mafic (i.e., Mg- and Fe-rich, silica-poor) ► [rock](#) rapidly dissolves olivine, pyroxene, and glass. Opaline silica could have been precipitated in hydrothermal or lacustrine (related to a lake) evaporitic environments on Mars. On Earth, it rarely persists more than a few million years, because it rapidly transforms into microcrystalline quartz during ► [diagenesis](#). The persistence of opaline silica on Mars over much longer geologic timescales (billions of years) indicates that water was not present for extended periods of time.

Cross-References

- [Basalt](#)
- [Chert](#)
- [Diagenesis](#)
- [Hydrothermal Environments](#)

- [Mars](#)
- [Rock](#)
- [Weathering](#)

Oparin's Conception of Origins of Life

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes,
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Nantes, France

History

In 1924, Alexander Ivanovitch Oparin (1894–1980), a young scientist in vegetal physiology, published in Moscow a very important text about the origin of life. With this text, he began a very long career devoted to this topic. He wrote important books and developed very active experimental researches.

He published this first text, entitled *Origins of Life*, in Russian. He described the evolution of earth and the transformation of matter from mineral molecules to organic molecules. Finally, according to him, little drops of organic matter could appear, which constituted the last step before becoming cells.

In 1936, Oparin published an important book entitled *Origins of Life*. In an interdisciplinary approach, he suggested a broad scenario of the origins of life on Earth, describing all the steps of the evolution of the Earth, of matter, and of primordial life. This book knew a great success and was translated into several languages, and especially into English in 1938.

This book is an exhaustive presentation of Oparin's ideas, very close to his 1924 conception. However, he introduced a lot of current scientific data and two specific points have to be underlined. Firstly, Oparin introduced the notion of coacervate coming from Bungenberg de Jong's work. Coacervates were microscopical vesicles formed in colloidal solutions and Oparin used them as a model of a primitive cell in his theory. Secondly,

Oparin claimed that the primitive atmosphere did not contain CO₂, and that it was reductive.

After the Second War, this book still was a point of reference. For example, John Desmond Bernal (1901–1971) quoted it (1951). In 1952, Harold Clayton Urey (1893–1981), the American physicist, wrote a synthesis on the primitive conditions and referred to Oparin (1938) about the lack of CO₂ in the primitive atmosphere and agreed with the Soviet scientist on this point.

During the following three decades, Oparin, who had important academic positions in the USSR, continued to be the leader of this topic in his country. He particularly worked on primitive metabolism and developed a heterotrophic hypothesis on the origin of life on Earth. However, in the lyssenkoist context, he neglected to work on heredity molecules.

Cross-References

- [Bernal's Conception of Origins of Life](#)
- [Calvin's Conception of Origins of Life](#)
- [Haldane's Conception of Origins of Life](#)
- [Miller, Stanley](#)
- [Monod's Conception on the Origins of Life](#)
- [Urey's Conception of Origins of Life](#)

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Open Cluster

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

An open star cluster is a loosely bound group of a few 10³ stars formed from the same giant

molecular cloud and thus having the same age and ► [metallicity](#) (chemical composition). This property makes them valuable tools for the study of stellar evolution. Contrary to ► [globular clusters](#), open clusters are relatively young (less than a few 10^8 years old) and they are found in the plane of the Milky Way. About a thousand open clusters are known in the galaxy, but their total number may be ten times higher. The best known example is the Pleiades (10^8 year). Various processes (tidal interactions with giant molecular clouds and spiral arms) tend to disperse its members and dissolve an open cluster.

Cross-References

- [Globular Cluster](#)
- [Metallicity](#)

Operational Taxonomic Unit

- [Phylotype](#)

Operon

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Polycistronic transcript](#)

Definition

An operon is a group of genes whose products have related or complementary functions and which are transcribed as a unit. Polycistronic or multi-genes are then independently translated by ribosomes into the individual, functionally related proteins. Many bacterial and archaeal genes are organized

into operons, while they are exceptional in eukaryotes. The operon model was proposed by F. Jacob and J. Monod in 1961 to explain the coordinated regulation of co-transcribed genes involved in the metabolism of lactose in *Escherichia coli*. The so-called *lac* operon spans about 6000 nts and includes a promoter, an operator, three adjacent structural genes coding for the enzymes required for lactose metabolism, and a terminator. Regulation of the *Lac* operon was the first complex genetic regulatory mechanism to be elucidated.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Gene](#)
- [Genome](#)
- [Transcription](#)

Ophiolite

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble, France

Definition

An *ophiolite* is a slice of oceanic crust and underlying mantle that is thrust onto a continent by obduction. The stratigraphic sequence observed in an ophiolite corresponds to the layering observed of oceanic crust (from top to bottom): an upper layer of oceanic siliceous or carbonate sediments; a layer of pillow basalt followed by a layer of sheeted near-vertical diabase dykes; layers of gabbro and plagioclase or mafic cumulates; and a basal layer of “tectonite,” the deformed harzburgite (a type of peridotite) of the uppermost mantle. Many ophiolites contain only some of these lithologies. Debate surrounds the question of whether any ophiolite represents normal oceanic crust formed at mid-oceanic ridges. The geochemical compositions of basalt indicate that many ophiolites are

segments of crust that formed in back-arc basins (extensional zones on the edge of the continent at subduction zones). Reactions between water and ophiolite at high temperatures (300 °C) can produce low-molecular hydrocarbons by abiotic Fischer-Tropsch-type reactions during serpentinization.

Cross-References

- [Basalt](#)
- [Fischer-Tropsch-Type Reaction](#)
- [Mantle](#)
- [Mid-ocean Ridge](#)
- [Obduction](#)
- [Oceanic Crust](#)
- [Peridotite](#)
- [Pillow Lava](#)
- [Plate Tectonics](#)
- [Serpentinization](#)
- [Subduction](#)

Optical Depth

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Optical thickness](#)

Definition

The optical depth is a dimensionless quantity, generally noted τ , that measures how absorbing – or ► [scattering](#) – a slab in a medium is, for an electromagnetic wave that propagates in this medium. Despite the term *optical*, this quantity does not refer to visual radiation only, but to any type of electromagnetic wave (from gamma-rays to radio). Depending on whether $\tau < 1$ or $\tau > 1$, a slab of medium is said to be optically thin or optically thick. In a medium of constant

density, the optical depth is proportional to the thickness of the slab.

In an absorbing medium, the intensity of inward radiation decreases as $\exp(-\tau)$ along the path it travels. In an emitting medium, such as a stellar ► [photosphere](#), or a planetary atmosphere in the infrared, the outward radiation is often well approximated by assuming that it comes entirely from the layer seen at optical depth $\tau = 1$ (Barbier-Eddington approximation).

Examples of media where the notion of optical depth applies: clouds of gas and dust in galaxies (visible, near-IR), stellar atmospheres (gamma-rays, visible), neutral or ionized interstellar medium (radio), planetary atmospheres (UV, visible, infrared).

Cross-References

- [Extinction, Interstellar or Atmospheric](#)
- [Opacity](#)
- [Radiative Transfer](#)
- [Scattering](#)

Optical Gravitational Lensing Experiment

David W. Latham¹, B. Scott Gaudi² and Nader Haghighipour³

¹Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

²Department of Astronomy, Ohio State
University, Columbus, OH, USA

³Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Synonyms

[OGLE](#)

Definition

OGLE (Optical Gravitational Lensing Experiment) is a collaboration of primarily Polish

astronomers that uses wide-field temporal photometric monitoring to study a broad range of astrophysical phenomena. The original goal of the OGLE collaboration was to search for dark matter with the gravitational microlensing technique. However, since its inception, OGLE has also played a central role in the search for exoplanets with microlensing. In addition, OGLE identified the first transiting planets found by photometry (as opposed to radial-velocity planets) and has contributed to the study of variable stars, Galactic structure, strong gravitational lenses, and ► [Kuiper belt](#) objects. OGLE project has gone through four phases. Phase III (2001–2009) was devoted to detecting gravitational microlensing effects and transiting planets. During this phase, OGLE project discovered several planets including ► [OGLE-2005-BLG-390Lb](#), the first super-Earth detected by the microlensing effect, and OGLE-2006-BLG-lb,c, the first multiple planet system detected by microlensing. Phase IV of OGLE project started in 2010. The main goal of this phase is to increase the number of planet detection via microlensing. At the moment, 23 planets have been detected by the OGLE project.

The Principal Investigator of the OGLE collaboration is Andrej Udalski from Warsaw University. The OGLE 1.3-m telescope is located at the Las Campanas Observatory in Chile.

Cross-References

► [Exoplanets, Discovery](#)

Optical Rotatory Power

► [Rotatory Power](#)

Optical Thickness

► [Optical Depth](#)

Orbit

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Gravity · Kepler · Newton

Definition

The orbit of a celestial body is its path around a central mass, caused by the acceleration due to the gravitational force between them. The planets and minor bodies such as asteroids and comets in the Solar System orbit the Sun, while any celestial body in the Solar System that orbits something other than the Sun is called a satellite (moon). Long-term orbital motion is affected by the gravitational forces due to all bodies in the vicinity, as well as to torques due to forces such as gas drag, ► [dynamical friction](#), and radiation pressure.

History

The concept of a celestial orbit can be generalized to include any motion of a celestial body around another body and dates back at least to the earliest written texts. However, Johannes Kepler was the first to establish the true qualitative characteristics of astronomical orbits, formulating his three laws of planetary motion between 1609 and 1619. Analyzing the results from painstaking observations of the motions of astronomical bodies by Tycho Brahe over many years, he determined that these bodies travel on elliptical orbits (with the Sun at one focus), speeding up as they approach the Sun and then slowing down as they move farther away. As simple as they seem today, these two conceptual breakthroughs revolutionized the Western world's view of the structure of the universe. Until this time, the majority view was that the Sun, planets, and star all revolved around the Earth; this theory is known as geocentrism, with the most well-known proponent being the second-

century Greco–Roman philosopher Ptolemy. Heliocentrism, the idea that the orbits of the planets are centered on the Sun, had first been proposed by Aristarchos of Samos in the third century BCE but was largely ignored until it was explored by Copernicus in 1543 and later supported by Galileo’s observations of the motions of Jupiter’s moons. However, these early models conceived the orbits as perfect circles and therefore required many ad hoc additions to fit the observed motions of planets in the sky. Kepler’s realization that the orbits could be elliptical turned heliocentrism into a viable predictive theory.

Kepler’s third law that the square of the period of a planet’s orbit is proportional to the cube of the distance from the Sun ($P^2 \propto a^3$) provided the first mathematical relation between two orbital quantities and formed one of the primary drivers for Isaac Newton’s derivation of the inverse square law of universal [gravitation](#) ($F_{\text{grav}} \propto 1/r^2$). Newton was able to show that two gravitationally bound bodies will orbit the center of mass of the two-body system, and if the difference in mass is large enough, the smaller body will essentially orbit the more massive body. This simple mathematical formulation (with modifications included for general relativity as proposed by Albert Einstein) forms the backbone of all of celestial mechanics and dynamical astronomy.

Overview

As first envisioned by Newton, orbital shapes can be organized into three different categories based on how much energy the orbiting body has: elliptical (including circular), parabolic, and hyperbolic. Parabolic and hyperbolic orbits are unbound, in that they begin and end at an infinite distance from the center of mass; the difference between the two is that a body on a parabolic orbit has zero net energy, while a hyperbolic orbit requires a positive total energy and therefore has a nonzero beginning and ending velocity. Newton realized that these shapes correspond to sections of a cone (conic sections), with one focus of the orbit lying on the rotational axis of the cone. The

conic section therefore confines the orbital motion to a two-dimensional plane, known as the orbital plane.

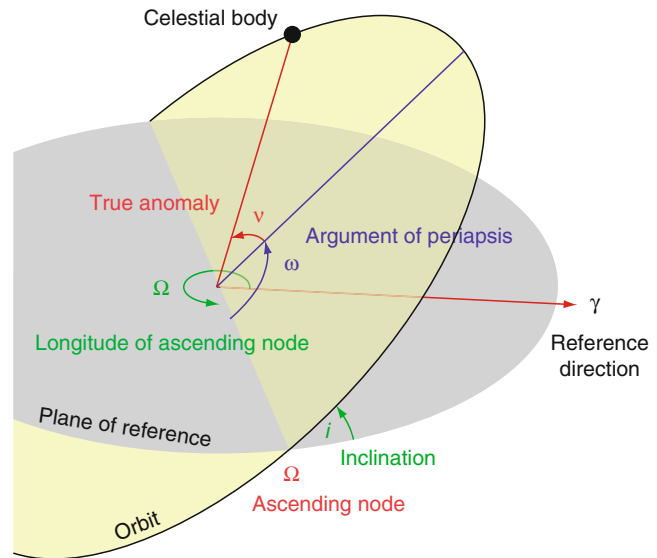
Basic Methodology

It is important to start with a discussion of terminology, since the language of celestial mechanics (the name for the study of orbital dynamics) can become very confusing due to the many specialized terms used to describe the properties of an orbit.

The general terms for the closest and farthest points of an orbit are the periapsis and apoapsis; these terms can be specialized for individual situations (i.e., perigee for orbits around the Earth, perihelion for orbits around the Sun, and periastron for orbits around any star). The line that connects the periapsis and the apoapsis is called the line of apsides; this line naturally passes through the central body, and the direction of the periapsis can rotate to trace a circle if the orbit is perturbed (known as apsidal precession).

The motion of an orbiting body can be described by six quantities known as orbital elements. These quantities can be coordinates of position and velocity, such as the Cartesian coordinates of a body in a specific reference frame, but more commonly orbits are described using the Keplerian orbital elements, since these are independent of a specific reference direction. The six Keplerian elements are the semimajor axis and eccentricity of the ellipse, and the inclination, argument of periapsis, longitude of the ascending node, and either the mean (temporal) or true (angular) anomaly (see Fig. 1). The most useful and general elements are semimajor axis, eccentricity, and inclination, which describe the size, shape, and tilt of the orbit with respect to the reference orbital plane (the plane of reference in the Solar System is known as the [ecliptic plane](#)). The semimajor axis is defined as one half of the major axis of the orbital ellipse; note that this is different than the distance to the central body when the orbit is not a circle. The eccentricity describes how elliptical the orbit is, ranging from 0 for a circular orbit to 1 for a parabolic orbit.

Orbit, Fig. 1 A diagram of an orbit, with several orbital elements labeled (inclination, argument of periapsis, longitude of the ascending node, and true anomaly). The additional orbital elements not labeled are the semimajor axis (i.e., size of the orbit) and the eccentricity (i.e., ellipticity) of the orbit (WikiCommons)



The inclination of the orbit is measured in degrees, ranging from 0° to 180° (values larger than 90° indicate a “retrograde” orbit such that the object moves in the opposite direction around the star). The other elements are less intuitive and less frequently used, since they primarily define a single orbital position and average out to zero for a population of randomly oriented bodies (as opposed to eccentricity and inclination that have a characteristic distribution for a randomized population), and they will not be discussed in detail here.

There are a number of processes that can lead to an evolution of the orbital parameters of a single body or a population of bodies; these effects are known as perturbations. These perturbations generally fall into two categories: gravitational perturbations due to interactions with other bodies in the system (such as secular perturbations or dynamical friction) or relatively steady-state forces that either add or remove energy from the orbit (such as gas drag or radiation pressure). Gravitational forces between two bodies will lead to an excitation of the orbit of the smaller body (such as the scattering of comet-sized bodies into the ► [Oort cloud](#) by Jupiter) and a damping of the orbital excitation of the larger body (such as the damping of planetary eccentricities during ► [planet formation](#) due to interactions with small planetesimals).

Applications

The study of orbital dynamics is fundamental to much of planetary astronomy in our own Solar System, as well as the study of other stellar and planetary systems. We deduce the orbital motions and positions of bodies in our own system by studying the proper motion of objects as they move across the sky over time – the same method has been used since classical times – and we are still using it to discover ► [Kuiper Belt](#) objects at the far reaches of the Solar System today. In other planetary systems, we can measure the radial velocity of the central star and use that motion to calculate the orbital motion of surrounding planets even when they are impossible to detect directly.

We can also explore the evolution of the orbits of bodies in planetary systems over time using computer simulations. Computational numerical simulations of planetary dynamics all aim to solve the same general problem: how to calculate the gravitational and nongravitational forces on a system of bodies accurately over long timescales (known as the n-body problem). The solution to the dynamical evolution of any system of three or more bodies cannot be solved exactly, but there are many different types of mathematical algorithms that have been developed to optimize the pursuit of an approximate solution (i.e., Runge–

Kutta, symplectic integration, etc.). Important applications for these tools include the study of the formation of planetary systems through long-term accretion of ► [planetary embryos](#), as well as the dynamical history of populations of small bodies in our Solar System (such as the Kuiper Belt).

Cross-References

- [Apsidal Angle](#)
- [Gravitation](#)
- [Kuiper Belt](#)
- [Period](#)
- [Planet Formation](#)

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Orbital Period

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

The orbital period (P) is the time required for a body to complete an orbit around a central mass. The orbital period can be calculated by Kepler's third law, which in the solar system takes the form

$$P^2 = a^3$$

where P is in years and the orbit's semimajor axis a is in AU. For different stellar masses the full equation that should be used is

$$P^2 = \frac{4\pi^2 a^3}{G(M_{\text{star}} + M_{\text{p}})}$$

where M_{star} and M_{p} are the stellar and planetary mass, respectively, and G is the gravitational constant.

Cross-References

- [Mean Motion Resonance](#)
- [Orbit](#)
- [Secular Dynamics](#)

Orbital Resonance

Jérôme Perez
Applied Mathematics Laboratory, ENSTA
ParisTech, Paris, France

Keywords

Gravitation · Instability · Period · Orbits

Definition

An orbital resonance is either a stabilizing or a disrupting phenomenon produced by the cumulative effect of gravity between at least two bodies in periodic orbits, generally around a third, more massive body.

Overview

The motion of a body in a fixed gravitational field is described by an ordinary differential equation. The solution of this problem is entirely determined provided we know its initial conditions.

In several physical cases, this solution has some periodic characteristics. The period of such a periodic motion depends essentially on a mean distance between bodies in gravitational interaction. For the two-body Keplerian problem, this is Kepler's third law: The square of the ► [orbital period](#) is directly proportional to the cube of the ► [semi-major axis](#) of its elliptical orbit (see ► [Gravitation](#)).

If several bodies are in orbit in a fixed gravitational potential and the ratio of the periods of two of these particular motions is rational (ratio of two integers), a special configuration occurs periodically. The cumulative effects of this configuration could be favorable for reaching a stabilized state or, on the contrary, could lead to a destructive process of the system or of part of it, by ejection of one or several of the bodies.

The solar system contains plenty of orbital resonances.

Between Mars and Jupiter, there exist thousands of small bodies that form the asteroid belt. In 1866, Kirkwood announced the discovery of gaps in the distances of these bodies' orbits from the Sun. These gaps were located at positions where, if there were a body, its period of revolution around the Sun would be an integer fraction of Jupiter's orbital period. In fact, these gaps were dug by orbital resonances. Likewise, Mimas, a minor satellite of Saturn, has a period that is twice the one of a body which would be orbiting at the location of the Cassini division seen in the Saturn's ring.

Sometimes resonances can maintain rather than exclude bodies from a peculiar orbit. Io, Europa, and Ganymede, the first three moons of Jupiter, show a special kind of orbital resonance called Laplace's resonance: their orbital period are in the ratio 1:2:4. In consequence, these three moons cannot be aligned together on the same side of Jupiter. This configuration could eject one of them.

Cross-References

- [Gravitation](#)
- [Lagrangian Points](#)

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OREx

- [OSIRIS-REx](#)

O-REx

- [OSIRIS-REx](#)

Organelle

Felipe Gomez

Instituto Nacional de Técnica Aeroespacial,
Centro de Astrobiología (CSIC/INTA), Madrid,
Spain

Definition

An organelle is a specialized subunit inside a cell. It is separated from the surrounding cytoplasmic media by a lipid bilayer and plays a particular role or function within the cell similar to that of organs in an animal's body. The absence of a ► [nucleus](#), a membrane-enclosed organelle containing the genome, is one of the major features that differentiate prokaryotes from eukaryotes. The most notable examples of organelles are those involved in energy transduction reactions in eukaryotes which were originated by endosymbiont bacteria: ► [chloroplasts](#) present in plants cells, algae and some protists which are responsible for ► [photosynthesis](#), and mitochondria in almost all eukaryotes where ► [respiration](#) for energy production takes place. Other important organelles are hydrogenosomes involved in energy generation in anaerobic conditions; the endoplasmic reticulum responsible for many functions, including the synthesis of new membrane material; lysosomes involved in protein degradation and amino acid recycling; peroxisomes responsible for the degradation of oxidative stress products, like hydrogen peroxide; microfilaments and microtubules responsible for the internal structure of

eukaryotic cells; and flagella and cilia involved in cell movement.

Cross-References

- ▶ [ATP Synthase](#)
- ▶ [Chloroplast](#)
- ▶ [Eukarya](#)
- ▶ [Mitochondrion](#)
- ▶ [Motility](#)
- ▶ [Nucleus](#)
- ▶ [Oxygenic Photosynthesis](#)
- ▶ [Photosynthesis](#)
- ▶ [Respiration](#)

Organic Cyanide

- ▶ [Nitrile](#)

Organic Dust, Influence on the Origin of Life

Sun Kwok
Faculty of Science, The University of Hong Kong, Hong Kong, China

Keywords

Origin of life · Earth, external delivery of organics · Stellar evolution

Definition

This topic considers the possibility that organic dust particles of extraterrestrial (interplanetary, stellar, or interstellar) origin played a role in the origin of life on Earth.

History

Current theories on the ▶ [origin of life](#) are centered on the hypothesis that under suitable conditions (e.g., a primordial soup), simple

molecules can be synthesized into complex organic compounds which later develop into self-replicating living organisms. An initial laboratory basis for this hypothesis was the Miller-Urey experiment, in which a mixture of gaseous molecules (hydrogen, water, ammonia, methane) when subjected to electric discharge yielded complex organics such as amino acids. The discoveries of insoluble organic matter in carbonaceous meteorites (Cronin et al. 1987), organic contents in interplanetary dust particles (Flynn et al. 2003), and complex organic dust synthesized by stars (Kwok 2004) have raised the possibility that externally delivered organics may have allowed the origin of life on Earth to bypass some of the first steps of organic synthesis on the early Earth (Ehrenfreund et al. 2006; Kwok 2009).

Overview

Isotopic analysis of carbonaceous meteorites has also discovered the presence of presolar grains, ▶ [star dust](#) that is made in the asymptotic giant branch of stellar evolution and ejected into the ▶ [interstellar medium](#) by stellar winds (Zinner 1998). The fact that one can actually hold star dust in our hands is proof that star dust can travel across the Galaxy and reach our Solar System intact. The fact that organic matter in Solar System objects has been found to have hydrogen isotopic ratios that differ from the terrestrial D/H ratio also suggests that there is interstellar organic dust in the Solar System (Ehrenfreund et al. 2002; Nakamura-Messenger et al. 2006; Sandford et al. 2006).

Once arrived in our Solar System, these star dust particles have to find a way to Earth. The most commonly discussed mechanism of delivering extraterrestrial organic dust to the early Earth is through the Late Heavy Bombardment (Chyba and Sagan 1992). The frequent collisions between the Earth and asteroids and comets during the early times of the Solar System imply that a significant amount of external organic materials could be delivered to Earth (Ehrenfreund et al. 2006). Alternatively, the Earth, formed

through the process of aggregation, may have contained a significant amount of primordial organic material. Since the organic star dust has a structure similar to that of ► [kerogen](#), the primordial organic matter could be extremely resilient and may have survived the formation of the Earth.

At this time, there is no direct evidence that the early Earth had been enriched/contaminated by a large amount of external organic matter. If it was, there is also not yet any evidence that this organic matter played any role in the origin of life. However, the possible implications can be significant. In the traditional endogenous origin of organic matter theories on the origin of life, the evolution to life could be a rare event due to unique circumstances of the Earth. However, in the external delivery hypothesis, life could be common in the Galaxy, as all planetary systems in the Galaxy could have been equally enriched by organic star dust.

Cross-References

- [Insoluble Organic Matter](#)
- [Interstellar Dust](#)
- [Late Heavy Bombardment](#)
- [Organic Dust, Synthesis by Stars](#)
- [Origin of Life](#)
- [Primordial Soup](#)

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Organic Dust, Synthesis by Stars

Sun Kwok
Faculty of Science, The University of Hong Kong, Hong Kong, China

Keywords

Star dust · Stellar evolution

Synonyms

[Organic grains](#); [Organic solid particles](#)

Definition

Organic dust consists of micron- or nanometer-sized carbon-based solid-state particles with aromatic (ring-like) and/or aliphatic (chain-like) structures. The solids could be in crystalline (periodic) form, or more likely, in amorphous (random) form. Possible examples of terrestrial counterpart are soot, which is a product of combustion of hydrocarbons in a flame, and ► [kerogen](#), the most common form of organics on Earth formed from decayed living matter.

History

The existence of interstellar dust has been known since the early twentieth century through the effect of selective extinction on the light of distant stars. The chemical composition of the dust particles was initially assumed to include graphite, iron, or ice. Development in stellar nucleosynthesis led to the understanding that the element carbon is synthesized in the asymptotic giant branch (AGB) phase of stellar evolution. This led to the suggestion by Fred Hoyle that carbon-based solid particles could be produced by stars (Hoyle 1955). The possibility that some of this star dust might be organic in nature was first suggested in the 1970s (Hoyle and Wickramasinghe 1977). Later, it was suggested that organic compounds can be detected in the infrared part of the spectrum through their C–H stretching mode (Knacke 1977; Duley and Williams 1979).

After the discovery of the ► [unidentified infrared emission \(UIE\)](#) bands, it was realized that some astronomical spectra resemble the spectral features observed in automobile exhaust. This led to the suggestion that the carriers of the UIE bands may be related to polycyclic aromatic hydrocarbon molecules (Allamandola et al. 1985). This represents the beginning of the serious studies of organic compounds in space.

Overview

Since organic solids can take on many different forms, the identification of a specific organic solid is not as straightforward as in the case for inorganic minerals. Minerals generally have highly ordered lattice structure in a crystalline form and therefore possess optically active lattice vibrational modes. These produce clear infrared spectral signatures, allowing the identification of exact minerals. Organic solids, however, have many electronic states, and their absorption bands are very broad. Macromolecular organic solids can be identified by their visible colors, albedo, and infrared bands. More specifically, the vibrational modes of various functional groups can be identified through comparison with laboratory spectra.

Amorphous carbonaceous solids are characterized by different sp^2/sp^3 hybridization ratios as well as mixed hybridization states. Organic particles of such structures are natural products of combustion. The first nucleation products for soot particles formed in flames have structures consisting of islands of aromatic rings linked by chains. Laboratory-synthesized carbonaceous nanoparticles are found by chemical analysis to consist of networks of chains and rings. Various laboratory experiments have been performed to simulate the synthesis of carbonaceous nanoparticles in stellar outflows. The products from vapor deposition are independent of energy injection techniques, which include laser ablation of graphite, laser pyrolysis of gases, arc discharge, microwave irradiation, UV photolysis, and flame synthesis.

By introducing hydrogen into familiar forms of carbon such as graphite (sp^2) and diamond (sp^3), a variety of amorphous C–H alloys can be created (Robertson 2002). Geometric structures of different long- and short-range order can be created by varying the aromatic-to-aliphatic ratio. The infrared spectra of these amorphous carbonaceous materials resemble the astronomical unidentified infrared emission bands seen in ► [planetary nebulae](#) and ► [protoplanetary nebulae](#) (Fig. 1). Since these amorphous carbonaceous solids have absorption bands in the visible, they can be easily excited by visible light from stars.

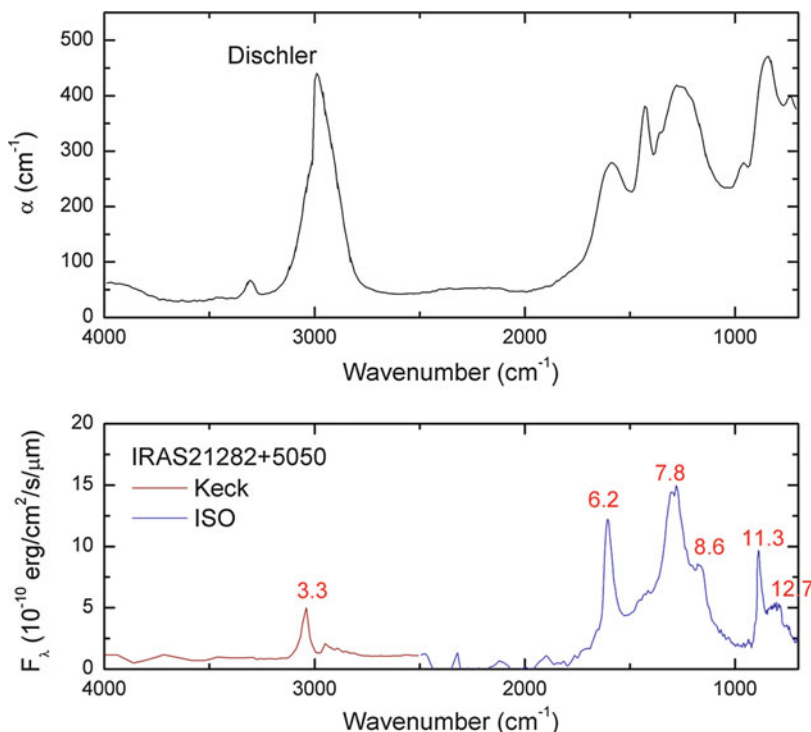
Many organic compounds, including hydrogenated amorphous carbon, exhibit photoluminescence, suggesting that photoluminescence by organic dust may be the source of the so-called extended red emission observed as a diffuse glow in some astronomical environments (Rusli and Amaratunga 1996).

Although carbon and hydrogen are the basic constituents of organic star dust, other abundant heavy elements such as nitrogen, oxygen, and sulfur are also likely to be present. These amorphous compounds are sometimes collectively referred to as CHONS.

Organic grains of similar structures have been found in the Solar System. The insoluble organic matter (IOM) in carbonaceous meteorites has

Organic Dust, Synthesis by Stars, Fig. 1

Laboratory infrared spectra of hydrogenated amorphous carbon (*top panel*) compared to the astronomical spectrum of the planetary nebula IRAS 21282 + 5050 (*bottom panel*). The laboratory spectrum is adapted from Dischler et al. (1983). Horizontal axis is in wavenumber (*inverse wavelength*). The red labels in the astronomical spectrum mark the unidentified infrared emission bands



mixed aromatic/aliphatic structures similar to those of terrestrial kerogen. Organic dust in the Solar System is generally assumed to be manufactured in the Solar System, although certain isotopic anomaly suggests that it could be of stellar or interstellar origin (Ehrenfreund and Charnley 2000).

Cross-References

- [Extended Red Emission](#)
- [Insoluble Organic Matter](#)
- [Interstellar Dust](#)
- [Planetary Nebula](#)
- [Polycyclic Aromatic Hydrocarbon](#)
- [Star Dust](#)

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Organic Grains

- [Organic Dust, Synthesis by Stars](#)

Organic Material Inventory

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

The organic material inventory (sometimes just “organic inventory”) is a list of amounts and composition of spacecraft materials that contain organic compounds (defined as carbon-containing compounds *excluding* carbides, carbonates, cyanides, and simple oxides, but often *including* propellants) that are carried on a spacecraft in quantities above a specified amount. This inventory is a component of required ► [planetary protection](#) documentation for missions to target objects for which there is an interest in studying organic compounds that could contribute to understanding of the origin and evolution of life in the Solar System.

Cross-References

► [Planetary Protection](#)

Organic Molecule

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

An organic molecule is any member of a large class of molecules containing carbon and then

limited by a number of somewhat arbitrary restrictions. For historical reasons, a strict definition of an organic molecule is difficult. The word “organic” dates back to the ancient Greeks. For centuries, many in the West believed in the concept of vitalism: that certain “organic” compounds could only be synthesized by the action of a vital “life-force” possessed only by living organisms. This implied that “organic” compounds were fundamentally different from the “inorganic” compounds, which could be obtained by laboratory manipulation.

The first well-documented experimental synthesis of an “organic compound” occurred in 1828 when Wöhler synthesized ► [urea](#) from the “inorganic” compounds potassium cyanate and ammonium sulfate. Urea had been considered an “organic” compound, as it was known to occur only in the urine of living organisms. Since then, many thousands of biological molecules have been synthesized by organic chemists.

Some sources define organic compounds as those containing C–H bonds; others include C–C bonds in the definition, still others merely require a molecule to contain carbon. This last definition would include compounds such as steel alloys and calcite, which most organic chemists would not consider part of their field of study. The C–H bond or C–C bond containing definitions would exclude urea and many other compounds commonly accepted by chemists as “organic.”

While the definition of what constitutes an organic compound can be ambiguous for a few small molecules such as urea, CO, and HCN, this is much less true for even slightly larger molecules. Indeed, today many millions of “organic” compounds have been synthesized by chemists, and the theoretical number possible is infinite. For example, the number of small organic molecules in what is considered the pharmacologically relevant size range (molecular weight $\sim < 500$ amu) is estimated by some to be on the order of 10^{60} .

Cross-References

- [Carbon](#)
- [Urea](#)

Organic Refractory Matter

William M. Irvine
University of Massachusetts, Amherst,
MA, USA

Synonyms

[ORM](#)

Definition

ORM is complex, nonvolatile organic matter. In meteorites, such material is normally called insoluble organic matter (IOM) and is broadly defined to have low to no solubility in a weak acid bath and is also referred to as protokerogen or humin. Many models of ► [interstellar dust](#) include an organic refractory mantle over a silicate core, with the ORM produced by ultraviolet or cosmic ray irradiation of an accreted icy grain mantle. Organic refractory matter can be synthesized in the laboratory by bombarding ices containing species thought to be present in comets and ► [interstellar ices](#) (i.e., water, methane, and ammonia) with high-energy photons or particles.

Cross-References

- [Comets, History of](#)
- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Meteorites](#)
- [Tholins](#)

Organic Solid Particles

- [Organic Dust, Synthesis by Stars](#)

Organicism

- [Vitalism](#)

Organometallic

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

The term Organometallic refers to compounds containing organic moieties bonded to a metal, often covalently. Many organometallic complexes feature coordination bonds between a metal and an organic ligand. The organic ligand often binds the metal through a heteroatom such as oxygen or nitrogen, in which case such compounds are considered coordination compounds. However, if any of the ligands form a direct metal–carbon bond, then the complex is usually considered organometallic. There are many naturally occurring organic coordination compounds. For example, the ► [protein](#) hemoglobin contains four ► [heme](#) groups in which an iron ion is coordinated to the nitrogen atoms of the porphyrin rings. Similarly, magnesium is coordinated via nitrogen atoms at the center of ► [chlorophyll](#). In contrast, the ► [coenzyme](#) methylcobalamin, which has a cobalt–methyl bond, is a true organometallic complex.

Cross-References

- ▶ [Chlorophylls](#)
- ▶ [Coenzyme](#)
- ▶ [Heme](#)
- ▶ [Protein](#)

Origin of Life

Antonio Lazcano

Facultad de Ciencias, UNAM, Cd. Universitaria,
Mexico City, Mexico

Keywords

Emergence and complexity · Heterotrophic hypothesis · Oparin-Haldane · Prebiotic evolution · Primordial autotrophy · Spontaneous generation

Synonyms

[Abiogenesis](#); [Biopoesis](#); [Emergence of life](#)

Definition

In evolutionary biology, the phrase “origin of life” refers to the first appearance of living entities. If the emergence of the biosphere is seen as the evolutionary transition between the nonliving and the living, then it may be meaningless to attempt to draw a strict line between these two worlds, and the appearance of life on Earth may therefore be better envisioned as a continuum that seamlessly joins the prebiotic synthesis and accumulation of organic molecules in the primitive environment with the emergence of self-sustaining, replicative chemical systems capable of undergoing Darwinian evolution.

Overview

The term “origin of life” has several possible meanings, but from the perspective of

contemporary biology and within the framework of evolutionary theory, it refers to the first appearance of primordial living entities. It is generally assumed that since antiquity early philosophers and naturalists appealed to spontaneous generation to explain the origin of life. However, with few exceptions, this was not the case. Spontaneous generation was seen mostly as a nonsexual reproductive mechanism, and it was not until Erasmus Darwin, Georges Louis Leclerc de Buffon, and Jean-Baptiste Lamarck incorporated spontaneous generation within their transformist views that it was conceived as the mechanism that had led to the first appearance of life on our planet (Farley 1977).

Like his predecessors, Charles Darwin surmised that plants and animals arose naturally from primordial nonliving matter, but like many others, he rejected the idea that putrefaction of preexisting organic compounds could lead to the appearance of organisms. Darwin’s letters, notebooks, and few published statements on the issue demonstrate that although he favored the possibility that life could appear by natural processes from simple inorganic compounds, his reluctance to discuss it in public was due at least in part to the recognition that it was difficult to develop fruitful experimental approaches to address the problem. Nevertheless, his theory established the framework that would lead to a number of attempts to explain the origin of life by introducing principles of historical explanation (Peretó et al. 2009).

Panspermia: Past and Present

Darwin’s *Origin of Species* was published in 1859, the very same year in which Pasteur began the experiments that would lead him to disprove spontaneous generation of microbes. His results had implications that went well beyond the limits of academia. Since the times of Lamarck and Buffon, spontaneous generation had been associated in France not only with evolutionary theory but also with secular attitudes and radical political views. In such an entangled atmosphere, spontaneous generation embodied not only support for evolution and transformist views but also implied an anticlerical political stance (Farley 1977; Fry 2002; Strick 2009).

Pasteur's results made it difficult to explain the origin of life by means of spontaneous generation, a conclusion that was interpreted as a major blow to one of the implicit assumptions underlying Darwin's views. Several devoted materialists like Emil du Bois-Reymond, Karl von Nageli, and August Weismann continued to support the idea of spontaneous generation, but others, like Hermann von Helmholtz, felt that they could sidestep the issue by assuming that viable microbes had been delivered to the primitive Earth by meteorites, attempting to keep the validity of evolution. In fact, toward the end of the nineteenth century, the belief that life on Earth had evolved from extraterrestrial organisms elicited a number of proposed mechanisms that could have transported microbes between planets (see, e.g., Arrhenius 1908), but little attention was given to the central issue of their actual origin (Oparin 1924, 1938; Kammenga 1982; Fry 2002).

The recent revival of the panspermia hypothesis has not changed this situation. Recent proposals that terrestrial life arose elsewhere and was transferred to our planet are based on the well-established exchange of solid material among the different bodies in the solar system, the assumption of more benign environments in some of these other planets during the early stages of planetary system, and the surprising resistance of a number of prokaryotic species to environmental insults such as high fluxes of UV light or corpuscular radiation. Thus, the panspermia hypothesis has been recently restated in a variety of contexts. However, its current advocates, like those of the late nineteenth century, simply transfer the question of the origin of life to another habitable planet in our galaxy without providing an explanation of how it happened.

The Origin of Life: A Question Without an Answer?

A century and a half after Darwin admitted how little was understood about the origin of life, we still do not know when and how the first living beings appeared on Earth. Despite the seemingly insurmountable obstacles surrounding the

understanding of the origin of life, or perhaps because of them, there has been no shortage of discussion about how it took place. Since the attributes of the first living entities are unknown, it is not surprising that an inventory of current views on the origin of life reveals a mixture of opposites of every kind.

Looking back across time since the origin of life occurred is a scientific exercise fraught with guesswork, since the evidence required to describe the prebiotic environment and the nature of the events that led to the first living systems is scant and difficult to understand. Since most of the rocks from early Archean times that have been preserved have been metamorphosed to a considerable extent, there is no direct evidence of the environmental conditions on Earth at the time of the emergence of life, nor any fossil register of the predecessors of the first cells. There is no direct information of the chemical composition of the terrestrial atmosphere during the period of the origin of life, nor of other general and local environmental conditions, which may have been important for the appearance of living systems (Bada and Lazcano 2009).

Moreover, any explanation of the origin of living systems should attempt, at least implicitly, the definition of a set of minimal criteria for what constitutes a living organism. However, this has proven to be an elusive intellectual endeavor, though not for lack of trying. The absence of such a definition sometimes gives the impression that what is meant by the origin of life is described in somewhat imprecise terms and that several entirely different and even opposing questions are often confused (Lazcano 2008). Prior to the discovery of catalytic activity of RNA molecules, for instance, the origin of the genetic code and of protein synthesis was considered synonymous with the appearance of life itself. This is no longer a dominant point of view: four of the central reactions involved in protein biosynthesis are catalyzed by ribozymes, and their complementary nature suggests that they first appeared in an **▶ RNA world** (Yarus 2010), that is, that ribosome-catalyzed, nucleic acid-coded protein synthesis is the outcome of Darwinian selection

of RNA-based biological systems and not of mere physicochemical interactions that took place in the prebiotic environment.

Phylogenomics and Extant Metabolism Do Not Explain the Origin of Life

The variations of traits common to extant species can be explained as the outcome of divergent processes from ancestral life forms that existed prior to the separation of the three major biological domains, that is, the last common ancestor of Bacteria, Archaea, and Eukarya. This entity was likely far removed, if not in geological time, at least in complexity from the first living systems. Although no evolutionarily intermediate stages or ancient simplified versions of the basic biological processes have been discovered in contemporary organisms, the differences in the structure and mechanisms of gene expression and replication among Bacteria, Archaea, and Eukarya have provided insights into the stepwise evolution of the replication and translation apparatus, including some late steps in the development of the genetic code. Such comparative approaches have made it possible to distinguish the origin-of-life problem from a whole series of other issues, often confused, that belong to the domain of the early evolution of microbial life.

Molecular phylogenetic, comparative genomic, and bioinformatic approaches fail to provide direct information on the nature of the first living beings. A cladistic approach to the origin of life is not feasible, since all possible intermediates that may have once existed have long since vanished. Phylogenetic analyses based on comparative genomics provide important clues to early stages of biological evolution, but at the time being their applicability cannot be extended beyond a threshold that corresponds to a period of cellular evolution in which protein biosynthesis was already in operation, that is, the RNA/protein world (Becerra et al. 2007).

Although there have been attempts to deduce the nature of the first living systems from extant metabolism (Wächtershäuser 1988), there is a lack of simple continuity between the biosynthetic and the (possible) prebiotic pathways (Lazcano and Miller 1999). For instance, it is

likely that the ► [Strecker synthesis](#) and the Bucherer-Bergs reaction played a major role in the prebiotic accumulation of amino acids, but these abiotic routes are very different from transamination and the reverse Krebs cycle found in extant cells. The prebiotic synthesis of purines is from HCN and its derivatives and not from glycine, formate, and NH_3 , as in current biology. It is true that the aminoimidazole carboxamide ribotide in the de novo purine nucleotide biosynthetic pathway is comparable to the aminoimidazole carbonitrile formed in the prebiotic pathway, and a few other examples are found in the formation of uracil, glutamic acid, pyrroles, pyrimidines, and acetic acids (Lazcano 2010a). However, the similarities between these abiotic reactions and their enzyme-mediated counterparts in biosynthetic pathways do not necessarily indicate an evolutionary continuity between prebiotic chemistry and biochemical pathways, but may simply reflect chemical determinism. In other words, the few cases in which some extant metabolic pathways and prebiotic chemical processes share similar steps may be due to the unique way in which given reactions can take place.

From the Primitive Soup to the RNA World

It is generally believed that after Louis Pasteur had disproved the spontaneous generation of microbes using his famous swan-necked flask experiments, the discussion of life's beginning had been banished to the realm of useless speculation. However, scientific literature from the first part of the twentieth century shows the many attempts by major scientists to solve this problem. The list covers a rather wide range of explanations that go from the ideas of Pflüger on the role of HCN on the origin of life to those of Svante Arrhenius on panspermia and includes Leonard Troland's hypothesis of a primordial enzyme formed by chance events in the primitive ocean, Alfonso L. Herrera's sulfocyanic theory on the origin of cells, Harvey's 1924 suggestion of an heterotrophic origin in a high-temperature environment, and the provocative 1926 paper that Hermann J. Muller wrote on the abrupt, random formation of a single, mutable gene

endowed with catalytic and autoreplicative properties (cf. Lazcano 1992, 2010b).

In spite of their diversity, most of these explanations went unnoticed, in part because they were incomplete, speculative schemes largely devoid of direct evidence and not subject to fruitful experimental testing. Although some of these hypotheses considered life as an emergent feature of nature and attempted to understand its origin by introducing principles of historical explanation, the dominant view was that the first forms of life had been photosynthetic microbes endowed with the ability to fix atmospheric CO_2 and to use it with water to synthesize organic compounds. A major scientific breakthrough occurred, however, when Oparin (1924) suggested a heterotrophic origin of life that assumed that prior to the emergence of the first cells, a prebiotic synthesis of organic compounds led to the accumulation of the primitive broth.

Such ideas were supported not only by the evidence of organic compounds in meteorites but also by the striking nineteenth-century experimental demonstrations that biochemical compounds such as urea, alanine, and sugars could be formed under laboratory conditions, as had been demonstrated by Wöhler, Strecker, and Butlerow, respectively. Oparin's proposal, which was based on his Darwinian credence in a gradual, slow evolution from the simple to the complex, stood in sharp contrast with the then prevalent idea of an autotrophic origin of life. Since a heterotrophic anaerobe is metabolically simpler than an autotrophic one, the former would necessarily have evolved first. Thus, based on the simplicity and ubiquity of fermentative reactions, Oparin (1924) suggested in a small booklet that the first organisms must have been heterotrophic bacteria that could not make their own food but rather consumed organic material present in the primitive milieu.

These ideas were further elaborated and refined in a more extensive book whose English translation was published in 1938 (Oparin 1938). In this book, Oparin's original proposal was revised, leading to the assumption of a highly reducing milieu in which iron carbides of geological origin would react with steam to form hydrocarbons.

Their oxidation would yield alcohols, ketones, aldehydes, etc. that would then react with ammonia to form amines, amides, and ammonium salts. The resulting protein-like compounds and other molecules would form a hot dilute soup, in which they would aggregate to form colloidal systems such as coacervates, from which the first heterotrophic microbes evolved. Like many others at the time, Oparin did not address in his 1938 book the origin of nucleic acids, because their role in genetic processes was not even suspected. Because of this, inheritance of primordial genetic information was assumed by Oparin to be the result of growth and division in the coacervate drops he advocated as models of precellular systems (Lazcano 2010b).

Similar ideas were being developed independently by other researchers. In 1929, John B. S. Haldane, the extraordinary British polymath, also argued that the origin of life had been preceded by the synthesis of organic compounds. Based on experiments by E. C. C. Baly, an English chemist who claimed that he achieved the syntheses of amino acids and sugars by the UV irradiation of a solution of CO_2 in water, Haldane suggested that the absence of oxygen in a CO_2 -rich primitive atmosphere had led to the synthesis of organic compounds and the formation of a "hot dilute soup." Haldane was also influenced by d'Herelle's discovery of phages and suggested that viruses represented an intermediate step in the transition from the prebiotic soup to the first heterotrophic cells. Life may have remained, wrote Haldane (1929), in the viral stage for many millions of years before leading to the first cells.

The hypothesis that the first organisms were anaerobic heterotrophs is based on the assumption that abiotic organic compounds were a necessary precursor for the appearance of life. Experimental evidence in support of Oparin's proposal of chemical evolution came first from Harold C. Urey's laboratory, whom had been involved with the study of the origin of the solar system and the chemical events associated with this process. Urey had also considered the origin of life in the context of his proposal of a highly reducing terrestrial atmosphere (Urey 1952). The first

successful prebiotic amino acid synthesis was carried out with an electric discharge and a strongly reducing model atmosphere of CH_4 , NH_3 , H_2O , and H_2 (Miller 1953). The result of this experiment was a large yield of a racemic mixture of amino acids, together with hydroxy acids, short aliphatic acids, and urea. One of the surprising results of this experiment was that the products were not a random mixture of organic compounds; rather, a relatively small number of compounds were produced in substantial yield. Moreover, with a few exceptions, the compounds were of biochemical significance.

It is very unlikely, however, that the RNA world would have arisen from such abiotic organic syntheses. The discovery of catalytically active RNA molecules gave considerable credibility to prior suggestions that the first living organisms were largely based on ribozymes, a hypothetical stage called the RNA world (Gilbert 1986; Joyce 2002). This possibility is now widely accepted, but the problems involved with the synthesis and accumulation of RNA components suggest that ribozymes were not a direct outcome of prebiotic evolution, but may have been one of the evolutionary outcomes of what are now referred to as pre-RNA worlds. However, the chemical nature of the first genetic polymers and the catalytic agents that may have formed the pre-RNA worlds that bridged the gap between the prebiotic broth and the RNA world are completely unknown and can only be surmised.

The catalytic versatility of RNA molecules clearly merits a critical reappraisal of Muller's viewpoints (Muller 1961). However, the discovery of ribozymes does not imply that autocatalytic nucleic acid molecules ready to be used as primordial genes were floating in the primitive oceans or that the RNA world emerged completely assembled from simple precursors present in the prebiotic soup. The evidence supporting the presence of a wide range of organic molecules on the primitive Earth, including membrane-forming compounds, suggests that the evolution of membrane-bounded molecular systems preceded cellular life on our planet and that life is the evolutionary outcome of a process, not of a single, fortuitous event.

A Modern Scientific Battlefield

As summarized by Eschenmoser (2008), two major camps can be recognized among those working on the origins of life, that is, those assuming that the emergence of autocatalytic "metabolic" cycles on the primitive Earth was essential for the appearance of genetic systems and those that assume the priority of genetic polymers endowed with catalytic properties. These two different viewpoints reflect a rather sharp division between those who favor the idea that life is an emergent interactive system endowed with dynamic properties that exist in a state close to chaotic behavior and those who are reluctant to adhere to a definition of living systems lacking of a genetic component whose properties reflect the role that Darwinian natural selection and, in general, evolutionary processes have played in shaping its central characteristics.

With few exceptions, such as the views advocated by Sidney W. Fox and others (cf. Fox and Dose 1977), during the years that followed the Miller-Urey experiment, attempts to understand the origin of life were shaped to a considerable extent by the unraveling of the molecular details of DNA replication and protein biosynthesis. Perhaps not surprisingly, Herman J. Muller profited from the rapid developments in molecular biology and the success in prebiotic syntheses to update his gene-first proposal by arguing that what had emerged in the primitive oceans had been, in fact, a primordial DNA. For Muller and his followers, the essence of life lies in the combination of autocatalysis, heterocatalysis, and mutability, which he equated with evolutionary potential. In doing so, he implicitly stated that life could be so well defined that the exact point at which it started could be established with the sudden appearance of the first DNA molecule (Muller 1961).

On the other hand, Wächtershäuser (1988) has argued that life started with the appearance of an autochemolithotrophic two-dimensional monomolecular layer bound to pyrite that lacked a genetic system. According to this proposal, the synthesis in activated form of organic compounds such as amino acid derivatives, thioesters, and keto acids is assumed to have taken place on the surface of FeS and FeS_2 in environments that resemble those

of deep-sea hydrothermal vents. Wächtershäuser's explicit adherence to Karl Popper's philosophical stance (Popper 1959) played a major role in shaping his ideas. The hypothetico-deductive system developed by Popper underlines at least in part Wächtershäuser's so-called methodology of retro-diction, which he has used to argue that "lines of descent can be traced back to the first archaic pathways." According to this scheme, chemoautotrophic carbon fixation took place by a reductive citric acid cycle, or reverse Krebs cycle, of the type originally described for the photosynthetic green sulfur bacterium *Chlorobium limicola*.

Wächtershäuser's insightful prediction that ferrous sulfide in the presence of hydrogen sulfide (H_2S) is an efficient reducing agent should not be underappreciated. Pyrite formation can produce molecular hydrogen, promote the formation of ammonia from dinitrogen, and can reduce a few organic molecules under relatively mild conditions. However, compared with the surprising variety of biochemical compounds that are readily synthesized in one-pot Miller-Urey type simulations, the suite of molecules produced under the conditions suggested by Wächtershäuser is quite limited. Wächtershäuser's proposal, which is part of a trend that assumes that genetic material was not essential for the origin of life, has been modified by Russell and Hall (1997) and Martin and Russell (2003), who have argued that a primitive version of the acetyl-CoA pathway existed within FeS-rich mineral boundaries.

Based on the hypothesis that core metabolic processes have not changed since the emergence of life, Morowitz (1992) has also argued that intermediary metabolism recapitulates prebiotic chemistry. He maintains that the basic traits of metabolism could only evolve after the closure of an amphiphilic bilayer membrane into a vesicle, that is, that the appearance of membranes represents the discrete transition from nonlife to life. According to his hypothesis, reverse Krebs cycle-dependent life appeared with "minimal protocells" formed by bilayer vesicles made up of small amphiphiles and endowed with pigments capable of absorbing radiant energy stored as a chemiosmotic proton gradient across the membrane.

Life as an Emergent Complex System

The development of metabolic approaches to the origin of life like that of Morowitz (1992) and his followers is increasingly based on complexity theories and self-assembly phenomena. The background of current metabolic views lies not in Oparin's proposals, but in the attempt to extrapolate to biology the deeply rooted tendency in physical sciences to search for all-encompassing laws that can be part of grand theory that can explain many, if not all, complex systems (Lazcano 2010a). These explanations of the origin of life are based on the idea that the emergence of autocatalytic "metabolic" cycles on the primitive Earth was an essential prerequisite for the appearance of genetic systems. According to this approach, life can be considered an emergent interactive system endowed with dynamic properties that exist in a state close to chaotic behavior. Some of these proposals reflect a reaction against the reductionism of molecular biology, as well as the adherence to all-encompassing views based on complexity theories and self-assembly that tend to be more popular among physical scientists than among biologists.

Of course, the many examples of self-organizing physical systems that lead to highly ordered structures demonstrate that, in addition to natural selection, there are other mechanisms of ordered complexity that operate. Self-assembly is not unique to biology and may indeed be found in a wide variety of systems, including cellular automata, the complex flow patterns of many different fluids, in cyclic chemical phenomena (such as the Belousov-Zhabotinsky reaction) and, quite significantly, in the autoorganization of lipidic molecules in bilayers, micelles, and liposomes. There are indeed some common features among these systems, and it has been suggested that "emergent properties" or "self-organizing principles" suffice to explain the origin of life with the emergence of self-organizing metabolic cycles that at first did not require genetic polymers.

The available evidence suggests that the origin of life and the onset of natural selection resulted from self-organization phenomena involving nonequilibrium physical and chemical processes that go beyond simple Newtonian

physics and that were based on the abiotic synthesis, stability, and accumulation of organic molecules endowed with differential reactivity, on nucleic acid self-assembly and chemistry, and the spontaneous assembly of prebiotic amphiphiles into micelles and bilayer membranes, among others (de Duve 2005; Lehn 2002; Budin and Szostak 2010). The many examples of self-organizing physical systems that lead to highly ordered structures suggest that, in addition to natural selection, there are other mechanisms of ordered complexity that may have played a role in the origin of living systems. The recognition that the emergence of life is the outcome of an evolutionary process constrained by the laws of physics and chemistry can lead to the acceptance that many properties associated with living systems, such as replication, self-assembly, or nonenzymatic catalysis are also found in nonliving entities (Lazcano 2010a, b). Moreover, if the origin of life is seen as the evolutionary transition between the nonliving and the living, then it is meaningless to attempt to draw a strict line between these two worlds and the appearance of life on Earth should, therefore, be seen as an evolutionary continuum that seamlessly joins the prebiotic synthesis and accumulation of organic molecules in the primitive environment, with the emergence of self-sustaining, replicative chemical systems capable of undergoing Darwinian evolution (Lazcano 2010a, b).

Conclusions

The remarkable coincidence between the monomeric constituents of living organisms and those synthesized in laboratory simulations of the prebiotic environment appears to be too striking to be fortuitous. Nevertheless, at the time being the gap between the primitive soup and the RNA world is discouragingly large. Life cannot be reduced to one single molecule such as DNA or a population of replicating ribozymes, but present-day biology indicates that it could not have evolved in the absence of a genetic replicating mechanism ensuring the stability and diversification of its basic components.

As shown by the work of Jack Szostak and his associates (Mansy et al. 2008), it is possible to overcome at least in part the intellectual dichotomy between those claiming that the appearance of the first life forms depended on informational oligomeric compounds, that is, the so-called genetic approach, and those that argue that it was based on autocatalytic metabolic cycles. Instead of engaging in arguments about when exactly life started, the recognition that it is the outcome of an evolutionary process constrained by the laws of physics and chemistry can lead to the acceptance that many properties associated with living systems, such as replication, self-assembly, or catalysis are also found in nonliving entities.

Perhaps we will never know exactly how life originated. As in other areas of evolutionary biology, answers to questions on the origin and nature of the first life forms can only be regarded as inquiring and explanatory rather than definitive and conclusive. This does not imply that all origin-of-life theories and explanations can be dismissed as pure speculation, but rather that the issue should be addressed conjecturally, in an attempt to construct not a mere chronology but a coherent historical narrative by weaving together a large number of observations and experimental results (Kamminga 1982).

Cross-References

- ▶ Baly's Experiment
- ▶ Bernal's Conception of Origins of Life
- ▶ Calvin's Conception of Origins of Life
- ▶ Cell
- ▶ Chemical Evolution
- ▶ Complexity
- ▶ Darwin's Conception of the Origins of Life
- ▶ Evolution, Biological
- ▶ Genetics
- ▶ Life
- ▶ Metabolism, Prebiotic
- ▶ Monod's Conception on the Origins of Life
- ▶ Oparin's Conception of Origins of Life
- ▶ Panspermia
- ▶ Phylogeny
- ▶ Prebiotic Chemistry

- ▶ [Replication \(Genetics\)](#)
- ▶ [RNA World](#)
- ▶ [Urey's Conception of Origins of Life](#)

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Origins of Life, History of

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes,
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Nantes, France

Introduction

In ancient times, the question of the origin of life was often linked to cosmological myths. In most civilizations, mythological narratives described the formation of the world and the appearance of living organisms and humans. These myths were

often related to religion. In the West, from the sixteenth century, some scientific and philosophical considerations about the Universe were strongly in tension with religious dogmas (Giordano Bruno, Galileo Galilei, etc.). During the Enlightenment, notably with Buffon's works and the Kant-Laplace cosmogonic hypothesis, new conceptions of the history of the Earth led to the hypothesis of a world initially without life. At the beginning of the nineteenth century, Lamarck claimed the transformation of species and suggested that they begin with spontaneous generations. However, he did not develop the topic of the primordial beginning.

This entry is focused on the nineteenth and twentieth centuries. It describes firstly the birth of evolutive abiogenesis theories during the second part of the nineteenth century, secondly the formulation of the synthetic hypotheses with Oparin (1924, 1938), Haldane (1929), and Bernal (1947, 1951), and thirdly the development of prebiotic chemistry during from the 1950s.

The Birth of the Evolutive Abiogenesis Theories

After the formulation of Darwin's theory and the initial debate between Louis Pasteur and Félix Pouchet, and the subsequent abandonment of the spontaneous generation theory around 1860, the question of the origin of life on the Earth was completely modified. Scientists could conceive of a unique and simple primordial ancestor of all the tree of life, but admitted that this process is impossible in the current nature.

Two main ways of research were developed. Some scientists claimed a panspermian theory in which life was brought to Earth from space. Life would be a property of matter, eternal as the Universe itself. This theory was notably claimed by William Thomson and also, at the beginning of the twentieth century, by Svante Arrhenius. Finally, around 1910, the results of a young French biologist, Paul Bécquerel, strongly limited the likelihood of this theory. He showed that spores and seeds could not resist the drastic conditions of the spatial environment, and he argued

that the panspermian theory had to be abandoned. Indeed, during the twentieth century, the partisans of this theory were very rare.

The other way was evolutionary abiogenesis, and it will be the topic of this entry. This theory claimed that life results from a progressive evolution of matter. In 1859 Darwin said only a few words about the origin of life in his book *The Origin of Species*. He explained that life began with unique and very simple forms; however, he gave no more details in his book. In 1871 in a letter to his friend, the botanist Joseph Dalton Hooker, he suggested a short scenario for the origin of life characteristic of an evolutionary abiogenesis theory, which was also developed in various formulations during the end of this century. It would be very interesting to compare Darwin's theory with Herbert Spencer's, Thomas Huxley's, or Ernst Haeckel's one. All these theories admitted the idea of progressive evolution of matter. At the beginning of the twentieth century, these very theoretical hypotheses were complemented by experimental works in organic chemistry.

Between the Two Wars: The Period of the Development of Hypothesis

Two main texts from the 1920s and the 1930s are often presented as fundamental in the history of theories of the origin of life. Indeed, in 1924 Alexandre Ivanovich Oparin and then in 1929 John Burdon Sanderson Haldane independently proposed complete and interdisciplinary scenarios of the origin of life on Earth. These two texts presented the evolution of matter as included in the evolution of Earth. And this evolution of matter depends on the primitive conditions on Earth. The primitive atmosphere and the primitive ocean were the places of organic synthesis and of complexification of molecules that led to life.

Oparin continued this work during his entire career and wrote a very detailed book in 1936 (translated in English in 1938), where he gave a scenario founded on new data. He claimed that the primitive atmosphere contained no carbon

dioxide and was reducing. He suggested also that some microscopic globular entities, the coacervates, formed in solution under certain conditions and could be a good model for the primitive form of cells. We can also notice that Oparin's theory suggested a heterotrophic primitive metabolism. During his entire career, Oparin continued his researches on coacervates and metabolism, and, in the context of the Lysenkoist theories, he neglected to include genetic molecules in his theory.

We have to underline that during the 1930s and the 1940s, the astronomer Alexandre Dauvillier chose a theoretical way different from Oparin's, a theory based on a photochemical origin of life. Then, John Desmond Bernal's theory (presented in a lecture in 1947 and published in 1951) was very important and innovative. He notably claimed that clays could be a very good support for origin of life chemical processes, both for their catalytic properties and for their crystalline structure. If molecules are confined on clays, there is no problem of dispersion.

However, this period was characterized by hypothesis, and experiments were very rare. The time of prebiotic chemistry began in the 1950s.

The Development of Prebiotic Chemistry

Melvin Calvin inaugurated this period with an experiment in which he exposed carbon dioxide to γ rays. He produced formaldehyde and claimed that this result was very important for understanding the origin of life on Earth. We can admit that this experiment was the first in prebiotic chemistry. Indeed, Calvin claimed to respect prebiotic conditions of the primitive Earth in his protocol. For example, he introduced carbon dioxide because he was convinced that this gas was present in the primitive atmosphere.

Few months later, Harold Urey contested this result concerning the presence of carbon dioxide. The American physicist agreed with Oparin regarding the reducing nature of the primitive atmosphere (that is to say, without carbon dioxide), and he suggested experiments with methane. In 1953, a young chemist, Stanley Miller,

produced amino acids from a mixture of hydrogen, ammonia, methane, and water vapor exposed to electrical discharges during 1 week.

Calvin's and Miller's experiments were the first in prebiotic chemistry, because in their protocols they imposed the constraint of the supposed prebiotic conditions of the primitive Earth. From this moment, a lot of experiments would be realized in such conditions. During the 1950s and 1960s, specialists of prebiotic chemistry tried to synthesize various organic molecules, characteristic of different levels of complexity and corresponding to three steps of the supposed process of origin of life on Earth.

The first step concerned amino acid and sugar synthesis. A few years later, attention turned to the synthesis of DNA bases, and at the beginning of the 1960s to uracil, an RNA-specific base. It seems that the results of molecular biology indicated goals for prebiotic chemistry. Indeed during this period, DNA and RNA became very significant molecules in biology.

In 1958, Fox and Harada obtained thermopolymerization of amino acids in prebiotic conditions and called their product proteinoids. In 1965, again in prebiotic conditions, Fox produced microspheres with these proteinoids.

These different works characterized the three steps of the model that specialists of origin of life theories tried to build: the synthesis of little molecules (sugars, amino acids, bases, etc.), the synthesis of macromolecules, and then cells themselves.

Conclusion

It is important to underline that since the 1950s the development of the research on the origin of life is dependent of an interdisciplinary approach, which leads the theories and the experiments. Firstly, data concerning the primitive conditions on Earth, coming from geology and planetary science, defined experimental conditions. Secondly, the results of molecular biology, the role of protein, DNA, and later RNA, indicated some goals for prebiotic synthesis. Last but not the least, micropaleontology gave a time scale to the model,

indicating the maximal duration of the process of emergence of the first cells.

The last decades have confirmed the necessary interdisciplinarity of astrobiology, which is described in this encyclopedia.

Cross-References

- [Abiogenesis](#)
- [Al-Andalus, Cosmological Ideas](#)
- [Al-Bīrūnī, Abū Rayḥān](#)
- [Al-Tūsī, Nasir al-Dīn](#)
- [Animalcules](#)
- [Baly's Experiment](#)
- [Bathybius Haeckelii](#)
- [Bernal's Conception of Origins of Life](#)
- [Bruno, Giordano](#)
- [Buffon's Conception of Origins of Life](#)
- [Cosmogony: Greece](#)
- [Cosmogony: Mesopotamia](#)
- [Cuvier's Conception of Origins of Life](#)
- [Darwin's Conception of the Origins of Life](#)
- [De Maillet's Conception of Origins of Life](#)
- [Diderot's Conception of Origins of Life](#)
- [Haeckel's Conception of Origins of Life](#)
- [Haldane's Conception of Origins of Life](#)
- [Huxley's Conception on Origins of Life](#)
- [Lamarck's Conception of Origins of Life](#)
- [Miller, Stanley](#)
- [Mythology](#)
- [Oparin's Conception of Origins of Life](#)
- [Planetary Theories and Cosmology, Islamic Theories](#)
- [Protoplasmic Theory of Life](#)
- [Spontaneous Generation, History of](#)
- [Urey's Conception of Origins of Life](#)

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ORM

- [Organic Refractory Matter](#)

Ornithine

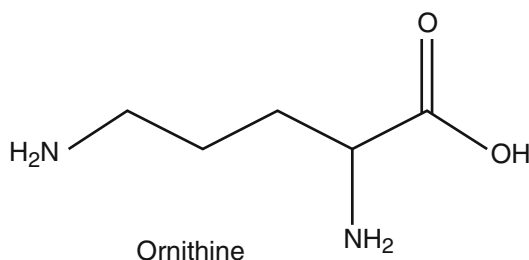
Mark Dörr
University of Southern Denmark, Odense,
Denmark

Synonyms

[Diaminovaleric acid](#)

Definition

L-ornithine is a natural, biological, noncoded diamino acid (with α - and δ -amino groups).



Ornithine, Fig. 1

L-ornithine (Fig. 1) first isolated by Jaffé from chicken excrement in 1877, hence its name (from Greek: *opvις* (ornis) = bird). It plays a major role as a carrier compound in the metabolic urea cycle. Ornithine can be derived from glutamate and is used in the biosynthesis of arginine and is therefore indirectly coupled to protein synthesis in mammals. Polypeptides containing unprotected ornithines undergo spontaneous lactamization. L-ornithine is produced through alkaline hydrolysis of citrulline and L-arginine, that is, the reverse of the biosynthetic process or the same direction observed in the urea cycle. Both L- and D-ornithine have been tentatively identified in the Murchison meteorite (Meierhenrich et al. 2004) at a concentration of $\sim <5$ ppb.

Molecular formula: $C_5H_{12}N_2O_2$
Molecular mass: 132.2 g mol^{-1}

Cross-References

- [Amino Acid](#)
- [Arginine](#)
- [Hydrolysis](#)
- [Peptide](#)

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Meierhenrich UJ, Muñoz Caro GM, Bredehöft JH, Jessberger EK, Thiemann WH (2004) Identification of diamino acids in the Murchison meteorite. *Proc Natl Acad Sci U S A* 101:9182–9186. Available at: <http://www.pnas.org/cgi/doi/10.1073/pnas.0403043101>

Orpheus

- [Theia](#)

Ortholog

- [Orthologous Gene](#)

Orthologous Gene

David Moreira

Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11,
Paris, France

Synonyms

[Ortholog](#)

Definition

Orthologous genes (or orthologs) are a particular class of homologous genes. They are found in different species and have diverged following the speciation of the species hosting them. Therefore, orthologous genes in different species derive from a common ancestral gene found in the ancestor of those species. Given their common origin, it is often the case that orthologous genes have the same function in the different species, but exceptions are not rare. The best way to infer that genes from different species are orthologous is by reconstructing their evolutionary relationships using molecular ► [phylogeny](#). Conversely, because orthologous genes evolve in parallel with the diversification of species, they are markers of choice for the reconstruction of the evolutionary history of species using molecular phylogeny.

Cross-References

- ▶ [Common Ancestor](#)
- ▶ [Gene](#)
- ▶ [Homology](#)
- ▶ [Paralogous Gene](#)
- ▶ [Phylogeny](#)

Orthophosphate

- ▶ [Phosphoric Acid](#)

OSIRIS-REx

D. S. Lauretta and C. W. V. Wolner
Lunar and Planetary Laboratory, University of
Arizona, Tucson, AZ, USA

Keywords

Asteroids · Carbon · Meteorites · Prebiotic ·
Origin of life · Sample return · Space mission ·
Spacecraft

Acronyms

OSIRIS-REx Origins, Spectral Interpretation,
Resource Identification, and
Security–Regolith Explorer

Synonyms

[OREx](#); [O-REx](#)

Definition

NASA New Frontiers mission that collected a sample of surface particles from Bennu, a carbonaceous near-Earth asteroid.

History

Asteroids are remnants from the earliest stages of solar system history (Michel et al. 2015).

Laboratory investigations of meteorites and interplanetary dust particles from asteroids reveal the nature of early solar system processes leading to terrestrial planet formation (Lauretta and McSween 2006). The presence in primitive meteorites of complex organic compounds has led to speculation that they could have seeded early Earth with prebiotic elements and molecules (Deamer 2020). However, meteorite samples are altered by the processes of ejection from their parent body, atmospheric entry, and contamination by terrestrial microbes. Studying the organic chemistry and geochemistry of a pristine carbonaceous asteroid sample is needed to understand the nature of extraterrestrial organic compounds. The purpose of the OSIRIS-REx mission was to sample a primitive, carbon-rich asteroid that represents the objects that may have brought prebiotic molecules and volatiles such as water to Earth (Pasek and Lauretta 2008).

Overview

OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer) was NASA's first asteroid sample return mission. The OSIRIS-REx spacecraft (Lauretta et al. 2017; Fig. 1) launched on September 8, 2016, from Cape Canaveral, Florida. It rendezvoused with its target, the primitive near-Earth asteroid (101955) Bennu (Fig. 2), on December 3, 2018.

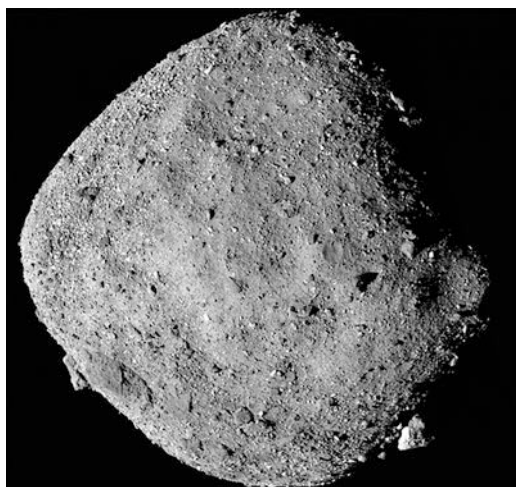
The mission used the payload of scientific instruments aboard the spacecraft (Lauretta et al. 2017) to characterize the global surface of Bennu in detail and select a safe site for sample collection (Lauretta et al. 2021). The spacecraft collected a sample of loose rock and dust particles (Fig. 3) from the surface of Bennu on October 20, 2020, to return to Earth in 2023 for laboratory analysis.

Bennu is among the darkest objects in the solar system (~4.5% reflectance) and is spectrally classified as a B-type asteroid (a subtype of C-asteroids characterized by a relatively featureless, blue-sloped spectrum). It was chosen as the target of the mission in 2005 because its orbit



OSIRIS-REx, Fig. 1 Artist's conception of the OSIRIS-REx spacecraft descending to the surface of the asteroid Bennu to collect a sample of surface particles. The

spacecraft's sample acquisition mechanism is extended in front of it on a mechanical arm. (Credit: NASA/Goddard/University of Arizona)

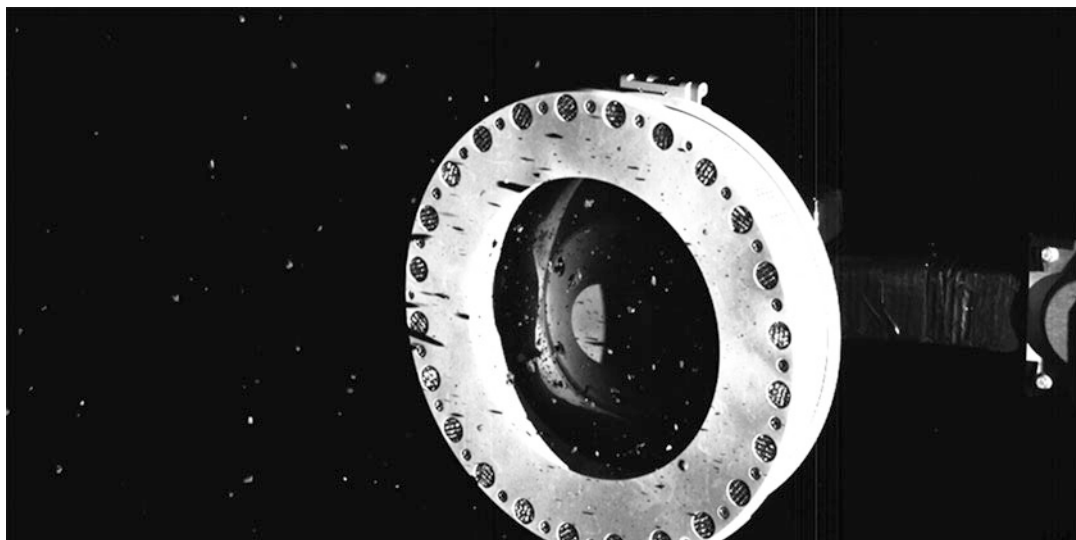


OSIRIS-REx, Fig. 2 This mosaic of asteroid Bennu is composed of 12 images collected on December 2, 2018, by the OSIRIS-REx spacecraft's PolyCam instrument from a range of 15 miles (24 km). The images were obtained at a 50° phase angle between the spacecraft, asteroid, and Sun. (Credit: NASA/Goddard/University of Arizona)

made it highly accessible for spacecraft rendezvous and Earth return, and because its spectral properties indicated a carbonaceous, volatile-rich composition (Lauretta et al. 2015). Bennu is a

small (~500 m diameter) asteroid that likely originated by gravitational self-collapse of rubble generated by the catastrophic disruption of a much larger (~100 km diameter) parent asteroid in the inner main belt 900–2000 million years ago (Walsh et al. 2013).

OSIRIS-REx spacecraft-based visible and near-infrared spectroscopy confirmed that Bennu is carbon-bearing (Simon et al. 2020), and the spectra are consistent with the presence of both organic molecules (aromatic and aliphatic CH bonds; Kaplan et al. 2021) and carbonate minerals (Kaplan et al. 2020). The carbonates sometimes occur as meter-scale veins in host rocks, suggesting extensive hydrothermal alteration on the scale of Bennu's parent asteroid that persisted for thousands to millions of years very early in solar system history (Kaplan et al. 2020). Bennu is also globally hydrated, with water bound up in its dominant lithology, Mg-rich phyllosilicates (Hamilton et al. 2019; Simon et al. 2020). Sample analysis, beginning in 2023, will provide new insights into the nature of these materials and their availability for habitability and the origin of life.



OSIRIS-REx, Fig. 3 Spacecraft image of the OSIRIS-REx sample acquisition mechanism collected on October 22, 2020, after the sampling event. The sample collection chamber (center) appears dark owing to optical extinction

from collected particles. Some particles on the order of 0.1–1 cm in diameter can be seen escaping into space. (Credit: NASA/Goddard/University of Arizona)

The sample's pristinity was ensured by stringent cleaning protocols during spacecraft fabrication and careful mission design during spacecraft operations (Dworkin et al. 2018). Any contamination was thoroughly documented with both active and passive monitoring. The mission archived materials and witness plates during spacecraft fabrication, integration, and testing. A complete database of all materials, elements, and analyses of witness plates on the spacecraft was compiled. The spacecraft fabrication materials are archived as part of the sample collection at the NASA Johnson Space Center.

After the sample is returned to Earth, all samples, witness plates, and space-exposed hardware will be available to the worldwide scientific community through the NASA sample allocation process. Ongoing sample analysis by generations of scientists using cutting-edge tools and methods guarantees an enduring scientific treasure that only sample-return missions can provide.

Cross-References

- [Apollo Asteroid](#)
- [Asteroid](#)

- [Carbonaceous Chondrite](#)
- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [C-Asteroid](#)
- [Extraterrestrial Delivery of Organic Compounds](#)
- [Hayabusa Missions](#)
- [Laboratory Characterization of Meteorites](#)
- [NASA](#)
- [Origin of Life](#)
- [Planet Characterization: High-Resolution Spectroscopy](#)
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Osmolite

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Synonyms

[Osmolyte](#)

Definition

Osmolites or [compatible solutes](#) are organic molecules which are compatible with cell metabolism even at molar concentrations and play protective

roles in adaptation to extreme environments. Microorganisms also accumulate organic solutes for osmotic adjustment. Thermophilic and hyperthermophilic organisms accumulate alcohol phosphates (e.g., inositol-phosphates) as compatible solutes for thermal stabilization, something which does not occur in bacteria or archaea that grow at low or moderate temperature. Osmolites or soluble compatibles can be classified into three groups: poly-alcohol molecules (e.g., manytol), quaternary amines (e.g., glycine betaine), and amino acids (e.g., proline). Compatible solutes have been studied in vitro and have shown significant effects on biomolecules as stabilizers of native macromolecules (proteins or nucleic acid structures).

Cross-References

- [Compatible Solute](#)
- [Enzyme](#)
- [Extremophiles](#)
- [Halophile](#)
- [Halotolerance](#)
- [Hyperthermophile](#)
- [Thermophile](#)

Osmolyte

- [Osmolite](#)

Osmotic Pressure

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

► [Water](#) diffuses through semipermeable [membranes](#) from low- to high-solute- concentration solutions. This process is known as osmosis. Osmotic pressure is the pressure produced on the semipermeable membrane of an organism by the difference in solute concentration between the internal and the external part of the cell. When the

solute concentration in the interior of the cell is as that of the medium, we say that the solution is isotonic, no diffusion takes place. Normally, cell systems develop in environments where the solute concentration is lower than the cytoplasmic solute concentration. In this case, water diffuses from the medium to the cytoplasm. Halophilic organisms grow in solutions where the solute concentration is much higher than the cytoplasmic one. In this case, there is a tendency for water to flow out of the cell to diminish the osmotic pressure on the membrane. This can produce severe problems for cells if they have no means with which to deal with it. Normally, halophilic organisms have cytoplasmic ► [compatible solutes](#), organic or inorganic, which try to compensate the high osmotic pressure generated by the ionic strength of the medium in which they develop.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Compatible Solute](#)
- [Eukarya](#)
- [Extremophiles](#)
- [Halophile](#)
- [Halotolerance](#)
- [Membrane](#)
- [Osmolite](#)

OTU

- [Phylotype](#)

‘Oumuamua

Sean N. Raymond
Laboratoire d’Astrophysique de Bordeaux,
CNRS, Université de Bordeaux,
Pessac, France

Keywords

Small Solar System bodies · Asteroids · Comets · Interstellar objects · Exoplanets

Definition

1I/‘Oumuamua was the first small object discovered on a hyperbolic orbit passing through the Solar System. Its characteristics – including its lack of observed activity in conjunction with its detected non-gravitational acceleration – remain challenging to explain.

Overview

1I/‘Oumuamua was discovered by the Pan-STARRS telescope on October 19, 2017 (Meech et al. 2017). Its discovery triggered excitement in the astronomical community and among the general public. Due to its inherent faintness and rapid orbital motion, the observing window for ‘Oumuamua was short and within a month of its discovery it was beyond the reach of ground-based telescopes.

While its physical nature remains debated (see discussion below), ‘Oumuamua’s measured characteristics are as follows:

- At the time of its discovery its orbit was hyperbolic, with an eccentricity of 1.2 and a v_{infinity} (velocity upon entering the Sun’s gravitational potential) of 26 km/s (Meech et al. 2017).
- Its photometric colors were observed by several groups to be broadly similar to those of volatile-rich small bodies in the Solar System (e.g., C- and D-type asteroids, cometary nuclei; Meech et al. 2017; Jewitt et al. 2017).
- It did not show any signs of outgassing or cometary activity to very stringent limits (see Table 1 of ‘Oumuamua ISSI Team et al. 2019).
- Its brightness varied by roughly an order of magnitude (by 2.5 astronomical magnitudes) on a roughly 8-h timescale but in a not-quite-repeating fashion.
- Its size and albedo were never measured directly. Infrared observations (non-detections) with the Spitzer Space telescope allowed Trilling et al. (2018) to place an upper limit on its albedo of 50%, although their most likely value was ~10%.
- Its orbit was not purely Keplerian. Non-gravitational acceleration was discovered by

Micheli et al. (2018) thanks to astrometric follow-up with the Hubble Space Telescope. This acceleration was pointed directly away from the Sun and was consistent with an r^{-2} radial scaling.

In the months after its discovery, a large number of papers studied ‘Oumuamua’s likely physical characteristics and its possible origin. The large photometric variations likely indicate a very stretched-out object (Meech et al. 2017). Analysis of the light curve combined with shape models suggests a flattened shape with a most likely aspect ratio of $\sim 6:6:1$, although a cigar-like shape of $6:1:1$ is also possible (Mashchenko 2019). The non-repeating nature of its brightness variations indicated that ‘Oumuamua was undergoing non-principal axis, or “tumbling” rotation (Fraser et al. 2018). Several possible processes can potentially explain the large axis ratio of ‘Oumuamua: these include erosion from many small impacts (Domokos et al. 2017), low-speed collisions among planetesimals (Sugiura et al. 2019), tidal disruption (Zhang and Lin 2020), and evaporation (Seligman and Laughlin 2020).

Several studies used the detection of ‘Oumuamua to estimate the number density of such objects in interstellar space. Ironically, a comprehensive study by Engelhardt et al. (2017) placed an upper limit on this number density using non-detections just a few months before ‘Oumuamua was discovered. Do et al. (2018) calculated a number density of $\sim 0.1 \text{ au}^{-3}$ of such objects. If interstellar objects have a top-heavy size-frequency distribution (SFD) like the observed asteroidal SFD or the SFD produced when planetesimals form via the streaming instability, then their mass density is in significant tension with the expected amount of mass that is expected to be ejected in planetesimals per star (Raymond et al. 2018a; Moro-Martín 2018). Resolving this issue likely requires a bottom-heavy SFD for interstellar objects, the implications of which remain to be put in context.

Galactic dynamics indicates that ‘Oumuamua is likely a young object. Its velocity upon entering the Solar System was only 9 km/s from the local standard of rest (LSR), far smaller than the stellar dispersion of $\sim 50 \text{ km/s}$. ‘Oumuamua’s galactic

motion is similar to that of stars younger than 1–2 billion years (Portegies Zwart et al. 2018), although it may be far younger and associated with the nearby Carina star-forming association with an age of only about 30 Myr (Hsieh et al. 2021).

‘Oumuamua’s astrophysical origins remain debated. Early models included a large number of exotic processes including ejection from binary star systems and fluidization and ejection due to stellar evolution, among many others (see ‘Oumuamua ISSI Team et al. 2019 for a review). One simple early model proposed that ‘Oumuamua was simply a leftover planetesimal from an exoplanet system that was ejected after a close encounter with a giant planet after first undergoing a tidal disruption event and losing its surface ice after repeated passages close to its star (Raymond et al. 2018b). That model could reconcile the volatile-rich appearance of ‘Oumuamua with its lack of outgassing and could roughly account for the number density by invoking a large number of tidal fragments.

Accounting for ‘Oumuamua’s measured non-gravitational acceleration has provided a number of challenges to models. If the outgassing needed to account for the non-gravitational acceleration came from a single, randomly placed jet then the outgassing should have spun the object to such a degree that it should have disrupted (Rafikov 2018). This problem is solved if the jet was not randomly placed but instead followed the Sun’s substellar point on ‘Oumuamua’s surface; models show that, under such an assumption ‘Oumuamua would not have disrupted but rather may have been driven to non-repeating rotation as observed (Seligman et al. 2019).

Analysis of ‘Oumuamua’s non-gravitational acceleration showed that sublimation of water cannot provide sufficient force to explain the observed non-gravitational acceleration (Sekanina 2019). This indicates that a comet-like model for ‘Oumuamua cannot be correct. Rather, matching the non-gravitational acceleration instead requires invoking exotic ices such as hydrogen or nitrogen ice. These ices are the foundation of two models for ‘Oumuamua’s origins. The first proposes that ‘Oumuamua is a hydrogen “iceberg” that formed in the extremely cold starless core of a molecular

cloud (Seligman and Laughlin 2020). The second proposes that 'Oumuamua is a collisional fragment of a Pluto-like exoplanet that was created and ejected during a dynamical instability in its host system (Desch and Jackson 2021; Jackson and Desch 2021). Each model can match 'Oumuamua's observed characteristics yet the two have drastically different implications for the formation of such objects.

'Oumuamua was also the subject of a media frenzy in 2018 and again in 2021 that was driven by astronomer Avi Loeb. Loeb had proposed that 'Oumuamua's non-gravitational acceleration was caused by radiation pressure from the Sun (Bialy and Loeb 2018) and suggested in popular articles and later a book that the object was of artificial origin. His proposal has been widely refuted by the scientific community as baseless (see 'Oumuamua ISSI Team et al. 2019).

The controversy regarding 'Oumuamua triggered several studies regarding how to sample or intercept unexpected, *once-in-a-lifetime* objects in the future. The Lyra project developed a space concept to intercept 'Oumuamua itself. The goal of the *Comet Interceptor* mission (Snodgrass and Jones 2019) – funded by the European Space Agency in 2019 – is to intercept a future long-period comet or interstellar object. The mission will have a spacecraft waiting in orbit around the Sun (at the Earth's L2 point) before its target is discovered. If such a spacecraft had been ready and waiting at L2 in 2017, and 'Oumuamua had been discovered a few months earlier, it could have intercepted 'Oumuamua (Seligman and Laughlin 2018).

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and proteins found in the cytoplasmic membrane, it contains polysaccharides. It is a rather complex structure only found in gram-negative bacteria. The lipid and polysaccharides are linked to form a lipopolysaccharide complex. For this reason, the outer membrane is often called the lipopolysaccharide layer (LPS). In the outer membrane, LPS associates with several proteins to form the outer leaflet of the membrane. Lipoproteins are also found in the inner leaflet of the outer membrane and their function is to anchor the membrane to the peptidoglycan. In the outer part of the membrane lipopolysaccharides replace phospholipids. Thus, although the outer membrane can be considered a lipid bilayer, its structure and function is quite distinct from that of the cytoplasmic membrane. Although the major function of the outer membrane of gram-negative bacteria is structural, its components can produce toxicity to animals. The outer membrane has special types of proteins called porins, which are channels responsible for the permeability of small molecules. The periplasm is the space delimited by the outer layer and the cytoplasmic membrane of the gram-negative bacteria in which different important cellular functions are performed.

Our Galaxy

- [Milky Way](#)

Outer Membrane

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

The outer ► [membrane](#) is a phospholipid- and polysaccharide-containing membrane that lies external to the ► [peptidoglycan](#) layer of ► [gram-negative bacteria](#). This layer is effectively a second lipid bilayer, but in addition to phospholipids

Cross-References

- [Gram-Negative Bacteria](#)
- [Membrane](#)
- [Peptidoglycan](#)

Outer Space Treaty

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

The “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies,” the Outer Space Treaty (OST) for short,

is the legal framework of international space law. It was proposed to the UN by the USSR, the UK, and the USA in 1966 and ratified by those countries and 108 others (as of February 2021), while another 23 have signed the treaty but have not completed ratification.

The Outer Space Treaty establishes the general principles applicable to the exploration and use of outer space and applies to all activities of states parties in outer space, whether such activities are carried out by governmental or nongovernmental entities or individuals.

Article IX, second sentence of the OST states: “State Parties shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, when necessary, adopt appropriate measures for this purpose,” which is the basis for the COSPAR planetary protection policy on which all subsequent recommendations and guidelines are based.

Cross-References

- [COSPAR](#)
- [Planetary Protection](#)

References and Further Reading

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies; <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouter spacetreaty.html>

Outflow Channels

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Keywords

Erosion · Flooding · Groundwater · Ice · Water

Definition

Outflow channels on ► [Mars](#) are large channel systems that emerge fully-sized from rubble-filled “chaotic” depressions, are generally tens of kilometers across and hundreds of kilometers long, and were formed by fluid flow of ► [water](#) from subsurface reservoirs.

Overview

Outflow channels were first detected on images from the Mariner 9 mission (Baker and Milton 1974). They are the strongest morphological evidence that large amounts of water once flowed on the Martian surface. Characteristic landforms of outflow channels are anastomosing (building a network of streams that both branch out and reconnect) channels, streamlined erosional “islands,” dry cataracts, and scour marks and grooves on the channel floors (Baker 1982). The closest terrestrial analog for outflow channels is the huge complex of anastomosing rock-cut fluvial channels in east-central Washington (USA). This so-called Channeled Scabland was first interpreted by J Harlan Bretz as the result of the catastrophic megaflooding derived from ice-dammed Pleistocene glacial lakes (e.g., Bretz 1923), an interpretation which challenged the conventional geologic wisdom of Uniformitarianism and was, therefore, heavily debated (Baker 2009). Uniformitarianism (as described by Bates and Jackson 1980) is the fundamental principle or doctrine that geologic processes and natural laws now operating to modify the Earth’s ► [crust](#) have acted in the same regular manner and with essentially the same intensity throughout geologic time, and that past geologic events can be explained by phenomena and forces observable today; the classical concept that “the present is the key to the past.” Many models of the formation of Martian outflow channels favor a catastrophic formation by the sudden release of large amounts of water from subsurface reservoirs. Pressurized aquifers might have existed below an impermeable frozen upper crust (the ► [cryosphere](#)), which was then cracked by the ascent of volcanic dikes (e.g., Head et al. 2003). Alternatively, outflow channels might have been eroded, at least partly, by glacial processes (Lucchitta 1982). Most, if not all,

outflow channels show evidence for a multistage formation with different phases of activity separated by geologically long periods of time. Outflow channel activity spans a long time, from $\gg 3.5$ Ga to geologically very recent times (Neukum et al. 2010). Outflow channels terminate into the northern lowlands of Mars and might have fed an ancient northern ocean (Baker et al. 1991), although this scenario is contentious.

Cross-References

- [Crust](#)
- [Cryosphere](#)
- [Mars](#)
- [Valley Networks](#)
- [Water](#)

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Outgassing

- [Degassing](#)

Oxalic Acid Dinitrile

- [Cyanogen](#)

Oxalonitrile

- [Cyanogen](#)

Oxalyl Cyanide

- [Cyanogen](#)

1,3-Oxazolidine-2,5-dione

- [Amino Acid N-Carboxy Anhydride](#)

Oxic

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Oxic is a term used to describe a condition, environment, or habitat in which oxygen is present.

Oxic Sediments

Rosalie Tostevin¹ and Simon W. Poulton²

¹Department of Geological Sciences, University of Cape Town, Rondebosch, South Africa

²School of Earth and Environment, University of Leeds, Leeds, UK

Keywords

Oxygen · Redox · Diagenesis · Organic carbon · Microbes · Respiration · Pore waters

Definition

Pore waters within oxic sediments contain measureable amounts of dissolved oxygen. In general, pore water oxygen concentrations decline with depth due to organic matter degradation. The depth of oxygen penetration varies depending on the sedimentation rate, mixing processes, the flux and type of organic carbon, and the oxygen content of bottom waters.

Overview

Sediments at the seafloor are porous and poorly consolidated and thus readily allow diffusion of bottom waters and the dissolved gases that they contain into the sediment. With depth, sediments undergo compaction and eventually lose contact with overlying seawater. While sediment pore waters at or close to the sediment-water interface in the global ocean commonly contain dissolved oxygen, the concentration of oxygen declines with depth due to organic matter degradation.

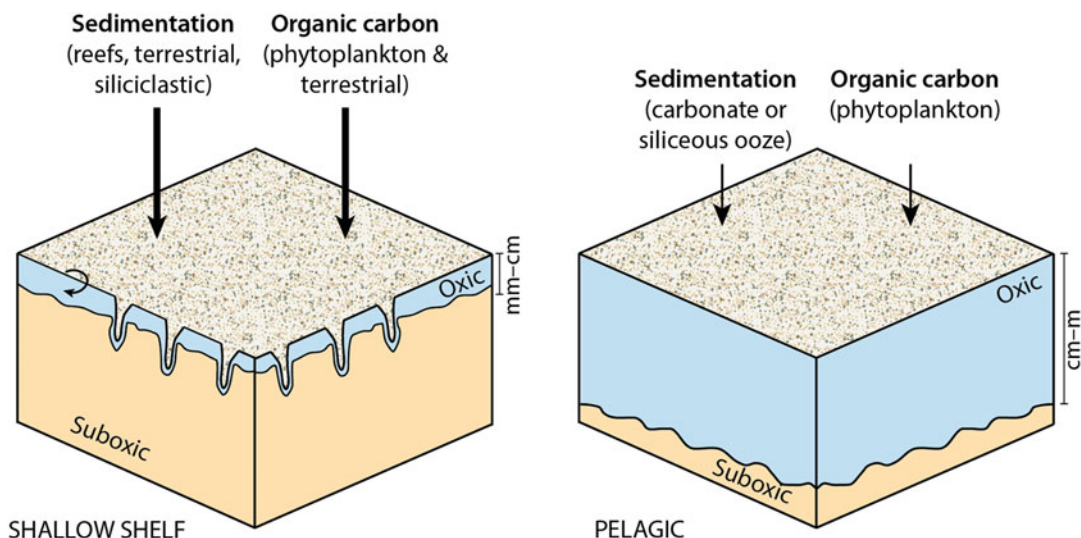
Deposited organic matter is degraded at the seafloor and during burial in the sediments, with less than 1% surviving to become part of the rock record (Emerson and Hedges 1988). Aerobic respiration is the first pathway used by microbes for organic matter degradation, as it is associated with the largest free energy yield. As such, aerobic respiration is responsible for the majority of organic carbon remineralization in the oceans and sediments (Bender and Heggie 1984). At low dissolved oxygen concentrations ($<10\ \mu\text{M}$), the rate of aerobic respiration begins to decline, and anaerobic respiration processes may proceed with alternate electron acceptors (► “Suboxic Sediments”, this volume). Aerobic respiration tends to be most prolific at the sediment-water interface, but oxygen may be present in pore waters for centimeters or even meters below the sediment-water interface.

The depth of oxygen penetration in sediments is highly variable and is controlled by the chemical, physical, and biological setting. One major

control is the concentration of oxygen in overlying bottom waters. The concentration of dissolved oxygen in surface waters is set by atmospheric oxygen levels, as well as the solubility of O_2 gas in water, which is itself controlled by salinity and temperature. At depth in the water column, oxygen is consumed by respiration, but the rate of decline depends on the local carbon cycle and mixing rates. Oxygen levels in oceanic bottom waters vary from up to $300\ \mu\text{M}$ below polar surface waters to $<5\ \mu\text{M}$ below oxygen minimum zones in intense upwelling regions. Higher oxygen levels at the sediment-water interface increase the average depth to which oxygen can persist in the sediments.

Sedimentation rate exerts another important control on the depth of oxygen penetration, by influencing the amount of time organic matter remains exposed at or near the sediment-water interface (Fig. 1). Under the high sedimentation rates common in coastal and shallow shelf environments ($\sim 1\ \text{mm year}^{-1}$), organic matter rapidly loses contact with overlying bottom waters. Therefore, a relatively large fraction of organic matter is often buried in such sediments, and oxygen in pore waters is rapidly consumed (Fig. 1). In contrast, under the low sedimentation rates common in deeper water settings ($<0.01\ \text{mm year}^{-1}$), organic matter remains exposed to oxic bottom waters for longer (thousands of years), and so there is less organic carbon leftover to drive anaerobic heterotrophic communities in the sediments.

Mixing in shallow water environments can disturb any stratification, bringing anoxic sediments from a few centimeters depth back into contact with oxic bottom waters. Mixing may occur mechanically, for example, during storm events or, biologically, through bioturbation (Kristensen 2000). More intense mixing results in re-oxidation of reduced species and allows deeper oxygen penetration (Fig. 1). The properties of the sediments can influence the degree of contact between bottom waters and pore waters. For example, fine-grained sediments, such as mud, have a lower porosity and so limit diffusion of oxygen from bottom waters into pore waters. This facilitates a steeper



Oxic Sediments, Fig. 1 The depth of the oxic zone in sediments is partly controlled by the sedimentation rate, the flux of organic matter, and mixing processes. In general,

the oxic zone extends deeper into the sediments in pelagic settings where sedimentation rates and organic carbon fluxes are lower

oxygen gradient than coarse-grained sediments, such as sand.

The flux and type of organic matter is also an important variable. Large fluxes of organic matter, as are common in coastal environments, can result in more rapid consumption of the available oxygen in shallow sediments. Furthermore, organic matter varies considerably in terms of its reactivity, with phytoplankton-derived carbon easier to digest than terrestrial organic matter which contains more refractory plant lignin. All of these parameters contribute to the exposure time of marine sediments to oxic conditions.

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Cross-References

► [Suboxic Sediments](#)

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Oxidant

► [Electron Acceptor](#)

Oxidation

Concepción Alonso
Universidad Autonoma de Madrid, Madrid, Spain

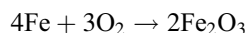
Keywords

Electron donor · Reducing agent · Reductive

Synonyms

[Combustion](#); [Corrosion](#); [Rusting](#)

Definition



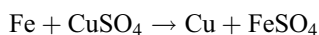
Oxidation can be defined with different terms such as: the loss of electrons or hydrogen, or the gain of oxygen by an atom or a molecule.

Overview

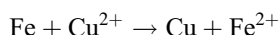
Oxidation in Terms of Electron Transfer

Oxidation is the loss of electrons.

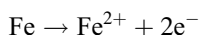
For example, in the reaction between iron and copper sulfate solution



copper sulfate and iron sulfate are both ionic compounds. If rewritten as an ionic equation, it turns out that sulfate ions are spectator ions and the reaction can be written as:



where the iron is *oxidized* from metal iron (Fe^0) to ferrous iron (Fe^{2+}) by the loss of two electrons:

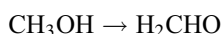


while the copper (II) ion, gaining two electrons is reduced to copper metal (Cu^0). Thus, in the reaction, the reductant or ► [reducing agent](#) loses electrons and is oxidized, and the oxidant or *oxidizing agent* gains electrons and is reduced.

Oxidation in Terms of Hydrogen Transfer

Oxidation is the loss of hydrogen.

- Methanol (alcohol) can be oxidized to methanal (aldehyde) by loss of hydrogen



Oxidation in Terms of Oxygen Transfer

Oxidation is the gain of oxygen.

- The reaction between elemental iron and oxygen to form iron oxide involves the oxidation of iron (commonly known as rusting)

In general terms, oxidation implies an increase in an atom's oxidation state. However, it is only correct to speak about the oxidation state of a metal atom when the compound is purely ionic. Molecules, atoms, or ions that have the ability to *reduce* others are said to be reductive and are known as reducing agents, *reductants*, or *reducers*. That is to say, the reductant transfers electrons to another substance, which is, as a result, oxidized. Since, it “donates” electrons it is also called an ► [electron donor](#). The electronic transfer reactions known as redox reactions are especially important in biology because most biochemical reactions imply reduction or oxidation reactions.

Substances that act as reductants include, among others, electropositive elemental metals like lithium, sodium, magnesium, iron, zinc, and aluminum. These metals readily donate or *give away* electrons. *Hydride transfer reagents*, such as NaBH_4 and LiAlH_4 , are widely used in organic chemistry. Another method of reduction involves the use of hydrogen gas (H_2) with a palladium, platinum, or nickel catalyst. These *catalytic reductions* are primarily used in the reduction of carbon-carbon double or triple bonds.

Cross-References

- [Electron Donor](#)
- [Redox Potential](#)
- [Reducing Agent](#)

References and Further Reading

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Oxidative Agent

- [Electron Acceptor](#)

Oxidative Phosphorylation

- [Respiration](#)

Oxidizing Atmosphere

Franck Selsis
CNRS, Laboratoire d'astrophysique de Bordeaux,
Passac, France

Definition

An oxidizing atmosphere is a (planetary) atmosphere which oxidizes immersed (surface) compounds. It sometimes refers to an O₂-rich atmosphere, for example the atmosphere of modern Earth. Most of the Earth's atmospheric oxygen is generated by biological photosynthesis; however, oxidation can also be an effect of photochemistry initiated by stellar UV radiation. The Martian atmosphere, for instance, is an oxidizing atmosphere. Its main constituents are CO₂, N₂, Ar, and H₂O, but the OH radicals and oxygen atoms produced by photolysis result in surface oxidation and the formation of O₂, O₃ and H₂O₂.

Cross-References

- [Dioxygen](#)
- [Great Oxidation Event](#)
- [Oxygenation of the Earth's Atmosphere](#)

Oxirane

- [Ethylene Oxide \(C₂H₄O\)](#)

Oxyatmoverision

- [Great Oxidation Event](#)

Oxygen (Molecule)

- [Dioxygen](#)

Oxygen Fugacity

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale
Supérieure de Lyon, Lyon Cedex 7, France

Keywords

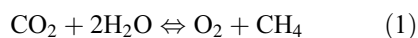
Mineral redox buffer · Redox reactions ·
Redox zonations

Definition

Oxygen fugacity is an equivalent of the partial pressure of oxygen in a particular environment (atmosphere, rocks, etc.) corrected for the non-ideal character of the gas.

Overview

There are multiple ways of characterizing how reducing or how oxidizing an environment is. An example of a redox reaction in an ideal gas mixture of carbon dioxide, methane, water, and oxygen is:

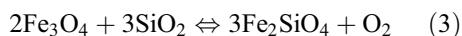


The status of this reaction can be evaluated by writing the equilibrium equation:

$$\frac{P_{\text{O}_2} P_{\text{CH}_4}}{P_{\text{CO}_2} P_{\text{H}_2\text{O}}^2} = K_1(T) \quad (2)$$

where P_i stands for the partial pressure of gas i and $K_1(T)$ is the reaction coefficient at temperature T . For real gases, pressure P_i should be replaced by fugacities f_i . Fugacity and pressure converge toward each other when the total pressure diminishes.

Likewise, the reduction of magnetite, which contains one Fe^{2+} and two Fe^{3+} , by silica gives fayalite (ferric olivine Fe_2SiO_4), which contains two ferrous ions Fe^{2+} :



For ideal solids and gas:

$$\frac{P_{\text{O}_2} [\text{Fe}_2\text{SiO}_4]}{[\text{Fe}_3\text{O}_4] [\text{SiO}_2]} = K_2(T) \quad (4)$$

where concentrations are in bracket. For pure phases, concentrations are equal to 1, while for real gases P_{O_2} is replaced by f_{O_2} . Taking the logarithm of both sides, we get:

$$\ln f_{\text{O}_2} = \ln K_2(T) = \frac{\Delta H_2}{RT} + \text{Const} \quad (5)$$

where ΔH_2 is the enthalpy of the reaction and R is the gas constant. At a given temperature, the quartz-fayalite-magnetite (QFM) mineral assemblage (see entry ► [“Mantle, Oxidation of”](#)) imposes or “buffers” a particular value of f_{O_2} . For all practical purpose, oxygen fugacity measures the electron trade among minerals and describes the proportions of Fe^{2+} and Fe^{3+} coexisting in the rock, rather the other way around. Under most conditions, the f_{O_2} is so low that oxygen is actually fully combined to the mineral phases and is not present as a gas. Oxygen fugacity is a robust estimate of the redox conditions because rocks are electrical insulators. Other buffers of oxygen fugacity exist, such as iron-wüstite (IW), which describes the coexistence of

metallic iron Fe^0 and Fe^{2+} in extremely reducing environments like the lunar mantle.

Cross-References

- [Archean Mantle](#)
- [Earth’s Atmosphere, Origin and Evolution of](#)
- [Mantle, Oxidation of](#)
- [Oxygenation of the Earth’s Atmosphere](#)
- [Redox Zonation](#)

Oxygen Isotopes

Ko Hashizume

Faculty of Science, Ibaraki University, Ibaraki, Japan

Keywords

Isotope anomaly · Fractionation mass independent · Organic matter · Photochemistry · Self-shielding · Solar composition · Water

Definition

Oxygen has three stable isotopes: oxygen-16, oxygen-17, and oxygen-18. In most studies on terrestrial samples, only the $^{18}\text{O}/^{16}\text{O}$ ratio is usually measured and discussed, where the mass-dependent fractionation law, expressed by $\delta^{17}\text{O} \approx 0.52 \times \delta^{18}\text{O}$, can be safely assumed (see ► [Delta, Isotopic](#), for the δ notation). The $\delta^{17}\text{O}$ values among extraterrestrial samples significantly deviate from the above shown relationship. This deviation bears prime importance in cosmochemistry and, naturally, in astrobiology.

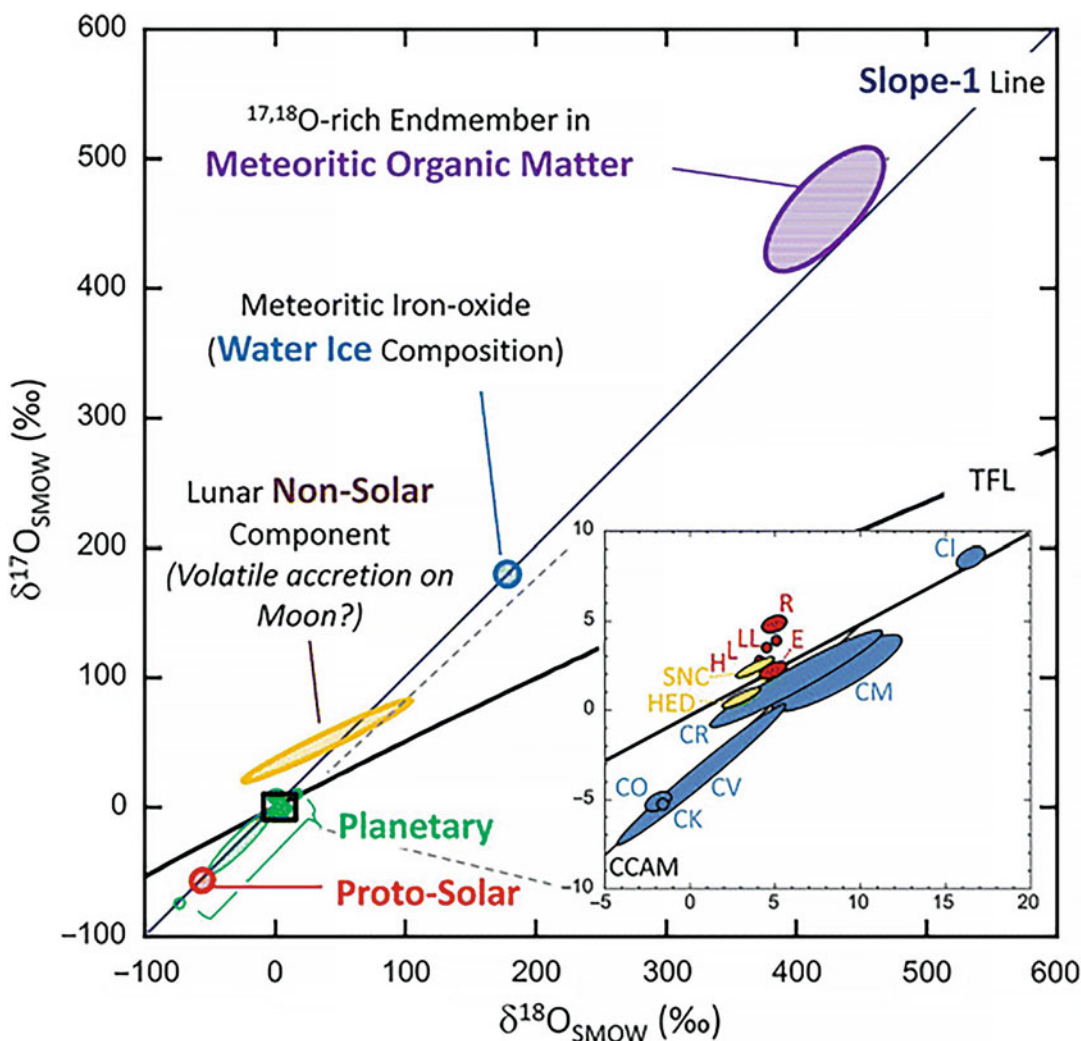
Overview

Oxygen is the most abundant element in the planetary system, except among the giant planets, Jupiter and Saturn, where hydrogen and helium

dominate their masses. Oxygen is accommodated as a major constituent in most types of building blocks, rocks (MO_x), water (H_2O), and organics (CHONS), which are essential in constructing a terrestrial planet, particularly a habitable planet. Oxygen isotope compositions among solid planetary materials are generally expected to bear keys to understand the history of these building blocks, from their births to their accretion into planets or asteroids, although the details are vigorously debated until now (Fig. 1).

Basic Methodology

The oxygen isotope ratios among samples are normally expressed in the δ -notation, that is, by the difference of the ratios in per mill unit relative to the ratios of the reference standard; $\delta^x\text{O} \equiv (R/R_{\text{std}} - 1) \times 1,000$; $R = {}^x\text{O}/{}^{16}\text{O}$ ($x = 17$ or 8). The international reference standard is the standard mean ocean water (SMOW) with ${}^{17}\text{O}/{}^{16}\text{O}$ and ${}^{18}\text{O}/{}^{16}\text{O}$ ratios of 3.73×10^{-4} and 2.005×10^{-3} , respectively.



Oxygen Isotopes, Fig. 1 The oxygen three-isotope diagram for important end-member compositions that contributed to planetary compositions. The inserted figure displays the O-isotope compositions among the bulk

meteorites. Note that the terrestrial fractionation “line” (TFL) is precisely a curve when plotted over a large range of δ values. Refer to the main text for other notations

Key Research Findings

Classically, it was considered that rocks and water were produced from a hot and homogenous solar gas through equilibrium condensation processes. In this case, we expect that the O-isotope compositions among the raw material and all products, that is, the solar and planetary compositions, respectively, are uniformly plotted on a single line in the $\delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ diagram with a relationship of $\delta^{17}\text{O} \approx 0.52 \times \delta^{18}\text{O}$, namely, the terrestrial fractionation line (TFL). (Readers are advised to refer to the cross-references for further basics on isotope fractionation, particularly on mass-dependent fractionation.) However, in 1973, Clayton and coworkers discovered that O-isotope compositions among carbonaceous chondrites deviate from the TFL but are plotted around a line with a much steeper slope of 0.94, so-called the carbonaceous chondrite anhydrous minerals (CCAM) line. Later works (Young and Russell 1998) demonstrated that the slope is exactly one among the less-altered components in the meteorites, but the slope displayed among assemblages of chondritic minerals actually measured is slightly smaller, because of the contributions from altered components, whose O-isotope compositions are somewhat mass-dependently fractionated from their original compositions. Note that the non-mass-dependent fractionation trend of oxygen is not a peculiar observation among the carbonaceous chondrites but is observed among essentially all available extraterrestrial materials, including meteorites possibly from Mars or from Vesta, one of the largest asteroids (Clayton 1993, 2005).

Many possible explanations have been submitted to explain the origin of the slope 1 trend. It was first explained that the non-mass-dependent O-isotope trend originated from contributions from a hypothetical ^{16}O -rich exotic component, possibly of nucleosynthetic origin (Clayton 1993). However, later measurements of O-isotope compositions among pre-solar oxide grains (Nguyen et al. 2007) suggest that the ^{16}O -rich component is rather rare among the pre-solar grains and thus may not contribute to alter the bulk meteoritic compositions. The alternative explanations

recently supported are the fractionations associated with chemical processes that took place in the early [solar nebula](#) or in the ancestral molecular cloud. The two different chemical processes proposed are mass-independent fractionation (MIF) and the CO self-shielding.

MIF is typically seen in the process that operates in ozone formation in the terrestrial upper atmosphere (Thiemens 1999). Ozone is formed in the pathway as follows: $\text{O} + \text{O}_2 \leftrightarrow \text{O}_3^*$; $\text{O}_3^* (+\text{M}) \rightarrow \text{O}_3$, where O_3^* denotes the vibrationally excited state and M is a third molecule that stabilizes the excited ozone by collision. The origin of MIF is considered to be the lower density of the vibrational quantum states for the symmetric isotopomer (OQO^*) compared to the asymmetric one (QOO^*), where Q is either ^{17}O or ^{18}O . The resident time of QOO^* is longer than OQO^* ; thus QOO is stabilized more efficiently than OQO . The QOO excess may occur for both ^{17}O and ^{18}O , by which the MIF signal is produced. Marcus (2004) proposed that similar reactions such as $\text{O} + \text{XO} \leftrightarrow \text{XO}_2^*$; $\text{XO}_2^* (+\text{M}) \rightarrow \text{XO}_2$ ($\text{X} = \text{Si}, \text{Ca}, \text{Al}, \text{etc.}$), involving MIF, might have occurred in the early solar nebula, during the formation of calcium-aluminum-rich inclusions, which are particularly enriched in ^{16}O , plotted on the CCAM line.

The CO self-shielding is proposed to take place during the photodissociation of CO in a gas medium that consists of H_2 and CO, irradiated by external radiation fields (van Dishoeck and Black 1988; Visser et al. 2009). At a wavelength of 91–108 nm, CO shows narrow and isotopically separated absorption bands leading to its photodissociation through the [predissociation](#) mechanism. In a gas medium irradiated by ultraviolet light, the wavelengths which correspond to the absorption bands for $^{12}\text{C} \ ^{16}\text{O}$, the dominant major isotopologue of CO, are more quickly attenuated than those for other minor isotopologues. The CO self-shielding is considered to be responsible for the carbon and oxygen isotope fractionations in molecular clouds (Visser et al. 2009). Many workers attempted to apply the self-shielding effect to the early solar nebula. First, Kitamura and Shimizu (1983) proposed that $^{17,18}\text{O}$ -rich O atoms derived from the self-

shielding effect in the photodissociation of O_2 , exchanged with mineral grains upon shock heating, may lead to $^{17,18}O$ -enriched planetary solid materials. However, Navon and Wasserburg (1985) pointed out that the $^{17,18}O$ -enrichment produced by the self-shielding will be rapidly erased by the reaction between the O atom and O_2 . Clayton (2002) proposed that CO self-shielding may occur at the inner edge of the solar nebula, in the proximity of the Sun. Later models assume that the CO self-shielding occurred at the cold environment, at the envelope of the outer solar nebula (Lyons and Young 2005), or in the parental molecular cloud, part of which later evolved to the solar nebula (Yurimoto and Kuramoto 2004). In these CO self-shielding models, the $^{17,18}O$ -rich isotope signature produced by the self-shielding is assumed to be transmitted to H_2O and finally trapped by the silicate minerals.

We may test these O-isotope fractionation models by the knowledge of several important end-member components. The most important one is the solar composition. The solar composition here refers to the composition of the solar gas at the surface of the Sun. The temperature at the solar surface is low enough to prevent occurrence of any nuclear reactions to alter the O-isotope composition. Also, the mixing of masses between the surface and the solar core is considered to be negligibly small. Therefore, the composition of the gas at the solar surface is considered to preserve the proto-solar composition, representing the bulk composition of the solar nebula. The MIF models assume that the solar O-isotope composition is the same as the terrestrial composition, whereas the CO self-shielding models assume an ^{16}O -rich solar composition. The solar isotope composition can be assessed the most accurately by direct measurement of the solar wind. The surface of the Moon is exposed to the solar wind for up to billions of years. Hashizume and Chaussidon (2005) discovered at the surface of several metallic grains contained in lunar soil samples, irradiated by the solar wind since 1–2 Gyr ago, an oxygen component enriched in ^{16}O by $>2\%$ relative to the terrestrial composition. They assigned the observed ^{16}O -rich oxygen to the solar-wind composition, concluding that the

bulk solar nebula was ^{16}O -rich. However, the situation was complicated by the finding of a distinct O-isotope composition at the surface of metallic grains from a different lunar soil sample, where O was enriched in $^{17,18}O$ by $\sim 3\%$ relative to the terrestrial composition (Ireland et al. 2006). This debate was finally brought to an end by the final result for the O-isotope determination of the solar-wind component captured by the Genesis space mission (McKeegan et al. 2011). The space probe circled the Sun for several years to accumulate solar wind on several substrates, which were returned to Earth in 2004. They estimated the solar composition to be enriched in ^{16}O by $\sim 3\%$ relative to the terrestrial composition ($\Delta^{17}O = \delta^{17}O - 0.52 \cdot \delta^{18}O = -28.4 \pm 1.8\%$). The origin of the $^{17,18}O$ -rich composition observed in some lunar samples is yet unresolved. However, it is tempting to speculate that it represents the oxygen composition of comets that accreted to the Moon, since water ice and organics, the major constituents of comets, could be enriched in $^{17,18}O$ (see below).

The other important end-member compositions, which may serve as tests for several models, are the primordial compositions of water ice and organic matter. The models by Yurimoto and Kuramoto (2004) or Lyons and Young (2005) predict that water ice is the carrier of the $^{17,18}O$ -rich isotope signature, connecting the $^{17,18}O$ -rich O atoms, first produced by the CO self-shielding in the gas medium, and the rocky materials at the midplane of the solar nebula, which finally trapped the isotope signature. Sakamoto et al. (2007) discovered in a primitive carbonaceous chondrite Acfer094, a poorly characterized iron-oxide mineral with O-isotope compositions as high as $\delta^{17}O \approx \delta^{18}O \approx 180\%$. They explained that the iron-oxide mineral was produced by reactions between primordial water and the metallic Fe-Ni or iron sulfides and argued that their observation demonstrates the role of water ice as a carrier of the O-isotope signature produced by the CO self-shielding. Hashizume et al. (2011) discovered that an Antarctic carbonaceous chondrite contains pieces of organic particles that display striking enrichments in ^{17}O and ^{18}O at almost parallel degrees, by as high as 530% relative to the terrestrial composition. The oxygen isotope anomalies were associated with carbon

isotope anomalies, roughly with a relationship of $\delta^{17}\text{O} \approx 1.05 \times \delta^{18}\text{O} \approx 0.5 \times \delta^{13}\text{C}$. By the CO self-shielding, the enrichment of ^{13}C is indeed expected to be associated with the $^{17,18}\text{O}$ enrichment. However, the ^{13}C -rich signature produced among the photodissociated products is considered to be compromised by a competing reaction. The ion molecule reaction ($^{12}\text{CO} + ^{13}\text{C}^+ \leftrightarrow ^{12}\text{C}^+ + ^{13}\text{CO} + 35 \text{ K}$) is particularly active at low temperatures, whose isotope effect is considered to exceed the effect by the self-shielding below a gas temperature of 60 K (Visser et al. 2009). The positive correlation between the $\delta^{17,18}\text{O}$ and $\delta^{13}\text{C}$ observed among the organics suggests that the temperature where the CO photodissociation occurred was higher than the one for the typical molecular cloud core (~10 K), which is the place proposed by Yurimoto and Kuramoto (2004) where the CO self-shielding might have occurred. Hashizume et al. (2011) argued that the organic formation associated with the $^{17,18}\text{O}$ -enrichment probably occurred at the envelope of the solar nebula, a slightly warm (>40 K) and dense gas medium intensively illuminated by the proto-Sun.

Future Directions

The non-mass-dependent O-isotope anomaly, broadly observed among solid planetary materials, was originally considered to represent the origins or formation processes of a subset of the rocky planetary materials. However, recent studies suggest that the O-isotope anomaly is deeply connected to the origins of the low-temperature condensates, that is, the volatiles, represented by the water ice and the organic matter, which are critically important materials in astrobiology. It is important to summarize the two advantages of O-isotopes over other light element (H, C, and N) stable isotopes as a tracer. (1) Oxygen has three isotopes. We may accurately discriminate the original mass-independent isotope signature from the mass-dependent fractionations that may occur by miscellaneous effects. (2) Oxygen is the major constituent in both low- and high-temperature condensates. The oxygen isotope ratios may become one of the most important

tools to trace the entire history of the important ingredients for a habitable planet: from their origins, their distribution processes in the solar nebula, accretion to planets/asteroids, and the processes within the planets, namely, the rock-water-organics interactions, possibly including the life-formation process.

Cross-References

- [Fractionation, Mass Independent and Dependent](#)
- [Interstellar Chemical Processes](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopolog](#)
- [Nucleosynthesis, Stellar](#)
- [Photochemistry](#)
- [Photodissociation Region](#)
- [Protoplanetary Disk, Chemistry](#)
- [Self-Shielding Effects on Isotope Fractionation](#)
- [Stable Isotopes](#)

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Oxygen Minimum Zone

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Anoxia · Archean ocean · Anaerobia · Denitrification · Hypoxia · Nitrogen cycle · Oxygenation of the Earth · Redox zonation

Acronyms

OMZ Oxygen-minimum zone

Synonyms

Dead zone; Shadow zone

Definition

The oxygen-minimum zone or OMZ is the zone in a body of water or depth in a water column in which the oxygen saturation is minimum and thus redox conditions are hypoxic (O_2 concentration $<75 \mu\text{mol/L}$) or anoxic (O_2 concentration $<1 \mu\text{mol/L}$).

Overview

In terrestrial oceans, the oxygen-minimum zone develops between 200 and 1000 m below the sea level. The development of the OMZ in oceans is mainly related to the consumption of oxygen by aerobic bacteria degrading dead organisms descending through the water column from the above-oxygenated ocean layer. At depths >1000 m, the ocean is again oxygenated because the bottom currents bring cold, oxygen-rich, polar waters. On the continental platform, sediments in contact with the OMZ are also in anoxic conditions, allowing the preservation of buried organic matter.

OMZ plays a key role in regulating the ecological community structure of the global ocean. In this zone, important metabolic activities take place regulating the cycle of several life-related elements, such as nitrogen. Indeed, in this poor-oxygen zone, organisms must develop peculiar strategies to survive, as denitrifiers, heterotrophic anaerobic bacteria which are able to consume oxygen from nitrates, through denitrification at very low O_2 level of a few μM (Sigman et al. 2009; Ulloa et al. 2012); or anammox bacteria which convert nitrite and ammonium ions directly into diatomic nitrogen by anaerobic ammonium oxidation at oxygen concentrations up to about $10\text{--}20 \mu\text{M}$ (Ulloa et al. 2012). Both metabolic processes transform nitrates and nitrites back into N_2 , completing the atmosphere-hydrosphere global nitrogen cycle (Sigman et al. 2009). Several astrobiology teams study the OMZ at

different climatic conditions in terrestrial lakes and oceans because it might represent the best analogue of the Archean anoxic oceans or those in the early Proterozoic when only the upper superficial layer was oxygenated. Studying the prokaryote communities living in the OMZ can give important clues on the evolution of specific organisms and the development of specific catabolic/metabolic activities enabling survival in a quasi-anoxic environment.

Oxygen minimum zones may have developed in oceans located on the icy moons of our Solar system. Europa is thought to host a subsurface ocean with substantial amounts of O₂ sourced from ice radiolysis. Pending the rate at which Europa's ice shell is mixed with the ocean, as well as the rates at which this O₂ is consumed, it may accumulate to concentrations comparable or even higher than those in Earth's oceanic oxygen minimum zones (Hand et al. 2009; Ward et al. 2019).

Cross-References

- [Denitrification](#)
- [Europa](#)
- [Nitrogen](#)
- [Nitrogen Cycle, Biological](#)
- [Redox Zonation](#)

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Oxygen Respiration

- [Aerobic Respiration](#)

Oxygen, Atomic

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

Oxygen is a chemical element with atomic number 8, represented by the symbol O. The name *oxygen* was coined in 1777 by Lavoisier. It derives from the Greek word “oxys” meaning “sharp,” referring to the sharp taste of acids, and “genēs” meaning “producer.” It is a chalcogen and is highly reactive, forming compounds such as oxides with most other elements. Oxygen is also the name of the molecular compound O₂, also known as ► [dioxygen](#), formed from two covalently linked oxygen atoms with a spin triplet electron configuration.

Oxygen is the third most abundant element in the universe by mass, after hydrogen and helium, and the most abundant element by mass in the Earth's crust. Dioxygen as a gas makes up 20.9% of the volume of Earth's atmosphere and is also present in the form of water vapor and CO₂. Oxygen makes up 49.2% of the Earth's crust by mass, mostly in the form of silicates, carbonates, and metal oxides, and is the major component of seawater at 88.8% by mass, in the form of water.

All major classes of biological molecules, including proteins, nucleic acids, carbohydrates, and fats, contain oxygen, as do the major inorganic compounds that comprise animal shells, teeth, and bone. Oxygen was independently discovered by Scheele in 1773 (or possibly earlier) and Priestley in 1774.

Naturally occurring terrestrial oxygen includes three stable isotopes: ^{16}O , ^{17}O , and ^{18}O . ^{16}O is the most abundant, making up 99.762% of the natural abundance. Most ^{16}O is synthesized at the end of the helium fusion process in stars, but some is made by neon burning. ^{17}O is primarily produced by the burning of hydrogen into helium during the CNO cycle. ^{18}O is produced when ^{14}N captures a ^4He nucleus during stellar fusion.

Due to its electronegativity, oxygen forms chemical bonds with almost all other elements to give corresponding oxides. The ► [oxidation](#) state of atomic oxygen is -2 in almost all known oxygen-containing compounds, but in a few compounds such as peroxides, the oxidation state is -1 .

Cross-References

- [Dioxygen](#)
- [Oxidation](#)
- [Oxygen isotopes](#)

Oxygenase

Felipe Gomez
Instituto Nacional de Técnica Aeroespacial,
Centro de Astrobiología (CSIC/INTA), Madrid,
Spain

Definition

Oxygenases catalyze the transference of oxygen from molecular oxygen to an oxidized substrate. They are a group of ► [enzymes](#) that form a class of oxydoreductases (enzymes that catalyze the transference of electrons from one molecule (called reductant) to another (the oxidant)). There are two classes of oxygenases: mono-oxygenases, which transfer an oxygen atom from molecular oxygen to the substrate and reduce the other atom to water, and dioxygenases, which are able to transfer both oxygen atoms to the substrate.

Cross-References

- [Enzyme](#)
- [Oxidation](#)

Oxygenation of the Earth's Atmosphere

David C. Catling
Department of Earth and Space Sciences,
University of Washington, Seattle, WA, USA

Keywords

Rise of oxygen · Oxygenation

Synonyms

[Atmospheric redox change](#); [Earth's oxygenation](#)

Definition

Earth's oxygenation is an increase in the concentration of atmospheric molecular oxygen (O_2) from levels of less than 1 ppmv before 2.45 Ga to 21% by volume today. Larger amounts of atmospheric oxygen became possible because of shifts in the competition between the production of oxygen derived from ► [photosynthesis](#) and the rate of consumption of oxygen by different geological processes. Evidence from ancient rocks suggests that oxygenation happened in steps, with a first rise of O_2 at 2.45–2.32 Ga and a second around 0.75–0.58 Ga. The latter increase was a precursor to the appearance of macroscopic animals.

Overview

The present atmosphere contains (by volume) 78.05% N_2 , 20.95% O_2 , 0.93% Ar, 0.038% CO_2 , and various trace gases. With the exception of argon, the concentrations of all of the major gases are biologically modulated. Oxygen, in particular, is almost solely biogenic because it has no

significant abiotic source. Consequently, before life existed, the atmospheric partial pressure of O_2 is estimated to have been $<10^{-13}$ bars. The importance of O_2 cannot be overstated: without sufficient O_2 , the Earth would have no large multicellular plants, no land animals, and no humans or consciousness. A particular type of photosynthesis, ► [oxygenic photosynthesis](#), is responsible for supplying O_2 to the atmosphere. Jan Ingenhousz, a Dutch physician and botanist, discovered oxygenic photosynthesis in 1779, by showing that when green plants are exposed to sunlight they produce oxygen. In the nineteenth century, many single-celled photosynthesizers were identified in addition to plants, which included algae and organisms that were initially called *blue-green algae*. Like other algae, the blue-green ones were assumed to have the same cellular structure as plant cells, as a matter of definition. However, in the 1970s, blue-green algae were recognized as bacteria and were reclassified as ► [cyanobacteria](#) through the efforts of Roger Stanier, a Canadian microbiologist. Our modern description of oxygenic photosynthesis is a process by which green plants, algae, and cyanobacteria split molecules of water into hydrogen and oxygen. The hydrogen is used inside cells to chemically reduce carbon

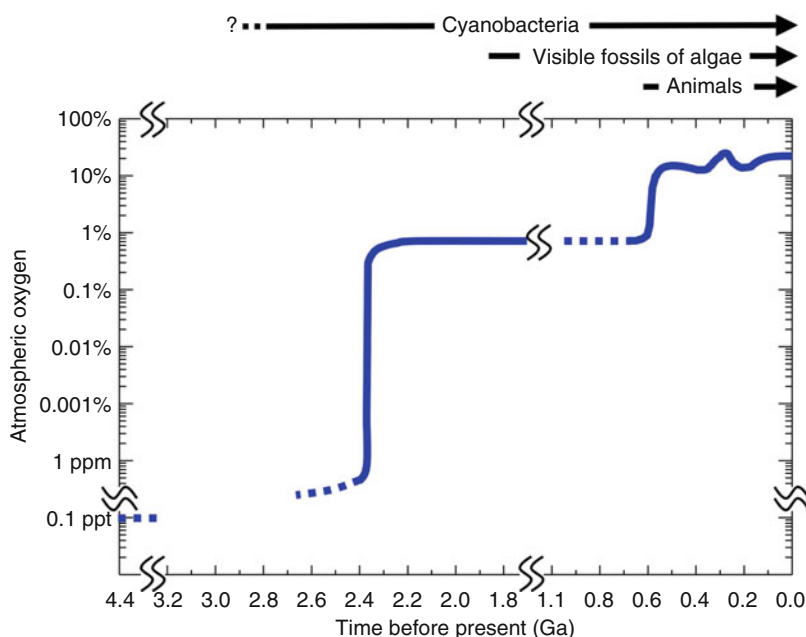
dioxide to organic matter, while the oxygen is released as O_2 waste gas.

In the twentieth century, geochemistry uncovered the history of Earth's atmospheric O_2 levels, showing that for roughly the first half of Earth history, up until about 2.4 Ga, O_2 concentrations were less than 1 ppmv (parts per million by volume) (Fig. 1). The first person to describe evidence that O_2 levels were significantly different on the early Earth was the geologist Alexander MacGregor. In the 1920s, MacGregor examined Archean (pre-2.5 Ga) sedimentary rocks in modern-day Zimbabwe and deduced that they formed in an atmosphere devoid of O_2 because they lacked the reddish-colored, oxidized iron minerals that are ubiquitous in analogous modern sediments. MacGregor's conclusion greatly influenced Preston Cloud, an American geologist, who further investigated the geologic record for information on past atmospheric O_2 . Cloud also championed a suggestion originally made in 1959 by the marine biologist John Nursall that the relatively late appearance of macroscopic fossils animals in the geologic record reflected the slowness in reaching a sufficiently O_2 -rich atmosphere.

Modern geochemical research shows that an initial transition to an oxygenated atmosphere

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Fig. 1 A schematic history of atmospheric oxygen according to geologic constraints discussed in the text



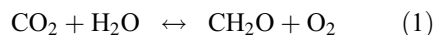
occurred in the period 2.45–2.32 Ga, but the O₂ levels attained were probably only 0.1–2% by volume and apparently insufficient for supporting macroscopic animals. This first “rise of oxygen” is also called the ► *Great Oxidation Event* (GOE). Although much less than today’s 21% by volume, the post-GOE O₂ levels were enough to dominate the redox chemistry of the atmosphere. Such O₂ levels were also ample for producing a stratospheric ozone (O₃) layer, which ever since has protected life on the Earth’s surface from biologically harmful ultraviolet radiation. The first fossils visible to the naked eye occur after the GOE at 1.87 Ga and are thought to represent a seaweed, *Grypania spiralis*. In a second increase in O₂, over the period 750–580 Ma, O₂ rose to levels of at least tens of percents of modern times, that is, a concentration between 2% and present levels. The first animal fossils appear in the Ediacaran Period (635–542 Ma), with the oldest soft-bodied fossils of Ediacaran Biota at ~575–565 Ma. While there is a consensus that sufficient O₂ was a necessary physiological precursor to animal life, there remains considerable debate among paleontologists about whether an increase in O₂ caused large animals to appear or whether other evolutionary and ecological factors were crucial.

Explaining why O₂ increased is more elusive than it might first appear. We might suppose that when cyanobacteria evolved, O₂ would have accumulated in the atmosphere. But the consensus interpretation of geochemical evidence (discussed below) is that cyanobacteria produced O₂ for several hundred million years or more before 2.4 Ga, while atmospheric O₂ levels remained <1 ppmv. A pertinent consideration is that the Earth’s overall chemical composition is reducing, so that reactions of O₂ with geothermal gases in the atmosphere or certain cations in the ocean (e.g.,

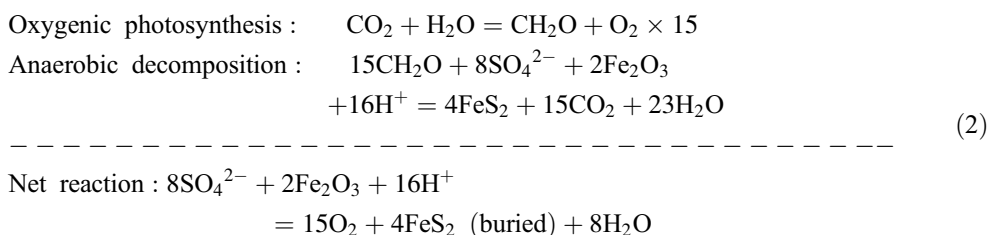
Fe²⁺) in an initially reducing environment must have acted as a powerful chemical buffer opposing the accumulation of atmospheric O₂. Consequently, we need to carefully consider the losses of O₂ as well as its source for understanding past changes in O₂ levels. In this regard, the modern oxygen cycle helps to elucidate some of the basic concepts of source and sink fluxes before discussing how sources and sinks were probably different on the ancient Earth.

The O₂ Balance Sheet: Gains and Losses

The theoretical subtleties of how photosynthesis can influence long-term atmospheric O₂ levels were not fully appreciated until the 1970s, in spite of the fact that a French geologist, Jacques Ebelmen, correctly described the key ideas in 1845. Ebelmen implicitly realized that photosynthesis is nearly a zero-sum activity. Oxygenic photosynthesis can be summarized by the following schematic equation:



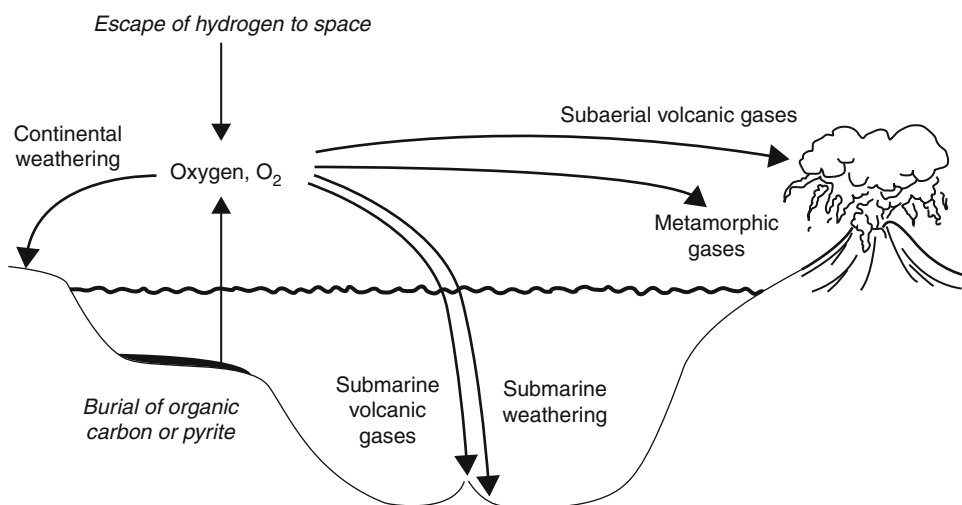
where “CH₂O” represents the average stoichiometry of organic matter. Oxygen consumption by respiration or decay of organic matter reverses Eq. 1, and produces no net oxygen on timescales greater than about 10² years. Oxygen only escapes respiration or oxidative decay on geologic timescales because a tiny fraction (0.1–0.2%) of organic carbon is buried, mainly in marine sediments, which segregates the oxygen from the organic matter. Some organic matter is also used in biogeochemical processes to make ► *pyrite* (FeS₂) from seawater sulfate ions (SO₄²⁻(aq)) as follows:



Consequently, pyrite burial also liberates oxygen into the atmosphere or ocean. Remarkably, Ebelmen correctly identified both organic carbon burial and pyrite burial as the long-term sources of atmospheric oxygen. Unfortunately, his ideas went unnoticed and the same concepts had to be reinvented.

While it is useful to think of the burial of organic carbon and pyrite as a “net source” of O_2 , it is important to appreciate that this “net” O_2 is lost to numerous other sinks for O_2 besides the reversal of Eq. 1. The geological sinks and sources of O_2 are shown in Fig. 2. By reviewing the average composition of new sediments, American geochemist Heinrich Holland has estimated that burial fluxes of organic carbon and pyrite produce oxygen at rates of 10.0 ± 3.3 and 4.7 ± 1.2 Tmol O_2 year⁻¹, respectively, where 1 Tmol = 10^{12} mol (Holland 2002). The reduction of oxidized iron from its +3 oxidation state to the +2 state ($2Fe_2O_3 = 4FeO + O_2$) and subsequent burial also adds a minor flux of O_2 , whereas the burial of sulfate minerals in sediments removes O_2 . Summing these burial fluxes, the total O_2 net source is 15.6 ± 4.0 Tmol O_2 year⁻¹ (Table 1). Dividing the current amount of oxygen in the atmosphere–ocean reservoir (3.78×10^{19} mol O_2) by the source flux (1.6×10^{13} mol O_2 year⁻¹)

gives ~ 2.4 Ma for the average amount of time an O_2 molecule spends in today's atmosphere–ocean system. Consequently, over such timescales, the net source of O_2 must be closely balanced by losses or O_2 levels would wildly fluctuate. We know that centimeter- to meter-sized animals, which require O_2 to grow and breathe, have been continuously present in the Phanerozoic eon (542 Ma to present) so that concentrations of atmospheric O_2 must have been within 0.2 ± 0.1 bar. The O_2 source is balanced by O_2 losses that include reactions in the ocean with dissolved minerals and gases from hot seafloor vents, and reactions of O_2 dissolved in rainwater with continental minerals, principally those containing elemental carbon, sulfide, and ferrous iron (Fig. 1). Gases that consume O_2 in the atmosphere or ocean are CH_4 , H_2 , CO , SO_2 , and H_2S . These are released either from hot rocks that melt (volcanism) or hot rocks that do not melt (metamorphism). Estimates of their fluxes are shown in Table 2. The O_2 sink from submarine and subaerial volcanic gases is ~ 2.3 Tmol O_2 year⁻¹, metamorphic gases consumes ~ 3.1 Tmol O_2 year⁻¹, and subduction of oxidized seafloor causes a loss of ~ 0.2 Tmol O_2 year⁻¹. The sink due to continental weathering is 12.0 ± 3.3 O_2 year⁻¹, which is estimated from the



Oxygenation of the Earth's Atmosphere, Fig. 2 Schematic diagram of source and sink fluxes of oxygen on geologic timescales

composition of average rock undergoing weathering (Table 2). Thus, within the large ~25% uncertainty of the data, the source flux of O₂ from organic carbon and pyrite burial of 15.6 ± 4.0 Tmol O₂ year⁻¹ is matched by the total sink flux of 17.7 ± 4.5 Tmol O₂ year⁻¹. In the past, changes in the relative proportions of source and sink fluxes evidently caused O₂ levels to change.

Oxygenation of the Earth’s Atmosphere, Table 1 Modern source fluxes of O₂ (Holland 2002). The pyrite flux corrects for an error in Holland (2002)

Oxygen fluxes	× 10 ¹² mol O ₂ year ⁻¹	Effect on O ₂
Organic carbon burial flux	10.0 ± 3.3	Production
Pyrite (FeS ₂) burial flux	4.7 ± 1.2	Production
Sulfate burial flux	−(0.3 ± 0.1)	(Loss)
Reduced iron burial flux	0.9 ± 0.4	Production
Total rate of oxygen production ~ (15.6 ± 4.0) × 10 ¹² mol O ₂ year ⁻¹ (taking sulfate as redox neutral)		

Evidence for Earth’s Oxygenation

The Great Oxidation Event at 2.45–2.32 Ga occurred in the Paleoproterozoic era (2.5–1.6 Ga), the first of three eras within the Proterozoic eon (2.5–0.542 Ga), which follows the Archean eon (before 2.5 Ga). After the Paleoproterozoic, the Mesoproterozoic (1.6–1.0 Ga) and the Neoproterozoic (1.0 Ga–542 Ma) eras follow. The second rise of O₂ (750–580 Ma) occurred in the Neoproterozoic. We can tell that O₂ levels changed by studying at the chemistry of rocks from these eras. The Great Oxidation Event (GOE) produced binary geochemical changes in the Paleoproterozoic because the atmosphere changed the oxidation states (from weakly reducing to oxidizing), whereas the Neoproterozoic changes are subtler because an oxic atmosphere merely became more oxygenated. Let us consider evidence for the GOE and Neoproterozoic increase of O₂ in turn.

Evidence for the Great Oxidation Event (GOE)

The different oxidation state of continental minerals that were formed before and after the GOE

Oxygenation of the Earth’s Atmosphere, Table 2 Modern sink fluxes of O₂ (Holland 2002; Catling and Kasting 2016)

Type of flux	× 10 ¹² mol O ₂ year ⁻¹	Effect
Continental oxidative weathering	−(12.0 ± 3.3)	(Loss)
<i>Surface volcanic gases</i>		
H ₂	−(0.5 ± 0.3)	(Loss)
CO	−(0.05 ± 0.03)	(Loss)
H ₂ S	−(0.06 ± 0.03)	(Loss)
SO ₂	−(0.9 ± 0.3)	(Loss)
Total sink from surface volcanic gases ~ − (1.5 ± 0.7) × 10 ¹² mol O ₂ year ⁻¹		
<i>Submarine volcanic gases</i>		
H ₂	−(0.05 ± 0.03)	(Loss)
H ₂ S	−(0.7 ± 0.4)	(Loss)
CH ₄ (axial)	−(0.02 ± 0.01)	(Loss)
CH ₄ (off-axis)	−(0.06 ± 0.04)	(Loss)
Total sink from submarine volcanic gases ~ − (0.8 ± 0.7) × 10 ¹² mol O ₂ year ⁻¹		
<i>Surface metamorphic gases</i>		
CH ₄ (abiotic)	~0.6	(Loss)
CH ₄ (thermal breakdown of organics)	~2.5	(Loss)
Total sink from metamorphic gases ~ − 3.1 × 10 ¹² mol O ₂ year ⁻¹		
<i>Seafloor oxidation and subduction</i>		
Fe ²⁺ conversion to magnetite and Fe ²⁺ release	~0.4 ± 0.2	(Loss)
Total rate of oxygen loss ~ (17.7 ± 4.5) × 10 ¹² mol O ₂ year ⁻¹		

records a change from an atmosphere essentially devoid of O_2 to one redox dominated by O_2 . The presence or absence of O_2 changes the chemistry of minerals that are formed because O_2 dissolves in rainwater and reacts with minerals. Three continental indicators are red beds, paleosols, and detrital grains (Holland 1984). ► *Red beds* are riverbanks, deserts, and floodplains with a reddish pigmentation that arises when an iron oxide coating on mineral grains is produced from the rusting of iron minerals. Before the GOE, no red beds are found in the geologic record, indicating a lack of O_2 , whereas afterward red beds are common. ► *Paleosols* are lithified soils. Before the GOE, paleosols show a loss of iron, which is consistent with leaching by ancient anoxic rainwater, whereas after ~ 2.2 Ga, iron is not leached. Iron will be flushed through a soil in the form of soluble ferrous iron ions (Fe^{2+}) if rainwater has little dissolved O_2 but if the air contains $>0.2\%$ O_2 , iron will be oxidized into insoluble and immobile oxides such as ► *hematite* (Fe_2O_3). Cerium is another redox-sensitive element that has also been examined in paleosols. Cerium oxidizes from Ce^{3+} to Ce^{4+} to form cerianite (CeO_2), so the presence of Ce^{3+} -rich minerals in paleosols from the Archean implies an early anoxic atmosphere. *Detrital grains* in sediments are those that are never completely dissolved during the process of weathering. Rounded detrital grains from sediments deposited by turbulent Archean rivers commonly contain minerals that would only survive at very low levels of O_2 . Detrital grains of pyrite (FeS_2), ► *uraninite* (UO_2), and siderite ($FeCO_3$) place bounds on the concentration of Archean O_2 of roughly $<2\%$, $<0.2\%$, and $<0.02\%$, respectively, compared to today's 21% O_2 . In modern oxygenated waters, uraninite dissolves to form soluble U^{6+} ions, pyrite oxidizes to soluble sulfate (SO_4^{2-}) and hematite, and siderite rusts to produce insoluble hematite.

The chemistry of seawater also changed after the GOE, with increased levels of sulfate and much decreased levels of redox-sensitive elements such as manganese and iron that are insoluble when oxidized. Marine sulfur isotopes are the data that indicate an increase in sulfate concentrations. Today, sulfate-reducing bacteria

produce most of the sulfide in marine sediments. These bacteria reduce $^{32}SO_4^{2-}$ in preference to $^{34}SO_4^{2-}$ so that bacterial sulfide is enriched in ^{32}S . However, this fractionation ceases in waters with <0.2 mM sulfate concentration. Archean sulfides have $^{34}S/^{32}S$ ratios close to an unfractionated mantle value, implying Archean oceans with <0.2 mM sulfate, compared to 28.9 mM in today's surface seawater. Rivers ultimately supply sulfate to the ocean by washing sulfate off the land where it is produced by the oxidation of sulfides by oxygenated rainwater. Consequently, the low concentration of seawater sulfate before the GOE is consistent with low atmospheric O_2 . By 2.3–2.2 Ga, sulfides with significant ^{34}S depletions formed ubiquitously in the ocean, reflecting increased sulfate and the rise of O_2 . When O_2 rose, it also oxidized and titrated manganese out of the ocean, producing the world's largest manganese deposit found in the 2.2 Ga Hotazel Formation in South Africa. The presence of ► *banded iron formations* (BIFs) provides evidence that the deep ocean was devoid of O_2 in the Archean, unlike today. By definition, BIFs are laminated marine sedimentary rocks containing ≥ 15 wt% iron, with alternating iron-rich and iron-poor layers. The iron mainly originated from hydrothermal sources in the deep ocean, such as ► *mid-ocean ridges*. Today, iron is oxidized in the deep ocean and deposited on the flanks of the ridges. But in the anoxic depths of Archean oceans, ferrous iron was transported to the continental shelves where it was (microbially) oxidized and precipitated as iron minerals in the BIFs. In the Paleoproterozoic, BIFs decline in abundance and disappear after ~ 1.8 Ga. Chromium (Cr) isotopes in the BIFs also record changes in atmospheric O_2 . When insoluble Cr^{3+} is oxidized to soluble Cr^{6+} during oxidative weathering, the heavy isotope ^{53}Cr is preferentially oxidized relative to ^{52}Cr . After transport from rivers to the ocean, the Cr isotopic fractionation is preserved in ocean sediments. An increase in the abundance of ^{53}Cr after 2.4 Ga compared to Archean samples further confirms the GOE.

The strongest evidence for the GOE is a large amount of mass-independent fractionation (MIF)

of ► **sulfur isotopes** in sedimentary rocks older than 2.45 Ga compared to little or no sulfur isotope MIF in rocks younger than 2.32 Ga. In modern rocks, ^{32}S , ^{33}S , and ^{34}S obey “mass-dependent” fractionation, in which the difference in abundance between ^{33}S and ^{32}S is approximately half that between ^{34}S and ^{32}S , that is, a linear relationship with mass difference. Most processes, such as microbial sulfate reduction, produce mass-dependent isotope fractionation. In contrast, mass-independent fractionation in sulfur isotopes is where the relative abundance of different isotopes deviates from linear, mass-dependent fractionation. Laboratory studies show that large MIF is produced exclusively from photochemical reactions, such as the photolysis of SO_2 . Three conditions are needed for the production and preservation of the sulfur isotope MIF: O_2 levels below about 1 ppmv, sufficient sulfur gas in the atmosphere, and relatively large concentrations of reducing gases. In a high- O_2 atm, sulfur gases are rapidly oxidized and rained out as dissolved sulfate. But in the absence of O_2 and in the presence of reducing gases such as 10^2 – 10^3 ppmv methane, sulfur exits the atmosphere as sulfide, elemental sulfur, or sulfate, which allows the mass-independent fractionation produced by anoxic photochemistry to be segregated and preserved in different sedimentary minerals. In summary, the sulfur isotope MIF provides evidence for an Archean atmosphere with both low O_2 and high methane.

Donald Canfield (of the University of Southern Denmark) has proposed that a significant fraction of the deep ocean remained sulfidic rather than oxygenated during much of the Proterozoic, after 1.8 Ga (Canfield 2005; Lyons et al. 2009). In this model, BIFs declined because increased sulfate in the surface ocean caused sulfate-reducing bacteria to provide a flux of sulfide to the deep ocean, which scavenged ferrous iron into insoluble iron sulfides. This is an alternative to a model where the disappearance of BIFs at 1.8 Ga is explained by the oxygenation of the deep ocean and the formation of insoluble iron oxides (Holland 2006). In today's ocean, <0.5% of the seafloor is *euxinic*, meaning oxygen free with

H_2S . Molybdenum (Mo) isotopes are useful indicators of oxygenation and euxinia because oxic uptake of Mo on marine solids preferentially removes ^{95}Mo relative to ^{98}Mo , leaving the ocean isotopically heavy. In contrast, in times of low oxygenation, marine Mo is isotopically light. In highly euxinic deep waters, Mo is scavenged efficiently and tends to capture the Mo isotope composition of seawater. Rocks that are ^{95}Mo -enriched from the 1.7 to 1.4 Ga MacArthur Basin in Australia suggest that the deep ocean in the mid-Proterozoic seafloor was commonly oxygen-poor, with a greater proportion of euxinia than today. The data suggest that the euxinia was probably only several percent of the ocean's area, but this is enough to have had a significant effect in depleting trace metals in the Mesoproterozoic Ocean, which may have impacted marine ecology for a billion years until the Neoproterozoic.

Evidence for a Neoproterozoic “Second Rise” in Oxygen

Sulfur and chromium isotopes in marine sediments indicate that O_2 increased in the late Neoproterozoic. At this time, marine sedimentary sulfides occur with ^{32}S -enrichment exceeding the isotope discrimination of sulfate-reducing bacteria. The interpretation is that isotopically light sulfide was re-oxidized at the sediment-water interface and cyclically re-reduced by sulfur-disproportionating bacteria, which increased the isotope fractionation. The greater sulfur isotope fractionation is therefore related to oxygenation of the near-shore seafloor. Canfield (2005) has estimated that the oxygenation required atmospheric O_2 concentrations in excess of 1–4%. A large increase in the abundance of marine ^{53}Cr relative to ^{52}Cr after 750 Ma also confirms an increase in atmospheric O_2 . Oxygen would have mobilized greater amounts of chromium during continental oxidative weathering, which is the mechanism of isotopic fractionation mentioned earlier. Fossil evidence for animals greater than a few millimeters or more in size also suggests that O_2 concentrations exceeded 2%, which is the minimum level that can support aerobic metabolism in such animals via O_2 supplied by diffusion.

When Did Oxygenic Photosynthesis Evolve?

In order to understand the early history of atmospheric O₂, we need to examine the evidence for the advent of oxygenic photosynthesis. In particular, the geologic record suggests that oxygenic photosynthesis arose 300 Ma or more before the GOE. This timing is inferred from a variety of proxies including biomarkers, nonmarine stromatolites, redox-sensitive metals, and sulfur isotopes, which we discuss in turn.

Biomarkers are recognizable derivatives of biological molecules, which are usually in the form of certain hydrocarbons found in kerogen (noncrystalline sedimentary organic matter) or oil. Chemical changes induced when sediments convert into rock strip biological molecules of functional groups but can often leave a distinctive molecular backbone, in a way that is analogous to the more familiar macroscopic process that removes flesh to leave fossilized skeletons that we can associate with particular life forms. Biomarkers from the Archean have been the subject of controversy because of the possibility of contamination from modern molecules or fluid migration over geologic time and uncertainties regarding their specificity for particular organisms and metabolisms. Recent advances in ultra-clean drilling and the ability to analyze oil-bearing fluid inclusions help to address concerns about contamination. Biomarkers for cyanobacteria are 2- α -methylhopanes, which are derived from compounds in cell membranes. Long chain varieties of these particular molecules (i.e., >C₃₁) occur very rarely outside the cyanobacteria. In addition, steranes derive from sterols, which are found in the membranes of eukaryotes and synthesized in a pathway that requires free molecular oxygen. For example, 11 molecules of O₂ are required to produce one molecule of cholesterol. No bacteria are known to synthesize C₂₆-C₃₀ sterols and archaea do not synthesize sterols at all. The simultaneous co-detection of long chain (>C₃₁) 2- α -methylhopanes with eukaryotic sterols is thus a reasonable biosignature for oxygenic photosynthesis. Such a combination of biomarkers has been found in fluid inclusions in the 2.45 Ga Matinenda Formation at Elliot Lake, Canada,

which consists of sandstones deposited prior to the GOE (Dutkiewicz et al. 2006). However, measurements of biomarkers from 2.72 to 2.56 Ga rocks in the Hamersley Province of northwest Australia (Eigenbrode et al. 2008) and 2.67–2.46 Ga rocks from the Transvaal of South Africa (Waldbauer et al. 2009) are now in doubt because recent work suggests that Archean biomarkers are contaminants (French et al. 2015).

► **Stromatolites** (laminated rocks formed by microbes) from a 2.72 Ga lake in the ► **Tumbiana Formation** in northwest Australia possibly confirm the presence of O₂ production. Geologic evidence shows that the lake lacked sulfate and hydrothermal reductants needed for non-oxygen-producing photosynthesis. Consequently, a process of elimination suggests that microbial communities using oxygenic photosynthesis may have constructed these particular stromatolites (Sakurai et al. 2005).

Furthermore, the mobility of redox-sensitive metals indicates the presence of some O₂ before the GOE, and therefore the presence of oxygenic photosynthesis. Molybdenum (Mo), rhenium (Re), and chromium (Cr) are soluble only when oxidized. Consequently, a spike in Mo and Re concentrations found in 2.5 Ga sedimentary rocks in the Hamersley district of northwest Australia suggests that a transient “whiff” of O₂ occurred in the atmosphere about 100 Ma prior to the GOE (Anbar et al. 2007). The whiff is confirmed by contemporaneous evidence of sulfur isotopic fractionation indicating a spike of sulfate. Enrichments of ⁵³Cr relative to ⁵²Cr (which are induced by oxidative weathering) are also found in banded iron formations at low levels for at least 300 Ma prior to the GOE, which is consistent with the biological production of O₂ (Frei et al. 2009). In summary, multiple lines of evidence suggest that oxygenic photosynthesis existed at least 0.3 billion years before the GOE.

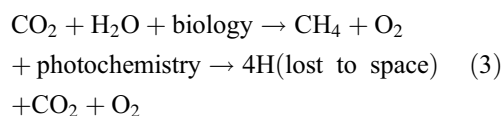
Theories for Oxygenation

At present, a framework has been developed for understanding why the GOE occurred, but the cause of the second rise of O₂ in the Neoproterozoic remains very obscure (Catling and Claire 2005).

The GOE happened because either O_2 production increased or O_2 consumption declined. The ancient, pre-2.45 Ga oceans were largely devoid of sulfate, so that organic carbon burial dominated O_2 production prior to the GOE, while pyrite burial was unimportant. Consequently, it has been argued that O_2 rose because the rate of organic carbon burial (O_2 production) increased, either as a pulse or long-term trend. One suggestion is that the growth of early continental shelves promoted organic carbon burial and oxygen production. But there are grounds for skepticism about this proposal. Organic matter extracts the light carbon isotope, ^{12}C , from seawater, but marine carbon, recorded in ancient limestone, does not significantly decrease in ^{12}C content between mid-Archean and Mesoproterozoic rocks. Notably, at 2.3–2.1 Ga, many marine carbonates are unusually depleted in ^{12}C relative to ^{13}C , which could be explained if there was a large pulse of burial of organic carbon, but then the ^{12}C content returns to its previous value. A burial pulse would merely generate a parallel pulse of O_2 , given the short residence time of O_2 and not a persistently increased level of O_2 . Instead, the pulse was more plausibly an effect of increased O_2 because the Paleoproterozoic excursions in the ^{12}C of limestones follow the rise of O_2 before 2.32 Ga.

A widely accepted explanation for why little atmospheric O_2 accumulated in the Archean is that a large flux of volatile and aqueous reductants, that is, chemicals that consume oxygen, scavenged the O_2 . In time, the geological sources of reductants declined to the point where the O_2 flux produced from organic carbon burial exceeded the kinetically rapid consumption flux. At this tipping point, oxygen flooded the atmosphere until O_2 levels reached a new plateau where continental weathering became the predominant balance for O_2 production. Various suggestions have been made for why the proportion of reductants in volcanic or metamorphic outgassing might diminish and cause such a tipping point. One suggestion is that a change in the style of outgassing from submarine to subaerial volcanism favored a decline in the proportion of reductants. Another consideration is that an

anoxic atmosphere would always allow a relatively high concentration of hydrogen-bearing reducing gases. At high altitude, the decomposition of such gases causes hydrogen to escape to space at a rate that is significant on geologic timescales, which oxidizes the whole Earth and diminishes further release of reductants. In particular, in an anoxic atmosphere, methane reaches concentrations hundreds of times greater than today's 1.8 ppmv. Most methane is ultimately produced microbially from fermentation of photosynthesized organic matter. Ultraviolet light decomposes methane in the upper atmosphere, causing it to lose hydrogen. When hydrogen escapes from the planet, oxygen is gained irreversibly through a schematic reaction as follows:



Evidence for this hypothesis is found in the redox components of the crust. If photosynthesis were the only process responsible for segregating redox components, the number of moles of equivalent O_2 in the Earth's crust should be balanced by equimolar reduced carbon (Eq. 1). But instead there is excess oxygen in the crust by a factor of 1.5–2.2 (Catling and Claire 2005; Sleep 2005). The excess can be quantitatively reconciled with time-integrated hydrogen escape and net oxidation expected from a methane-rich Archean atmosphere.

Various geological and biological causes have been suggested for the Neoproterozoic second rise of oxygen, but the problem remains unsolved. Geological proposals include the enhanced production of clays that adsorbed and buried organic matter, or the assembly of a supercontinent whose weathering added nutrients to the sea and stimulated organic carbon burial. Also, it has been suggested that moderately high levels of methane throughout the Proterozoic could have promoted hydrogen escape and oxidized the Earth. Biological proposals include continental weathering accelerated by lichen, and the evolution of zooplankton with fecal pellets that enhanced organic

burial. However, presently, all of these ideas for the cause of the second rise of O_2 are, at best, just qualitative proposals.

Conclusion and Future Directions

The atmosphere evolved from an anoxic to oxygenated state. There are multiple lines of geochemical evidence for a rise of O_2 or *Great Oxidation Event* (GOE) at 2.45–2.32 Ga. However, oxygenic photosynthesis appears to have existed at least 0.3 billion years beforehand. A self-consistent explanation for the delay between the origin of oxygenic photosynthesis and oxygenation of the atmosphere is that excess volatile reductants efficiently scavenged O_2 . This sink on O_2 diminished until the GOE occurred. Following the GOE, sulfate levels increased in the ocean as a result of a greater role for oxidative weathering in balancing O_2 production from the burial of organic carbon and pyrite. In the late Precambrian, around 750–580 Ma, a second rise of O_2 occurred, along with a further increase in marine sulfate. This second rise appears to have been a precursor to the appearance of macroscopic animals.

Considerable further research will no doubt further constrain the levels of O_2 through geologic time and our understanding of the past biogeochemical cycles of various elements – such as carbon, sulfur, and nitrogen. Measurements of new isotopic systems, such as those of trace metals, will no doubt bring advances. ► [Bio-markers](#) also have the potential to reveal what microorganisms and microbial processes were present in the Precambrian biosphere. But currently, Archean biomarkers are plagued by the issue of contamination (French et al. 2015).

Cross-References

- [Archean Environmental Conditions](#)
- [Archaean Traces of Life](#)
- [Banded Iron Formation](#)
- [Biomarkers](#)
- [Cerium, Anomalies of](#)
- [Earth, Formation, and Early Evolution](#)
- [Earth's Atmosphere, Origin and Evolution of](#)

- [Great Oxidation Event](#)
- [Hematite](#)
- [Isotope Biosignatures](#)
- [Nitrogen Isotopes](#)
- [Oceans, Origin of](#)
- [Oxygenic Photosynthesis](#)
- [Photosynthesis](#)
- [Pilbara Craton](#)
- [Redox Zonation](#)
- [Siderite](#)
- [Sulfidic Oceans](#)
- [Sulfur Cycle](#)
- [Sulfur Isotopes](#)
- [Transvaal Supergroup, South Africa](#)

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Oxygenic Photosynthesis

Usha F. Lingappa and Woodward W. Fischer
Division of Geological & Planetary Sciences,
California Institute of Technology, Pasadena,
CA, USA

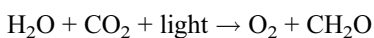
Keywords

Photosynthesis · Primary production ·
Oxygen · Light · *Cyanobacteria* ·
Chloroplasts · Plants · Algae · Chlorophyll ·
Reaction center · Photosystem II ·
Photosystem I · RuBisCO

Definition

Photosynthesis is the biological process of converting the energy in visible light into chemical energy available for the cell to fix CO₂ into biomass for growth. Oxygenic photosynthesis is a unique version of photosynthesis that uses water as the electron donor, producing dioxygen as a product.

Chemical Formula



Acronyms

3-PGA	3-Phosphoglycerate
ATP	Adenosine triphosphate
CIII	Complex III
Fd	Ferredoxin
FNR	Ferredoxin-NADP ⁺ reductase
GAP	Glyceraldehyde-3-phosphate
GOE	Great Oxygenation Event
NADPH	Nicotinamide adenine dinucleotide phosphate
PC	Plastocyanin
PSI	Photosystem I
PSII	Photosystem II
Q	Quinol/quinone
RuBisCO	Ribulose 1,5-bisphosphate carboxylase oxygenase
RuBP	Ribulose 1,5-bisphosphate
WOC/ OEC	Water-oxidizing complex/Oxygen-evolving complex

Overview

Oxygenic photosynthesis is fundamental to life as we know it today. This metabolism accounts for the vast majority of primary productivity on Earth and maintains our atmosphere rich in O₂ and far from chemical equilibrium with the solid Earth, thus representing a presumptive biosignature on a planetary scale. It is carried out by members of the bacterial phylum *Cyanobacteria* and the constitutively related chloroplasts of algae and plants, with major global contributions from both terrestrial and marine ecosystems.

Oxygenic photosynthesis evolved once, roughly 2.4 billion years ago, in the *Cyanobacteria* and was a key turning point in the history of life on Earth. Unlocking the ability to use the abundant resource of H₂O as an electron donor for photosynthesis allowed for a massive increase in primary productivity and expansion of the biosphere, while the production of O₂ transformed Earth surface environments and led to the evolution of aerobic biochemistries – the latter, by extension, enabled complex multicellular life.

Mechanics

To capture sunlight, photosynthetic organisms use pigment molecules like the tetrapyrrole chlorophyll to absorb light energy, generating an excited state of the pigment molecule. This excited state migrates from pigments in light-harvesting antenna systems to the reaction center – a protein complex with a pair of pigments that utilizes the excitation energy of the chlorophyll to engender charge separation and electron transfer. When the chlorophyll pair (P) is promoted to the excited state (P^*), it moves an electron to an acceptor molecule, simultaneously generating a strong oxidant (P^+) and a strong reductant (A^-) in different parts of the reaction center. The oxidizing power of P^+ is used to pull electrons from an electron donor, and the reducing power of A^- is sent down the electron transport chain – along its path contributing to the transmembrane potential and thereby ATP synthesis and eventually the generation of low-potential reducing power for CO_2 fixation in the form of NADPH (Fig. 1).

To span the vast amount of redox space between H_2O and NADPH, oxygenic photosynthesis uses two distinct reaction centers coupled in series – photosystem II (PSII), which oxidizes H_2O to O_2 and donates electrons to the quinol pool, and photosystem I (PSI), which takes electrons that have run through complex III from plastocyanin and donates them to a ferredoxin – which can be used at the start of the process to fix carbon. Part of what makes oxygenic photosynthesis special is the ability to derive electrons from water. The key catalyst that enables this is a Mn_4CaO_5 cluster known as the water-oxidizing complex (WOC) or oxygen-evolving complex (OEC), ligated by the PSII complex. The Mn atoms in this cluster cycle through a range of oxidation states, acting as a redox capacitor to bridge the single-electron process of photochemical electron transfer with the four-electron process of oxidizing H_2O to O_2 .

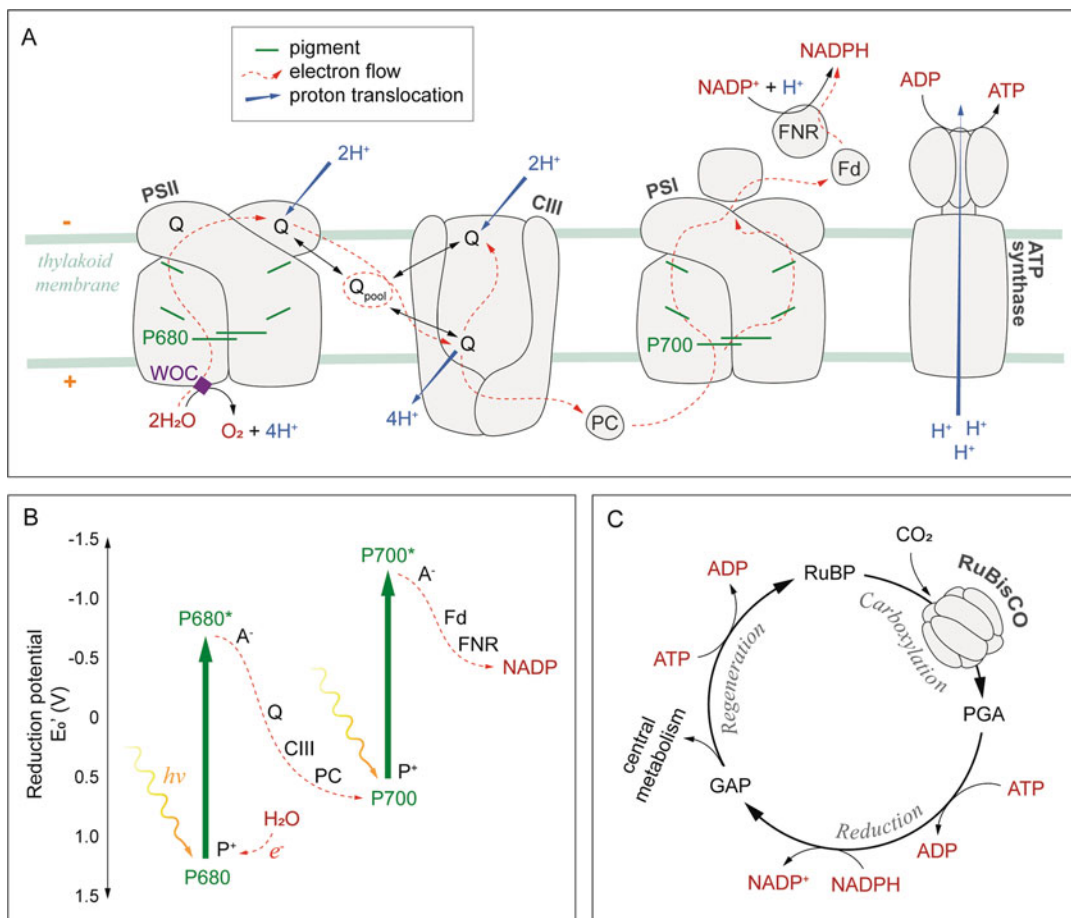
The carbon fixation pathway used in oxygenic photosynthesis to convert CO_2 to sugars for various cellular processes is the Calvin cycle, also known as the Calvin-Benson-Bassham cycle or the reductive pentose phosphate cycle. This cycle consumes the reducing power and ATP

generated as a part of the photochemical reactions involving the electron transport chain that begins at PSII. The Calvin cycle involves numerous biochemical reactions, but can be summarized as three phases – carboxylation, reduction, and regeneration. In carboxylation, the enzyme RuBisCO – the most abundant protein on the planet – adds a CO_2 molecule to ribulose 1,5-bisphosphate (RuBP), a 5-carbon sugar, to generate two molecules of 3-phosphoglycerate (PGA), a 3-carbon sugar. In reduction, PGA is phosphorylated and reduced to produce glyceraldehyde-3-phosphate (GAP), consuming ATP and NADH. Finally, in regeneration, five molecules of GAP are used to regenerate three molecules of RuBP. Thus, for every three molecules of CO_2 that get fixed, six molecules of GAP are produced, five of which are used to regenerate RuBP, with one remaining GAP exported to other metabolic pathways.

Evolution

Anoxygenic photosynthesis is biochemically simpler than oxygenic photosynthesis; it uses single photochemical reaction centers – rather than the coupled photosystems of oxygenic photosynthesis – and electron donors with much lower reduction potentials rather than H_2O . Anoxygenic phototrophy evolved very early in Earth history; geological data suggest this occurred likely prior to 3.4 billion years ago. Today, anoxygenic phototrophy is known to exist in the bacterial phyla *Proteobacteria*, *Chloroflexi*, *Chlorobi*, *Acidobacteria*, *Firmicutes*, *Gemmatimonadetes*, and the candidate phylum WPS-2, and is known to use electron donors such as H_2 , Fe(II), sulfide, and other reduced sulfur species, nitrite, arsenite, and organic compounds. However, none of these phyla appear to be ancestrally phototrophic, leaving the identity of the lineage that invented anoxygenic phototrophy an enduring evolutionary mystery. It is possible that this lineage is now extinct.

There is debate about the evolutionary timing of oxygenic photosynthesis, but a wide array of geological observations indicate that it had evolved from an anoxygenic ancestor in the *Cyanobacteria* by 2.4 billion years ago. This



Oxygenic Photosynthesis, Fig. 1 (a) Schematic diagram of the oxygenic photosynthesis electron transport chain. (b) The Z-scheme, depicting the energetics of electron transfer in oxygenic photosynthesis. Electron flow from a lower-potential electron donor to a higher-potential electron acceptor is thermodynamically favorable. The input of light energy to induce charge separation in the special pair (P680 in the case of PSII, P700 in the case of

PSI) generates a very high-potential electron acceptor (P^+) and a very low-potential electron donor (A^-), allowing for favorable electron flow along the electron transport chain. (c) The Calvin cycle, simplified as three stages – carboxylation, reduction, and regeneration. This pathway uses ATP and NADPH generated by the light-dependent reactions shown in panel A. The enzyme RuBisCO catalyzes the key step of CO_2 fixation

transition involved the evolution of a reaction center with a much higher reduction potential, the innovation of the WOC/OEC to bridge the single-electron photochemistry of the reaction center with the requisite four-electron chemistry for H_2O oxidation, and the coupling of two separate reaction centers in series in the electron transport chain. With the advent of oxygenic photosynthesis came the first meaningful environmental fluxes of O_2 ; this transformed Earth surface environments dramatically and irreversibly, impacted all global biogeochemical cycles, and

redirected the evolutionary trajectory of life by enabling aerobic metabolisms. This defining moment in Earth history is known as the Great Oxygenation Event (GOE).

All photosynthetic eukaryotes (algae and plants) derived their photosynthetic machinery from *Cyanobacteria*, as their chloroplasts originated by the endosymbiosis of a *Cyanobacterium* with a eukaryotic host cell. The earliest algal fossils date to 1.05 billion years ago, while the first land plants emerged circa 488 million years ago.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Photosynthesis](#)
- [Anoxygenic Photosynthesis](#)
- [Calvin-Benson Cycle](#)
- [Carbon Cycle, Biological](#)
- [Chlorophylls](#)
- [Chloroplast](#)
- [Cyanobacteria](#)
- [Cyanobacteria, Diversity and Evolution of](#)
- [Dioxygen](#)
- [Great Oxidation Event](#)
- [Huronian Glaciation](#)
- [Lichens](#)
- [Metabolism](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Photoautotroph](#)
- [Photobiology](#)
- [Photoferrotrophy](#)
- [Photosynthesis](#)
- [Photosynthetic Pigments](#)
- [Phototroph](#)

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Oxygenic Phototrophic Bacteria

- [Cyanobacteria, Diversity and Evolution of](#)

Oxyphotobacteria

- [Cyanobacteria, Diversity and Evolution of](#)

Ozone

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

Ozone, O₃, is an important trace constituent of the ► [stratosphere](#), where it forms the ► [ozone layer](#). It consists of three atoms of oxygen arranged as an open triangle. Ozone is produced in the three-body reaction $O + O_2 + M = O_3 + M$, where M represents a stabilizing molecule (N₂ or O₂) and O is produced by the photochemical dissociation of O₂. Some other components (NO, Cl, CFCs) catalyze the reaction of ozone destruction $O_3 + O = 2O_2$. The importance of ozone for life preservation lies in its unique capability to block solar UV radiation in a range particularly harmful to organic macromolecules (230–290 nm). It is also a greenhouse gas.

Cross-References

- [Fractionation](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Ozone Layer](#)
- [Stratospheric Ozone](#)
- [UV Climate](#)

Ozone Layer

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Oxygen photochemistry · Ozone · UV screening

Synonyms

Stratospheric ozone

Definition

The ► **ozone** layer refers to the ozone within the stratosphere of the Earth, where over 90% of the Earth's ozone resides. This layer absorbs the Sun's high-energy ultraviolet radiation of wavelengths <290 nm. The concentration of ozone is measured in Dobson units (DU).

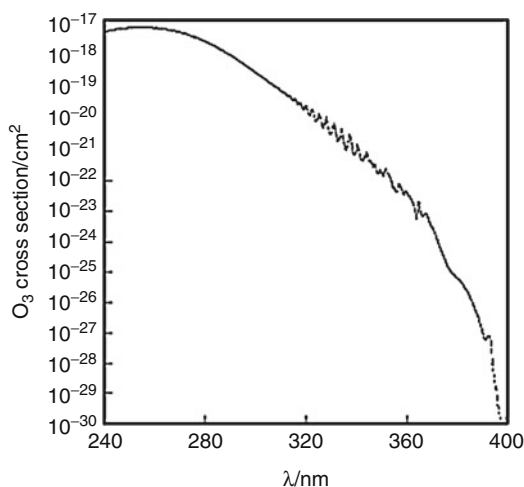
History

The existence of an ozone layer in the upper regions of our atmosphere was detected in 1913 by Charles Fabry and Henri Buisson. In 1924, G.M.B. Dobson built the first spectrograph to measure the seasonal variation of ozone. From 1928 to 1958, Dobson established a worldwide network of ozone monitoring stations that are operating up to date. In his honor the "Dobson unit" was defined as measure of the columnar density of ozone above the Earth surface (see definition below).

Overview

On Earth, the stratospheric ozone layer is found at an altitude from 20 to 40 km. It is created when ultraviolet radiation from the Sun strikes the oxygen molecules in the stratosphere. By this photochemical process oxygen molecules (O_2) are dissociated to atomic oxygen (O). The atomic oxygen quickly combines with further oxygen molecules to form ozone (O_3). Ozone can be split again into molecular oxygen (O_2) and atomic oxygen under the influence of short wavelength ultraviolet radiation from the Sun (Fig. 1). This continuing process is called ozone-oxygen cycle.

The concentration of ozone in the stratosphere is measured in Dobson units (DU) – named after



Ozone Layer, Fig. 1 Absorption cross-section of ozone as a function of wavelength

Gordon M.B. Dobson, who built the first instrument for measuring total ozone from the ground. It measures the total amount of ozone present in a vertical column of air above a certain location at the surface of the Earth. It is defined in terms of the equivalent millimeter thickness of ozone at an atmospheric pressure of 1013 hPa and a temperature of 298 K: 1 mm of ozone is equivalent to 100 DU. Concentrations of ozone in the stratosphere vary naturally according to temperature, weather, latitude, and altitude. Furthermore, aerosols and other particles ejected by natural events such as volcanic eruptions can have measurable impacts on ozone levels. Near the tropics, values typically reach about 260 DU; these values increase toward the poles.

The stratospheric ozone layer is very effective at screening out solar UV radiation at wavelengths <290 nm. As a result, most of the biologically harmful part of the solar UV radiation does not reach the surface of the Earth. Surface UVB radiation levels are highly variable because of sun angle, cloud cover, and also because of local effects including pollutants and surface reflections. Decreasing ozone concentrations result in higher irradiances of the energetic part (UVB) of the solar spectrum with possible biological

consequences (Häder 1997). The Antarctic ozone hole is an area of the Antarctic stratosphere wherein the total ozone amount is less than 220 DU. It occurs during the Antarctic spring, from September to early December, when over 50% of the lower stratospheric ozone is destroyed. Over the past two decades, the ozone hole has steadily grown in size (up to an area of 27 million km²) and length of existence (from August through early December).

In the Archean (3.8–2.5 billion years ago), the Earth's atmosphere was essentially anoxic and therefore it probably lacked a protective ozone column. Thus, UVB (280–315 nm) and UVC (200–280 nm) radiation could have penetrated to the Earth's surface with their associated biological effects. Using data obtained from the UV-inactivation of *Bacillus subtilis* spores in a space experiment, it has been shown that without the UV screen by stratospheric ozone the biologically effective UV doses would be about 1000 times higher than today (Horneck et al. 1996; Cockell and Horneck 2001). Most of the damage would have been caused by UVC radiation on DNA, which is the decisive target for inactivation and mutation induction at this UV range.

Mars has no planetary ozone layer, although regional small concentrations of ozone may occur

during northern winter periods. As a result, most of the Martian surface is reached by the high energetic solar UV radiation of wavelengths >200 nm.

Cross-References

- [Ozone](#)
- [Photobiology](#)
- [Solar UV Radiation, Biological Effects](#)
- [UV Climate](#)
- [UV Radiation Dose](#)
- [UV Radiation, Biological Effects](#)

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P

P-P Chains

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The p-p chain is the series of nuclear reactions converting four protons to one ${}^4\text{He}$ nucleus and releasing an energy of about 6.6 MeV/nucleon or 5×10^{18} erg/gr. This provides the main source of energy for Main sequence [► stars](#) of less than 1.3 M. while in more massive stars the [► CNO cycle](#) dominates. The first reaction of the series ($p + p \rightarrow D + e^+ + \nu_e + 0.42 \text{ MeV}$) involves a slow, weak interaction (the conversion of a proton into a neutron), which is responsible for the long lifetimes (>10 Gyr) of the Sun and other low mass stars.

Cross-References

- [CNO Cycle](#)
- [Nuclear Reaction](#)
- [Stars](#)

p-RNA

Ramanarayanan Krishnamurthy,
Eun-Kyong Kim and Tammy Campbell
Chemistry, The Scripps Research Institute,
La Jolla, CA, USA

Keywords

Watson-Crick · Pentopyranosyl ·
Oligonucleotides · Nucleic acids ·
Homochiral · Heterochiral · Base-pairing

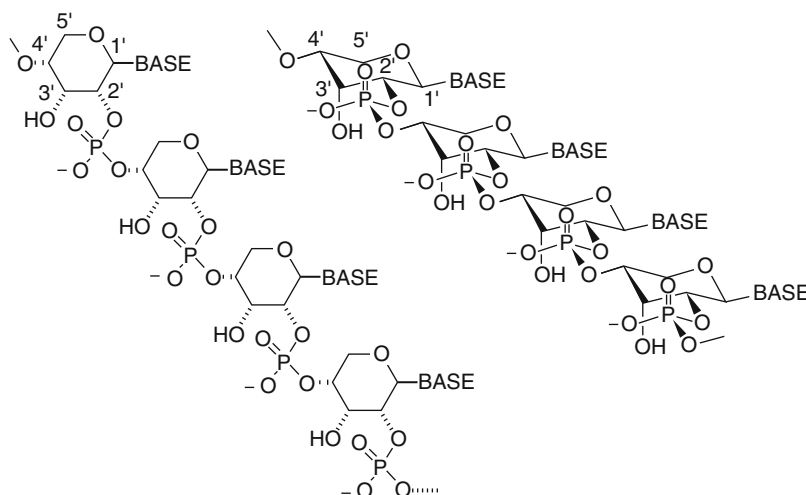
Synonyms

[Pentopyranosyl-RNA](#); [Pyranosyl-RNA](#); [Ribopyranosyl nucleic acid](#)

Definition

Pyranosyl-RNA (“p-RNA”) is an [► oligonucleotide](#) in which the ribose units exist in the pyranose form and are linked together repetitively by phosphodiester groups between the hydroxyl groups at positions C-2' and C-4' (Fig. 1).

p-RNA, Fig. 1 A constitutional and an idealized conformational representation of pyranosyl-RNA (p-RNA); base = adenine, guanine, cytosine, uracil, thymine, as well as 2,4-diaminopurine, xanthine, iso-guanine, and iso-cytosine



History

The systematic experimental study of nucleic acid alternatives has played an important role in understanding the chemical etiology of the structure of nucleic acids as functioning biomolecules (Eschenmoser 1993b). In 1992, Eschenmoser conceived the structure of p-RNA in context of the study toward the chemical etiology of the natural nucleic acid structure (Eschenmoser 1993a). The existence of p-RNA was predicted through a comprehensive and systematic qualitative conformational analysis of all possible hexo- and pentopyranosyl oligonucleotide systems that could be derived from the products of the aldol reaction of glycolaldehyde phosphate with itself and with formaldehyde (Pitsch et al. 1994).

Overview

Pyranosyl-RNA is a constitutional ► **isomer** of RNA, composed of the very same building blocks as natural RNA. p-RNA contains the D-ribose building unit in the pyranosyl (six-membered ring) form with the phosphodiester bonds linking the C(4') atom of one pyranosyl unit with the C(2') atom of the neighboring pyranosyl unit. Among the four possible pentopyranosyl (ribo-, arabino-, lyxo-, and xylo-) oligonucleotides, ribo-pyranosyl nucleic acid (p-RNA) has been studied

extensively with respect to its base-pairing properties, structure, and function (Pitsch et al. 1993, 1995; Eschenmoser 1993b, 1997, 1999, 2011; Krishnamurthy et al. 1996; Schlönvogt et al. 1996; Micura et al. 1997; Bolli et al. 1997a, b; Beier et al. 1999; Jungmann et al. 1999; Pitsch et al. 2003).

p-RNA oligomers form duplexes that are more selective (Watson-Crick mode, antiparallel orientation of strands) and stronger than the corresponding natural (furanosyl) RNA and DNA oligomers; the Hoogsteen or reverse Hoogsteen pairing modes seem not to be accessible (Pitsch et al. 1995; Eschenmoser 1993b, 1997). Watson-Crick purine-pyrimidine base-pairing in p-RNA is highly enantioselective; p-RNA duplexes comprised of strands of identical chirality were observed to be the strongest among the various possible combinations (Krishnamurthy et al. 1996). In spite of having a less flexible pyranose-unit containing backbone, p-RNA is capable of adopting secondary structures with similar ease as RNA, such as hairpin structures, containing three bases in the loop (Micura et al. 1997).

The overall base-pairing and nonenzymatic replicative properties of p-RNA (and other hexo- and pentopyranosyl-NA) have been discussed in the context of nature's choice of RNA (DNA) as the molecular basis for a genetic system (Beier et al. 1999; Eschenmoser 1999). Two primary conclusions drawn from these studies are that

(a) Watson-Crick base-pairing mode is not unique and specific to the double helix type of conformation characteristic of a ribofuranose system, but is widespread among potentially natural alternatives derived from the structural neighborhood of RNA, and (b) the selection of RNA (and DNA) seems not to be based on the criterion of maximizing base-pairing strength; rather, RNA and DNA seem to have optimal pairing capabilities with respect to achieving turnover in strand replication.

Basic Methodology

The basic methodology underlying the identification and investigation of p-RNA consisted of four parts:

- (1) Identification of p-RNA: a qualitative conformational analysis of repetitive base-pairing arrangements of the four possible pentopyranosyl-NAs led to the selection of p-RNA as a candidate to be synthesized and further investigated.
- (2) Synthesis of p-RNA: the required nucleoside building blocks of p-RNA were generated by synthetic organic chemistry, such as the reaction of a protected ribose with nucleobases by *Vorbrüggen* or *Hilbert-Johnson* nucleosidation, followed by synthetic manipulations to generate the phosphoramidites. The corresponding oligonucleotides were synthesized on a gene synthesizer using the phosphoramidites (automated solid-phase oligonucleotide synthesis) and isolated by ► [HPLC](#) techniques.
- (3) Investigation of the physical and chemical properties of p-RNA: the base-pairing and structural properties were investigated by UV, CD, and NMR spectroscopy.
- (4) Evaluation of the properties of p-RNA: the relevant base-pairing and structural properties of p-RNA were compared with those of natural RNA and DNA. The comparison of these properties and the capacity to replicate by (nonenzymatic) template-directed ligation were used to reason out why ribopyranose nucleic acid is probably not a biological functioning molecule in extant biology.

Key Research Findings

NMR investigations revealed that the p-RNA-(**CGAATTCG**) duplex adopts a quasi-linear (ladderlike) structure with a weak left-handed twist (Schlönvogt et al. 1996). There is a large inclination of the backbone relative to the base-pair axes. Such a marked inclination of the backbone/base-pair-axes has a profound effect on the base-pairing properties of p-RNA such as (a) the highly sequence-dependent thermal stabilities, (b) the stronger and more selective base-pair formation, (c) the duplex stabilizing effect of the 2'-end dangling base, and (d) alternate or block sequences containing pyrimidine-purine arrangements forming more stable duplexes than the inverse series.

Remarkably, p-RNA undergoes extensive cross-pairing with oligonucleotides derived from the three other members of the (4'→2')-pentopyranosyl family; extensive intersystem cross-pairing among the members was observed, in spite of the differences in the stereo-centers of the (4'→2')-phosphodiester-linked oligonucleotides (Jungmann et al. 1999). However, no duplex formation was observed between the pentopyranosyl-derived oligonucleotides with RNA or DNA.

The distinctive chemical properties of p-RNA confer it with certain functional advantages when compared to the natural RNA and DNA oligomeric systems. For example, investigations of the (nonenzymatic) template-directed ligation of p-RNA sequences (via the 2',3'-cyclophosphate activation) have demonstrated this process to be (a) very efficient (due to the absence of purine-purine self-pairing in Hoogsteen or reverse Hoogsteen mode), (b) highly regioselective (forming only the desired 4'→2' linkage over the undesired 4'→3', due to the large backbone/base-pair inclination. In contrast, the corresponding template-directed ligation of RNA forms exclusively the unnatural 5'→2' linkage over the natural 5'→3') (Bolli et al. 1997b), and (c) highly chiroselective (replacement of D-ribopyranosyl with L-ribopyranosyl nucleoside unit hampers the ligation reaction) (Bolli et al. 1997a, b). Hairpin-forming p-RNA sequences also act as

templates for mediating the ligation reaction. However, product inhibition (as a consequence of high base-pairing strength) has impeded any prospects for catalytic “turnover.” On the other hand, such strong base-pairing strength facilitates cooperative co-oligomerization of short hemi-self-complementary tetrameric sequences (activated as the 2',3'-cyclophosphate) resulting in an efficient self-templating oligomerization process that leads to the formation of duplexes of higher oligomers (demonstrated up to 24-mers) starting from homochiral 4-mers (Pitsch et al. 2003).

Applications

In the field of biosensor technologies and molecular diagnostics, there have been a lot of efforts devoted toward developing methods for the detection and identification of target biological agents, e.g., nucleic acids. Typical methods for the analysis of DNA amplification products by PCR involve ► [hybridization](#) assays, such as DNA microarray, real-time PCR, and flow cytometry. p-RNA has been utilized for the development of methods and devices for immobilizing and detecting nucleic acid amplicons. Amplicons are comprised of a forward primer conjugated to a synthetic binding unit and a reverse primer conjugated to a detectable moiety that can hybridize to a complementary strand. This complementary strand serves as a synthetic capture unit localized at a predetermined location on the surface of the substrate. By binding the synthetic capture unit with the synthetic binding unit, the amplicon becomes immobilized under sufficient conditions, producing a complex in which the detectable moiety of the amplicon complex indicates the presence of the target nucleic acid in the sample. p-RNA can be incorporated into the synthetic binding and capture units due to its strong, selective, and reversible pairing properties (Huang et al. 2010).

DNA sequencing has also been useful for understanding the function of genes in human or other organisms and for applying many of the basic techniques of molecular biology by the

control of genes. p-RNA molecules can be used as nucleic acid probes in sequencing by hybridization. The probes comprise predefined patterns of universal nucleotides (nucleic acid analogues including p-RNA) and designate nucleotides (canonical nucleic acids), the so-called gapped probes. In the process of sequencing, gapped probes allow each probe to operate in more than one way, requiring a smaller number of probes than conventional probes composed entirely of natural nucleic acids. By the inclusion of p-RNA in the probes, efficient and rapid sequencing of longer nucleotide sequences can be realized compared to sequencing using traditional probes (Preparata et al. 2003).

Future Directions

p-RNA and other biomolecules, such as a peptides, proteins, or nucleic acids, conjugated through a covalent linkage may function as a sequence recognition unit since the conjugates contain two pairing systems which are orthogonal to one another. Specifically, coupling of the first oligonucleotide analog with the second oligonucleotide analog such as p-RNA may form anti-sense molecules capable of binding specifically to a target sequence of polynucleotides and also capable of activating a nuclease or catalyzing cleavage of the target polynucleotides.

Additionally, the inherent properties of p-RNA make it suitable for use in the field of nanotechnology, such as the production of novel supramolecular materials. For instance, p-RNA which contains a non-hydrogen-bonding tryptamine self-pair forms new supramolecular system exhibiting comparable stability to the natural pair due to strong interstrand stacking in the p-RNA duplex (Hamon et al. 1999). This model pairing system can be derivatized with a fluorescent probe without the necessity of additional labeling.

Cross-References

- [Chirality](#)
- [Furanose](#)

- [Nucleic Acids](#)
- [Origin of Life](#)
- [RNA](#)
- [RNA World](#)
- [Watson-Crick Pairing](#)

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PAH

- [Polycyclic Aromatic Hydrocarbon](#)

PAH Hypothesis

Marco d'Ischia and Paola Manini
Department of Chemical Sciences, University of
Napoli Federico II, Naples, Italy

Keywords

Polycyclic aromatic hydrocarbons (PAHs) ·
Unidentified infrared emission · Nitrogen-
containing PAHs · Mixed aromatic-aliphatic
organic nanoparticles (MAONS)

Definition

The Polycyclic Aromatic Hydrocarbon (PAH) hypothesis states that the infrared spectra of many galactic and extragalactic objects, dominated by emission features at 3.3, 6.2, 7.7, 8.6, and 11.2 μm , are due to the infrared (IR) fluorescence of PAHs upon absorption of ultraviolet (UV) photons. Despite early criticisms based on the lack of a good match between authentic PAH spectra and the astronomical spectra, most of the weaknesses of the original PAH hypothesis have been addressed. In the currently accepted version, the refined PAH hypothesis includes, besides pure PAHs, mixtures of PAH-related species, PAH clusters, cations, grandPAHs, and nitrogen-containing PAHs (Peeters 2011).

Overview

The PAH hypothesis (not to be confused with the PAH world hypothesis, Platts 2004) links the main carriers of UIE bands to PAH compounds and complex mixtures of related species supposed to be present in both galactic and extragalactic environments (Allamandola et al. 1989, Cook and Saykally 1998). UIE bands refer to infrared emissions from circumstellar regions, interstellar media, star-forming regions, and extragalactic objects, which have remained for a long time unassigned since their original discovery. The main features of UIE occur around 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 μm , but include also weak emissions within the $\sim 5\text{--}18$ μm range. Following several observations correlating UIE bands with carbon compounds, in the mid-1980s independent papers by Leger and Puget (1984) and Allamandola (1985) concurred to suggest that the main carriers of the UIE bands were PAHs.

Basic Methodology

Evidence supporting the PAH hypothesis includes:

1. The banded (rather than continuous) nature of the spectrum and the close association of this emission with UV radiation, suggesting that emission is due to gas phase molecules excited by a single UV or visible photon rather than thermal emission from a solid material (Blasberger et al. 2017, Lopez-Puertas et al. 2013).
2. The correlation between the fraction of the total infrared energy that is emitted from planetary nebulae through these features and the amount of available carbon.
3. The correlation between the features of varying emission bands, suggesting that a single class of chemical species is responsible for these spectral signatures.

The assignments supporting the PAH hypothesis can be summarized as follows:

- 3.3 μm band assigned to C-H stretching mode
- 6.2 μm band assigned to C-C stretching mode
- 7.7 μm band assigned to coupled C-C stretching and C-H in-plane bending modes
- 8.6 μm band assigned to C-H in-plane bending mode
- Bands in the 10-15 μm region assigned to C-H out-of-plane bending modes.

Key Research Findings

Beyond the PAH Hypothesis

Although the pillars of the PAH hypothesis were generally accepted, several issues were raised over the subsequent two decades which questioned the validity of assumptions based on pure PAHs as the sole actual carriers of UIE bands (Peeters 2011). Main arguments that were reported include: (1) poor match between experimental and/or theoretical PAH spectra and the astronomical spectra; (2) marked variability in band profiles for interstellar vs circumstellar emissions; (3) the position of the 6.2 μm band cannot be reproduced by the strongest C-C stretching of pure PAHs, indicating that pure PAHs alone cannot account for spectral data.

The possibility that the IR emission spectra could be better matched by structurally modified

PAHs rather than by pure PAHs then gained increasing credit and received a good deal of attention. Accordingly, several modification processes leading to diverse PAH-related species were considered to account for UIE bands, including:

- (a) heteroatom substitution and particularly inclusion of nitrogen in the PAH scaffold to give polycyclic aromatic nitrogenated hydrocarbons (PANHs) (e.g., Peeters et al. 2002, Bauschlicher et al. 2009) like those supposed to be present in Titan's tholins and including conjugated imine and nitrile functionalities;
- (b) aggregation to form PAH clusters such as dimers and trimers (Rapacioli et al. 2005, Simon and Joblin 2009);
- (c) ionization to give random mixtures of PAH cations (Rosenberg et al. 2014).
- (d) reduction to hydrogenated derivatives (Hammonds et al. 2009).
- (e) PAH-metal complexes (e.g., Hudgins and Allamandola 2005, Bauschlicher and Ricca 2009, Simon and Joblin 2010, Joalland et al. 2009) in which a metal atom is located either below or above the carbon skeleton;
- (f) post-synthetic induction of nonplanar structural defects in aromatic core molecular structures (π domains) confined in disordered carbon mixed-phase aggregates (Galué and Díaz Leines 2017);
- (g) variations in the size distribution of the PAH family (Bauschlicher et al. 2008, Bauschlicher et al. 2009, Cami 2011);
- (h) UV processing of the aliphatic components of carbonaceous objects leading to variable proportions of aliphatic versus aromatic moieties (Sloan et al. 2007, Acke et al. 2010).

The grandPAH Hypothesis

Andrews et al. (2015) analyzed the PAH emission at different photodissociation regions and found that the emission features in the 5–15 μm range would lend support to the concept of grandPAHs, previously defined as a set of the most stable PAH species that can survive in the harsh conditions of the interstellar medium (Tielens 2013). The concept of grandPAHs

relies on some main points including: a) the spectroscopic similarity between the three observed spectra even in the smallest details; b) the insensitivity of the PAH emission to the shape of the radiation field. Subtle variations in the abundance distribution of the preferred set of PAHs can explain the observed minor variations between the observed spectra.

PANHs

Parker et al. (2015) emphasized the possible importance of aromatic structures with embedded nitrogen atoms (nitrogen-substituted polycyclic aromatic hydrocarbons, PANHs) in the organic pool of prebiotic relevance in meteorites. PANHs attracted interest since the discovery of vitamin B3 (niacin) and pyrimidines and purines in carbonaceous chondrites like Murchison (Schmitt-Kopplin et al. 2010) suggesting an extraterrestrial origin. The discovery that dihydro(iso)quinolines and potentially more complex PANH-type scaffolds can be produced via facile low temperature reaction channels involving pyridyl radicals with 1,3-butadiene in ultra-low temperature environments provided a more solid background to implicate PANHs in the gas phase of the interstellar medium. In particular, the formation of van der Waals complexes between conjugated molecules with double or triple bonds and an attacking aromatic radical, which lowers the initial reaction barrier to a virtually barrierless addition route leading to a resonance stabilized free radical intermediate, paves the way to an incredibly rich chemistry in the realm of aromatic nitrogen compounds which may parallel that involved in PAH formation and processing. The inclusion of nitrogen into aromatic scaffolds network does not affect the chemistry to any significant degree due to isoelectronicity of nitrogen to methyldiyne (CH) groups. This implies that the reaction routes leading to mass growth and PAH formation are open to nitrogen-bearing systems as well. It is relevant in this connection that PANH derivatives were detected in tholins, a model system for Titan's haze (Sagan et al. 1992), supporting a more relevant astrochemical role of nitrogenated heterocyclic PAHs than so far believed (Landra and Mebel 2010).

Mixed Aromatic-aliphatic Organic Nanoparticles (MAONs)

The central tenet of the PAH hypothesis ascribing the UIE features to purely aromatic carriers was further challenged by studies highlighting the importance of discrete and broad aliphatic spectral features pointing to amorphous organic solids with a mixed aromatic-aliphatic structure, or mixed aromatic-aliphatic organic nanoparticles (MAONs) (Kwok and Zhang 2011). The MAON-based interpretation of spectral data relies also on the marked analogy of this putative carrier with the kerogen-like insoluble organic matter (IOM) in carbonaceous chondrites. The apparent structural and physico-chemical similarity between chondritic IOM and circumstellar dust would shed light on the possible stellar origin of Solar System organics. Moreover, taking as a working hypothesis the formation of MAONs from mixtures of cosmic gases would entail that UIE carrier conceivably features, besides a structural complexity, also a varied chemical composition to include, in addition to carbon and hydrogen, such elements as oxygen, nitrogen, and sulfur. Functional groups bearing O, N, and S may be revealed by analyses at higher spectral resolution and may further compound the original structural model underpinning the PAH hypothesis beyond the emerging aliphatic-aromatic paradigm.

Photochemical Processing of PAHs

Given the widespread occurrence of PAHs in astronomically relevant environments, a crucial question is whether and to what extent PAHs may be susceptible to degradation by UV and cosmic radiation. Although they appear to be abundantly present in photon-dominated regions, their IR emission bands are strongly suppressed toward dense clouds, indicating their confinement to cold grains ($T \leq 30$ K) in the form of interstellar ices. Accordingly, the elucidation of the photochemical behavior of PAHs in water ices has been an important goal since the pioneering studies by Allamandola and colleagues (Bernstein et al. 1999, Bernstein et al.

2001) as well as by other groups (Gudipati and Rui 2012). In all cases a broad range of products including mainly hydroxylated and quinone species was observed, purportedly arising from water-mediated oxygenation pathways. Significant erosion processes leading to the release of CO₂ likely via formaldehyde were also detected, indicating a complex interplay of UV-dependent photochemical pathways accounting for the generation in the interstellar space of oxygen-incorporating PAH-related species of possible relevance to IOM formation and generation of life molecules.

Future Directions

Since the mid-1980s the PAH hypothesis, implicating PAHs as the main carriers of UIE bands, has been subjected to continuous revisions and refinements. As a result, to-date this hypothesis has gradually evolved to incorporate a variety of concepts and phenomena that have relegated PAHs from the original role of dominant carriers of IR emission to that of mere precursors or components of very complex and aggregated organic systems including also aliphatic, cationic, and heteroatom-substituted moieties. If viewed from this broader perspective, the PAH hypothesis still retains its validity after 35 years and can provide the fundamental background to trace the pathway from interstellar medium carbon species to complex organic matter like chondritic IOM of possible prebiotic relevance in planetary environments. In this connection, it would be attractive to revisit the old and largely abandoned PAH world hypothesis in terms of a direct involvement in abiogenesis of PAH-based organic species or domains, like those found to be present in chondritic IOM.

Cross-References

- [Infrared Spectroscopy](#)
- [Origin of Life](#)
- [Polycyclic Aromatic Hydrocarbon](#)

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Paleomagnetism

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

Paleomagnetism is the record of the Earth's past magnetic field preserved in rocks. The orientation of the magnetic field, retained in ferromagnetic minerals (Fe-Ti oxides and sulfides), mirrors the Earth's magnetic field at the time the minerals passed through their Curie point (i.e., the temperature at which certain magnetic materials undergo a sharp change in their magnetic properties). By measuring the orientation (inclination and declination) and the intensity of this magnetism, it is possible to establish the paleo-latitude of the sample at the time of its cooling or recrystallization. Apparent ► [polar wander](#) curves (the shift in the geographical poles relative to Earth's surface) determined using paleomagnetic data record the displacement of continents and provide evidence of past tectonic plate movements. Variations in intensity of the remnant field record changes in the strength of the Earth's magnetic field and the start of crystallization of the inner core. Paleomagnetism has also been measured on Mars and

shown that natural remnant magnetism is concentrated in the southern hemisphere, suggesting a single-hemisphere dynamo generator.

Cross-References

- [Magnetic Field](#)
- [Magnetic Pole](#)
- [Magnetite](#)
- [Mars](#)
- [Plate Tectonics](#)
- [True Polar Wander, Theory of](#)

Paleoproterozoic Carbon Isotope Excursion

- [Lomagundi Carbon Isotope Excursion](#)

Paleoproterozoic Ice Ages

- [Huronian Glaciation](#)

Paleoproterozoic Snowball Earth

- [Huronian Glaciation](#)

Paleosols

Kosei E. Yamaguchi
Geochemical Laboratory, Department of
Chemistry, Toho University, Funabashi, Chiba,
Japan

Keywords

Atmosphere rock alteration (mechanical and chemical) · Weathering profile

Definition

A paleosol is a layer of lithified ancient ► [“Weathering Profile”](#) or paleoweathering profile (not necessarily a lithified “soil”) that formed in place by alteration of its parent geologic materials by physical, chemical, and in many cases, biological ► [“Weathering”](#) processes. In the astrobiological context, Precambrian paleosols have been targets of in-depth research, and also focus hot debate, in attempts to constrain the chemical composition, particularly the redox state, of the coeval atmosphere. Paleosols, especially their uppermost parts, were in direct contact with the atmosphere during their formation and were affected directly (through atmosphere land exchanges) and indirectly (through percolating rainwater) by its chemistry. However, in many cases, the uppermost parts of paleosols were eroded away (weathered sections are easily removed by physical processes) before deposition of the overlying sedimentary materials.

Overview

General overviews of paleosols are given in Kraus (1999) and Retallack (2001). “Paleosols” are not necessarily fossil “soils”; they are, in a broad sense, paleoweathering profiles to variable degrees. Hereafter, we focus on the astrobiological aspects of paleosols as important materials that potentially record atmospheric evolution in the distant past. Continental weathering and its elemental fluxes into the oceans should have been very different under an oxic atmosphere or under an anoxic atmosphere, because (bio)geochemical behaviors of what we call “redox-sensitive elements,” such as iron, are very different (e.g., Ohmoto 1996; Rye and Holland 1998). (Bio)geochemical reactions that mobilize or stabilize elements in weathering profiles are influenced by (1) the redox state of weathering fluids, which is in turn affected by atmospheric chemistry and (2) development of terrestrial biota as a source of organic acids that would accelerate rock weathering. Because of such potentials, Precambrian paleosols have

been focus of in-depth research, and at the same time, of controversies (e.g., Ohmoto 1996).

The biggest problem is probably to unambiguously identify a complete section of paleosol. Misidentification of a middle (or deeper) part with an uppermost part (because it was eroded away) leads to serious misinterpretation of geochemical data of the profile (e.g., Rye and Holland 1998; Beukes et al. 2002; Yang and Holland 2003; Yamaguchi et al. 2007). Middle or deeper weathering horizons of modern weathering profiles typically show a signature indicating reducing conditions (e.g., leaching of Fe), even when an oxic atmosphere overlies the uppermost part of the paleosol. Therefore, discovering reducing horizons in paleosols developed before the inferred GOE at around 2.4 Ga (e.g., Rye and Holland 1998; Yang and Holland 2003) does not necessarily indicate that the coeval atmosphere was reducing/anoxic.

Paleosols have been used to constrain not only O₂ but also CO₂ or CH₄ concentrations in the ancient atmosphere (e.g., Rye et al. 1995; Sheldon 2006). Rye et al. (1995) proposed that the concentration of CO₂ as a greenhouse gas in the 2.2 Ga old atmosphere was not high enough to sustain warm climate under the faint young sun, and that CH₄, an additional and powerful greenhouse gas, was required. This suggestion indicates that the atmosphere was not oxic, because substantial amounts of CH₄ and O₂ do not usually coexist. Remnants of arguably the oldest terrestrial life have been reported from a 2.6 Ga paleosol in South Africa (Watanabe et al. 2000). More studies with older samples may extend such records further back in time.

Cross-References

- [Red Beds](#)
- [Weathering](#)
- [Weathering Profile](#)

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Pallas

Carmen Tornow
Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Definition

(2) Pallas named after Greek goddess Pallas Athena is located in the main asteroid belt between 2.13 AU and 3.41 AU (<http://ssd.jpl.nasa.gov/sbdb.cgi>). Its inclination is higher than the one of the majority of numbered asteroids. Pallas revolves in 4.61 years around the sun and rotates in 7.81 h around itself. With a radiometric diameter of 545 km, it is the second largest asteroid after (1) Ceres. However, due to its lower density (2762 kg/m³) it has only 81% of the mass contained in (4) Vesta. As a B-type asteroid its chemical composition can be related to the one of carbonaceous chondrites subjected to some thermal processing.

History

The discovery of Pallas on March 28, 1802, by astronomer Heinrich W. M. Olbers was a lucky coincidence since it passed Ceres during this time. Olbers tried to verify the positions of Ceres predicted by Carl F. Gauss, 1801. At that time astronomers thought that a planet would orbit between Mars and Jupiter according to the Titus–Bode hypothesis. This conjecture seemed to be confirmed by the detection of Ceres. However, the discovery of Pallas has put serious doubts on this assumption. The point-like appearance of Ceres and Pallas has motivated William Herschel in 1802 to recommend a separate category for these objects called asteroids (<http://dictionary.reference.com/browse/asteroid>), which was finally accepted by the community. However, both notations (asteroid and planet) were used over many decades of years. Continuing his study of asteroid families Kiyotsugu Hirayama 1928 has identified a small set of objects linked with Pallas and sharing its orbital and spectral characteristic parameters within some range of variability. Today, the existence of the Pallas asteroid family with a clearly larger set of members is well accepted.

Cross-References

- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [Carbonaceous Chondrite](#)
- [Ceres](#)
- [Keplerian Orbits](#)
- [Vesta](#)

Palus, Paludes

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute
of Geological Sciences, Freie Universität Berlin,
Berlin, Germany

Synonyms

[Marsh](#)

Definition

Paludes are lunar low-albedo surface features considered to be small (150–300 km in diameter) and isolated lunar Mare patches. They are situated near larger lunar maria.

The three named lunar paludes are Palus Epidemiarum (marsh of epidemics), Palus Putredinis (marsh of decay), and Palus Somni (marsh of sleep).

Cross-References

► [Mare, Maria](#)

continents had at one time formed a single supercontinent which he called the “Urkontinent”, before later breaking up and drifting. The term Pangaea appeared in 1928 during a symposium in Tulsa, Oklahoma, to discuss Alfred Wegener’s theory of continental drift.

Cross-References

► [Gondwana](#)
 ► [Laurasia](#)
 ► [Plate Tectonics](#)
 ► [Rodinia](#)
 ► [Supercontinent](#)

Pangea

Nicholas Arndt
 Maison des Géosciences, LGCA, Université
 J. Fourier, St-Martin d’Hères, France

Definition

Pangea is the name of the supercontinent that existed through most of the Paleozoic, from about 480 to 180 Ma. It comprised the older portions of all present landmasses. The single enormous ocean surrounding Pangea was accordingly named Panthalassa. The reasons for the formation of the Pangea supercontinent are poorly understood. Around 180 Ma ago, it started to split apart, initially into the supercontinents ► [Laurasia](#) and ► [Gondwana](#), subsequently into the present continents. The ponding of mantle plumes below the pangean continental lithosphere may have weakened it and favored large-scale continental rifting and breakup.

History

In his book *Die Entstehung der Kontinente und Ozeane*, the German astronomer and meteorologist Alfred Wegener postulated that all the

Panglacial

► [Snowball Earth](#)

Panorama Formation

► [North Pole Dome \(Pilbara, Western Australia\)](#)

Panspermia

Jean-Pierre de Vera
 German Aerospace Center (DLR), Institute of
 Space Operations and Astronaut Training,
 Microgravity User Support Center (MUSC),
 Cologne, Germany

Keywords

Habitable planets · Impact · Interplanetary transfer of life · Origins of life · Space exposure experiments

Synonyms

[Interplanetary transfer of life](#)

Definition

Panspermia (Greek: πανσπερμία from $\pi\tilde{\alpha}\zeta/\pi\tilde{\alpha}\nu$ (pas/pan) “all” and σπέρμα (sperma) “seed”) is the hypothesis that “seeds” or “spores” of life can survive space travel and spread throughout the Universe. Consequences of this hypothesis are that life on Earth may have originated at some other place in the Universe and its evolution on Earth is due to a fertilization of the planet through such interplanetary or interstellar transfer of “seeds.” Consequently, life could be delivered to and start a new evolution on all habitable planets, moons, and satellites.

History

The term *Panspermia* is known to have been mentioned in the fifth century BC for the first time by the Greek philosopher Anaxagoras. He might have influenced scientists in the Middle Ages, as, for example, Giordano Bruno (1548–1600). Giordano had access to old Greek scriptures in the libraries of the medieval monasteries and universities and he proposed the existence of multiple worlds. However, he did not propose interplanetary transfer of life between these worlds. The idea of Panspermia was revived in the nineteenth and twentieth centuries by scientists like J. J. Berzelius (1779–1848), W. T. Kelvin (1824–1907), H. von Helmholtz (1821–1894), S. Arrhenius (1859–1927), and F. Hoyle (1915–2001). During that time the main idea originated that if life once started at some place, it may be able to spread to other environments suitable for replication. Some controversial theories even proposed that diseases may originate in space with space-borne viruses causing, for example, influenza (Hoyle and Wickramasinghe 1979, 1986; Hoyle et al. 1984). But according to Henderson et al. (1989) the likelihood of this theory to hold true is very low.

Overview

Panspermia can occur in three different ways. (1) The classical Panspermia hypothesis

postulates the transfer of uncovered “seeds” by radiation pressure through space (Arrhenius 1903, 1908). (2) The so-called Lithopanspermia (Greek: litho = stone) hypothesis assumes that a ► [rock](#) hosts the organisms during interplanetary transfer. Panspermia should not be confused with the hypothesis based on the formation of chemical compounds in interstellar molecular clouds that assumes that the first prebiotic molecules also formed there. The interstellar molecular clouds are formed after the explosions of the first generations of ► [stars](#) in supernovae. This prebiotic complex organic material can be transported by solar or ► [stellar winds](#) into deep space and may have “seeded” a planet that may then be host to the resulting formation and evolution of life. The seeds are assumed to be interstellar dust grains, ► [meteorites](#), and ► [comets](#) (Chyba and Sagan 1992; Martins et al. 2008).

Francis Crick also intriguingly postulated a “directed Panspermia” where intelligent beings would be deliberately “seeding” the Universe (Crick and Orgel 1973). In 1998 scientists started to systematically analyze the likelihood of Lithopanspermia by performing suitable experiments. The Mars-Earth System served as a model system in these studies. Because ► [Mars](#) is similar to Earth in many aspects and may have had a similar early evolution and because of its proximity to Earth, it is conceivable that life may have originated on Mars and spread to Earth. The discussion was furthered by the albeit controversial discovery of fossil nanostructures in the Martian meteorite ► [ALH 84001](#) in 1996. In general, Panspermia could occur if: (1) rock hosting microorganisms from an inhabited “home” or “donor” planet was ejected into space; (2) the ejected material traveled a potentially long time (about thousands to millions of years) through space without disintegration of the life forms; and (3) the host rock entered into the atmosphere of a habitable “acceptor” planet where the ► [microorganisms](#) would come back to life and replicate. All three elements of the scenario have been thoroughly tested and additional tests are still in progress. Crater impact researchers have provided data on shockwave pressures that will be reached in the spallation zone during an impact

event. Studies of craters on Mars are the basis of this data and have helped to get the most realistic conditions for impact simulation experiments. The shockwave experiments were run by shooting into (Mastrapa et al. 2001), or by the use of explosive devices on rocky material hosting microorganisms, creating realistic simulation of asteroid impacts, which are reaching according to calculations of shockwave pressures up to 50 GPa (Stöffler et al. 2007; Horneck et al. 2008). The results of these experiments showed that the tested microorganisms such as ► [bacteria](#) and ► [lichen](#) spores survived. The second step of the Panspermia scenario was tested by ground-based space simulations and by space exposure experiments on ESA or NASA space hardware devices like ► [BIOPAN](#) mounted on the satellite FOTON and launched by Soyuz rockets (de la Torre et al. 2010), or by the exposure platforms ► [EXPOSE-E](#) and [EXPOSE-R / -R2](#) on the ► [International Space Station](#) launched by Space Shuttles or Soyuz rockets (Cottin et al. 2015, 2017; de Vera et al. 2019). The results of these experiments support the Lithopanspermia hypothesis. But tests of the entry part of the hypothesis in an experiment named ► [STONE](#) using the reentry devices of the FOTON satellite were negative because the tested organisms failed to survive. New tests using satellite reentry devices are planned for the near future. To better design realistic experiments, it is important to consider that various models of Panspermia exist.

Basic Methodology

The three elements of (Litho-)Panspermia can be studied by using ► [asteroid](#) impact simulation devices and space exposure platforms. Asteroid impact events producing shockwaves are achieved by experiments using explosive devices or projectile experiments. Further steps of Panspermia are checked by space exposure tests on space exposure platforms like ISS or FOTON and by reentry experiments that are performed on reentry devices of satellites like the FOTON capsule.

Key Research Findings

The performed Panspermia experiments have shown that besides very resistant prokaryotic microorganisms (bacteria and archaea), even eukaryotic microorganisms (lichens and spores of fungi) are able to survive asteroid impact events and space travel, whereas the reentry process seems to be the most harmful for both of these groups of microorganisms.

Future Directions

Experiments on verification or falsification of the Panspermia hypothesis are ongoing using various organisms and species. Especially the reentry experiments are not completed, and new sets of tests are still in progress.

Cross-References

- [ALH 84001](#)
- [Asteroid](#)
- [Bacteria](#)
- [BIOPAN](#)
- [Comet](#)
- [Crater, Impact](#)
- [Eukarya](#)
- [EXPOSE](#)
- [Foton Capsule, Spacecraft](#)
- [International Space Station](#)
- [Lichens](#)
- [Mars](#)
- [Meteorites](#)
- [Microorganism](#)
- [Origin of Life](#)
- [Planet](#)
- [Prebiotic Chemistry](#)
- [Prokaryote](#)
- [Replication \(Genetics\)](#)
- [Rock](#)
- [Satellite or Moon](#)
- [Stars](#)
- [Stellar Winds](#)
- [STONE](#)
- [Supernova](#)

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Paraformaldehyde

- Formaldehyde
- Polyoxymethylene

Parallax

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

In astronomy, parallax is the apparent difference in angular position of a celestial object with respect to background stars, as seen from different positions as the Earth travels along its orbit around the Sun (and in recent times, as the Sun moves in its orbit around the center of our Galaxy). As a tabulated quantity for stars (the annual parallax), it is equal to the angle subtended from a star by the mean radius of the Earth's orbit. The farther the star, the smaller the parallax. The inverse of the parallax is thus a direct measurement of the

distance of a star, which is usually expressed in ► [parsecs](#). A parsec is the distance for which the annual parallax is 1 arc sec. Historically, parallax was the first reliable way to determine distances to nearby stars, and it remains a key technique today, with the use of spacecraft such as ► [Hipparcos](#). Radio astronomers have used VLBI techniques to accurately measure parallax and hence distances, for example, to the center of the Milky Way. Units: arc second.

Cross-References

- [AU](#)
- [Gaia Mission](#)
- [Hipparcos](#)
- [Parsec](#)

Paralog

- [Paralogous Gene](#)

Paralogous Gene

David Moreira and Purificación López-García
Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris,
France

Synonyms

[Paralog](#)

Definition

Paralogous genes (or paralogs) are a particular class of homologous genes. They are the result of gene duplication and the gene copies resulting from the duplication are called paralogous of each other. After duplication, the paralogous genes can keep the same function (for example, the multiple

copies of ribosomal RNA genes found in many genomes), but they often diverge and develop different functions (for example, the translation elongation factors Tu and G). Paralogous genes can be retained in the genome after their duplication, but some copies can also be lost. This can generate complex patterns of presence/absence of the different paralogues that may render very difficult the interpretation of ► [phylogenetic trees](#), leading sometimes to erroneous inferences about the relationships between species. This is usually called the “hidden paralogy” problem.

Cross-References

- [Gene](#)
- [Homology](#)
- [Orthologous Gene](#)
- [Phylogenetic Tree](#)
- [Phylogeny](#)

Parameterization of Spectral Data

- [Spectral Parameters, Solar System Planets](#)

Parametric Release

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

Parametric release is an alternative to end-product sterility testing of articles that have undergone sterilization processing. In general, to authorize the release of a product, a manufacturer performs tests and analysis on the final product. For parametric release, instead of testing each end product (which is difficult for high-volume items, and risks contaminating a now-sterile article), checking the parameters of the various

sterilization processes used during the production is deemed sufficient, if those processes have been certified. For example, parametric release is accepted by the US Food and Drug Administration for certification of many pharmaceutical products for injection. Parametric release is permitted based on objective evidence that the processes have been performed successfully; this includes monitoring of the process, documentation, and verifying that in-process data matches the predefined specifications. A similar approach is adopted for the planetary protection discipline, where sterilization/bioburden reduction credit is given based on verifying in-process data.

Cross-References

- [Planetary Protection](#)
- [Sterilization](#)

Parent Body

Jacques Crovisier
LESIA, Observatoire de Paris, Meudon, France

Keywords

Asteroid · Comet · Meteor · Meteorite · Meteoroid · Planet

Definition

A parent body is the object from which a given ► [meteorite](#) or meteoroid was ejected. Most meteorites come from the fragmentation of asteroids following collisions. Meteor showers are due to sizable dust particles shed by ► [comets](#).

Overview

With the exception of lunar and Martian meteorites, it is believed that most meteorites are derived from parent bodies in the ► [asteroid](#) belt. This

idea progressively emerged in the mid-nineteenth century from the works of Robert P. Greg (1826–1906), Auguste Daubrée (1814–1896), and Adolphe Boisse (1810–1896) (see Marvin [2006](#)).

There is a large diversity among both meteorites and asteroids. However, few specific asteroids are firmly identified as parent bodies. The comparison of spectral and mineralogical characteristics is basically hampered by the alteration of the asteroid surfaces by space weathering. The problem is further complicated because present asteroids may not be primordial, but the product of collisions themselves.

Could some meteorites, such as carbonaceous chondrites, be coming from comet nuclei? As was discussed by Campins and Swindle ([1998](#)) the question is still open. The specific case for the Orgueil meteorite, which could have come on a comet-like orbit, was studied by Gounelle et al. ([2006](#)).

The connections between comets and meteor showers, based upon orbital considerations, are easier to establish. The first link was obtained by Giovanni Schiaparelli (1835–1910) who related 109P/Swift-Tuttle and the Perseid meteors. This is now well-documented for most meteor showers (Jenniskens [2006](#)), which are related to present or extinct comets, or near-Earth asteroids.

A cheap way to study extraterrestrial matter, in contrast to costly sample return space missions, is to analyze this matter provided in the form of meteorites on the Earth's surface or of meteoroids or stratospheric dust particles in the Earth's atmosphere. It is therefore of paramount importance to relate this material to its parent bodies.

Cross-References

- [Asteroid](#)
- [Comet](#)
- [Fragmentation of Interstellar Clouds](#)
- [Interplanetary Dust Particle](#)
- [Meteorites](#)
- [Micrometeorites](#)
- [Minor Planet](#)
- [Planet](#)

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Parent Molecule (Ion, Species)

- [Precursor](#)

Parent Molecule, Comet

Jacques Crovisier
LESIA, Observatoire de Paris, Meudon, France

Definition

A parent molecule is a molecule directly released from cometary material, e.g., by ► [sublimation](#) of cometary ices. It contrasts with daughter molecules, which are their degradation products. Historically, daughter molecules (CN, C₂, C₃, CH,

OH, NH. . .) were first observed in cometary spectra from their electronic bands in the visible and the nature of their parents was the subject of speculations. Parent molecules (H₂O, CO, CO₂, NH₃, HCN, hydrocarbons. . .) were definitely identified more recently from their vibrational bands and rotational lines in the infrared and radio spectral domains, as well as from in situ mass spectroscopy.

Cross-References

- [Comet](#)
► [Daughter Molecule, Comet](#)

Parity Nonconservative Energy Difference

- [PVED](#)

Parity Violation Energy Difference

- [PVED](#)

P

Parker Solar Probe

Lina Z. Hadid¹ and Olivier Witasse²

¹Laboratory of Plasma Physics (LPP), CNRS, Paris-Saclay University, École Polytechnique, Palaiseau, France

²European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands

Keywords

Sun · Corona · Heliophysics · NASA mission · Solar wind

Acronyms

PSP	Parker Solar Probe
A.U.	Astronomical Unit
Rs	Solar Radii
WISPR	Wide-field Imager for Solar Probe
SWEAP	Solar Wind Electrons Alphas and Protons
ISIS	Integrated Science Investigation of the Sun energetic particle
SPC	Solar Probe Cup
SPAN	Solar Probe ANalyzers

Definition

Parker Solar Probe is a NASA mission designed to investigate the fundamental plasma physics of the near-Sun plasma environment by flying into its outermost atmosphere known as the corona, a region which has never been explored before. It will perform the closest-ever in situ and remote sensing observations of the coronal and solar wind plasma as close as 9.8 solar radii (Rs) from the center of the Sun (0.045 A.U.).

History

The idea of the Parker Solar Probe mission dates back to the 1958 Simpson Committee Report which proposed several space missions including “a solar probe to pass inside the orbit of Mercury to study the particles and fields in the vicinity of Mercury.” The concept of this mission, originally called “Solar Probe” has been revised many times over more than five decades, nevertheless its main objective has always been a close encounter with the Sun.

It is only until 2014 that “Solar Probe” mission was confirmed and started to be developed as part of NASA’s Living with a Star (LWS) Program. In 2017, the spacecraft was renamed “Parker Solar Probe” in honor of the solar astrophysicist Eugene Newman Parker who developed the theory of the supersonic solar wind and predicted the “Parker spiral” shape of the solar magnetic field.

Overview

Parker Solar Probe (PSP) is a NASA mission that was launched on August 12, 2018, from Cape Canaveral, Florida, in the USA, to explore for the first time the Sun’s outermost atmosphere, known as the corona. PSP will fly through the expanding solar corona to understand the underlying fundamental processes as close as 9.8 solar radii (Rs) from the center of the Sun (0.045 A.U.).

The primary science objectives of PSP are to: (1) trace the flow of energy that heats the corona and accelerates the solar wind; (2) determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind; and (3) determine what mechanisms accelerate and transport energetic particles.

It is important to study the Sun in order to understand how life on Earth developed. In addition, the knowledge of the space environment is a necessity to protect spacecraft and astronauts.

In order to unlock the mysteries of the solar corona and so to complete the mission science objectives, PSP performs 24 elliptical orbits around the Sun over a 7-year nominal mission duration. Moreover, it uses seven Venus gravity assists to gradually reduce its perihelion from about 35 Rs (0.16 AU) for the first orbit to 9.86 Rs (0.0459 AU) in the final three orbits.

The PSP payload includes a combination of four in situ and remote sensing instruments to observe the magnetic and electric fields, the plasma, and the energetic particles. These observations will expand our knowledge of the origin and evolution of the solar wind and revolutionize our understanding of the solar corona. The four suites of instruments are FIELDs, WISPR, SWEAP, and ISIS investigations.

1. FIELDs consortium (Bale et al. 2016): It consists of two fluxgate magnetometers (MAG), a search coil magnetometer (SCM), and five electric antennas. This experiment aims to measure the magnetic and electric fields, and indirectly infers the electron density using the plasma quasi-thermal noise spectroscopy.
2. WISPR (Wide-Field Imager for Solar Probe, Vourlidas et al. [2016]): This experiment is the

only imaging instrument aboard the spacecraft. It is a white-light telescope that capture images of the solar corona and inner heliosphere, including images of the solar wind, shocks, and transient structures as they approach and pass by the spacecraft.

3. SWEAP (Solar Wind Electrons Alphas and Protons, Kasper et al. [2016]): This experiment comprises two electrostatic analyzers (Solar Probe Analyzers, SPAN-A and SPAN-B) and a Faraday cup (Solar Probe Cup, SPC) to measure the electrons, protons, and helium ions in the solar wind and coronal plasma. Moreover, it can determine their bulk properties such as velocity, density, and temperature as well as full 3D distribution functions.
4. ISIS (Integrated Science Investigation of the Sun Energetic Particle, McComas et al. [2016]). This instrument suite comprises two independent energetic particle instruments (EPI-Hi and EPI-Lo, where EPI stands for energetic particle instrument) covering different and overlapping energy ranges to measure the flux of energetic protons, electrons, heavy ions, and their distribution functions (10 keV to 100 MeV).

Cross-References

- [ESA Solar Orbiter Mission](#)
- [Solar Particle Events](#)
- [Sun \(and Young Sun\)](#)

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Parsec

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[pc](#)

Definition

The parsec is the distance from which the average Earth–Sun distance ($149.6 \cdot 10^6$ km 1 AU) subtends an angle of 1 arc sec. This is one of the basic units of astronomy, and was originally based on the measurement of the ► [parallax](#) effect. Other distance units (kpc, Mpc, etc.) derive from it. The name derives from the French “par seconde” (per second).

Cross-References

- [AU](#)
- [Parallax](#)

Partial Antigen

- [Hapten](#)

Partitioning

- [Fractionation](#)

Pasteurization

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

[Pasteurization is the name given to a particular heat-treatment process that reduces the number of viable microorganisms (typically by a factor of 10^5) but does not necessarily bring the number of remaining organisms to zero. This process is applied mainly to food products of known microbial cleanliness level, using moderate temperatures (under 100 °C). It is not approved as a standard process for planetary protection to reduce the bioburden on thermosensitive components but could be proposed for use for specific mission applications.

Cross-References

- ▶ [Bioburden Reduction](#)
- ▶ [Disinfection](#)
- ▶ [Inactivation](#)
- ▶ [Planetary Protection](#)
- ▶ [Sterilization](#)

Patera, Paterae

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

Patera is an irregular crater or a complex one with scalloped edges (definition by the International Astronomical Union, <http://planetarynames.wr.usgs.gov/jsp/append5.jsp>) and is used as a descriptor term for naming surface features on

▶ [Mars](#), ▶ [Venus](#), and the Jovian satellite, ▶ [Io](#).

Cross-References

- ▶ [Crater, Impact](#)
- ▶ [Io](#)
- ▶ [Mars](#)
- ▶ [Satellite or Moon](#)
- ▶ [Venus](#)

pc

- ▶ [Parsec](#)

PCR

- ▶ [Polymerase Chain Reaction](#)

PDR

- ▶ [Photodissociation Region](#)

Pentopyranosyl-RNA

- ▶ [p-RNA](#)

Peptide

- ▶ [Oligopeptide](#)
- ▶ [Protein](#)

Peptide Nucleic Acids

► [PNA](#)

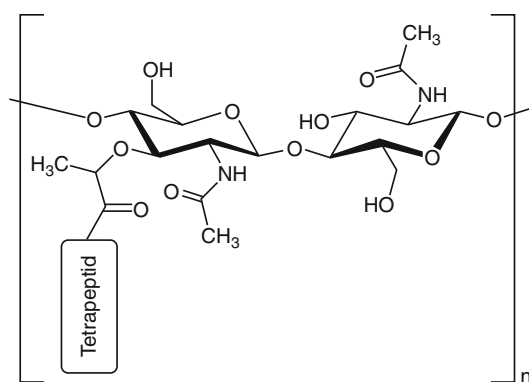
Peptidoglycan

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Torrejón de Ardoz, Madrid, Spain

Definition

Peptidoglycan is a polymer with a structural role in the bacterial ► [cell wall](#). It is a barrier that provides structural strength to the ► [bacteria](#). It is made of polysaccharides attached to oligopeptides in linear chains (*N*-acetylglucosamine and *N*-acetylmuramic acid alternating with cross-linked oligopeptides (no more than five amino acids)). The oligopeptides are attached to *N*-acetylmuramic acid. Due to the cross-linked oligopeptide, it constitutes a 3D structural layer, which is thicker in the case of ► [Gram-positive bacteria](#) (Fig. 1).



Peptidoglycan, Fig. 1 Peptidoglycan basic monomer with two elements (*N*-acetylglucosamine and *N*-acetylmuramic acid). Cross-linked oligopeptide constitutes a 3D network with structural role in the bacterial cell wall

Cross-References

- [Bacteria](#)
- [Cell Wall](#)
- [Gram-Negative Bacteria](#)
- [Gram-Positive Bacteria](#)
- [Periplasm](#)

Perchlorates on Mars

Daniela Tirsch¹ and Alessandro Airo²

¹German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

²Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Fachbereich Geowissenschaften, Berlin, Germany

Definition

Perchlorates are salts derived from the perchlorate acid (HClO₄). They form through oxidative processes in the atmosphere and accumulate with the dust (Smith et al. 2014). In 2008 perchlorates were detected by the Phoenix lander in the Martian soil. Sample analysis by the NASA rover “Curiosity” at Gale crater suggest the presence of perchlorates in an aeolian dune at the location called “Rocknest”. Perchlorates are of particular relevance in terms of ► [Habitability on Mars](#) because they could oxidize and therefore decompose possible organic compounds. Furthermore, on Earth perchlorates found in the Atacama Desert have been shown to serve as Nutrients for microbes.

Cross-References

- [Habitability on Mars](#)
- [Nutrients](#)

References

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Perennial Heat Source

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

For planetary protection, a perennial heat source is a device, usually containing radioactive materials, like radioisotopic thermoelectric generator (RTG) or radioisotopic heating unit (RHU), that will continue to produce heat for a significant length of time after a spacecraft has ceased operation.

Perennially Frozen Ground

► [Permafrost](#)

Periastris

► [Periastron](#)

Periastron

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Periastris](#); [Pericenter](#)

Definition

For an object in an elliptical Keplerian orbit around a star, periastron is the point of closest approach of the object to the star (and to the center

of mass of the system). The terms *perihelion* and *perigee* are used for the same concept when orbits are around the Sun or Earth, respectively. Apastron, aphelion, and apogee are the corresponding points of largest separation.

Cross-References

► [Aphelion](#)

Pericenter

► [Periastron](#)

Peridot

► [Olivine](#)

Peridotite

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

Peridotite is an ultramafic (silica-poor, magnesium-rich) intrusive rock. It is coarse-grained and pale to dark green and is composed of >90 % mafic (ferromagnesian) minerals: typically, ► [olivine](#), orthopyroxene, and clinopyroxene. Minor phases include plagioclase, spinel or garnet, amphibole or biotite, and Fe-Cr-Ti oxides. Peridotite is the dominant component of the upper ► [mantle](#) of the Earth and other planets and is thus the most common rock in the Solar system. Peridotite is also found as a main component of some ► [shergottites](#), one of the classes of Martian ► [SNC meteorites](#).

Cross-References

- ▶ [Asthenosphere](#)
- ▶ [Igneous Rock](#)
- ▶ [Mantle](#)
- ▶ [Olivine](#)
- ▶ [Shergottites](#)

Period

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Definition

The period is the length of time between two successive realizations of a well-defined physical state of a system that appears repeatedly on a fully regular basis. The phenomenon is then said to be periodic. For instance, a planet at a given position along its ▶ [orbit](#) around a star will be at exactly the same position after a time equal to one period of revolution. Spin, waves, oscillations are other examples of periodic phenomena. The period, whose unit is the second, is the inverse of the frequency, which is expressed in Hertz (Hz).

Cross-References

- ▶ [Orbit](#)

Period (Half-Life Period)

- ▶ [Half-Life](#)

Periphyton

- ▶ [Biofilm](#)

Periplasm

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto
Nacional de Técnica Aeroespacial, Torrejón de
Ardoz, Madrid, Spain

Definition

Periplasm is the inner space located between the cell plasma membrane and the outer cell wall, or peptidoglycan in ▶ [Gram-negative bacteria](#). Periplasm is easily recognized by electron microscopy. Periplasm is a gel-like structure that contains fluids with hydrolytic enzymes and binding proteins involved in the transport of material into the cell. The existence of similar functions associated with ▶ [Gram-positive bacteria](#) allows the existence of an equivalent structure in this type of microorganism to be postulated.

Cross-References

- ▶ [Bacteria](#)
- ▶ [Chemotaxis](#)
- ▶ [Gram-Negative Bacteria](#)
- ▶ [Gram-Positive Bacteria](#)
- ▶ [Transport, Biological](#)

Permafrost

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the
Earth System, Université du Québec à Montréal,
Montréal, QC, Canada

Synonyms

[Perennially frozen ground](#)

Definition

Permafrost is soil that remains below the freezing point of water (0 °C) for more than two consecutive years. It is mainly located at high latitudes (24% of the exposed land in the Earth's northern hemisphere) and high altitude (alpine permafrost). Permafrost exists at all latitudes on Mars and subsurface ice probably is abundant. Asteroid 25143-Itokawa and Eros show surface morphologies that suggest the occurrence of a permafrost and occasionally meltwater. Earth's permafrost is a site of microbial activity within thin films of liquid water between ice and soil particles. The occurrence and distribution of these microbial communities are studied as possible analogues of life forms on icy planets and satellites of the Solar system.

Cross-References

- [Antarctica, Natural Analogue Site](#)
- [Itokawa Asteroid](#)
- [Mars](#)

Permeability

David Deamer
Department of Chemistry, University of
California, Santa Cruz, Santa Cruz, CA, USA

Keywords

Bilayer · Concentration gradient

Definition

Permeability is a measure of the ability of a fluid or gas to pass through porous solids or aggregates. In the biological sense, it also refers to the relative ability of solutes to diffuse through the ► [lipid bilayer](#) barrier of ► [membranes](#). Biological membranes and lipid vesicles are relatively permeable to small, uncharged molecules such as water,

carbon dioxide, and oxygen, and relatively impermeable to ionized solutes like sodium, potassium, chloride, and ► [amino acids](#).

Overview

All cellular life is defined by boundary membranes that provide a selective barrier to the free diffusion of solutes such as ions (sodium, potassium, chloride, phosphate, protons) and nutrients (glucose, amino acids). The permeability barrier is the lipid bilayer, and cells have evolved a variety of ► [proteins](#) that act as channels and transporters to select which solutes can enter or leave a cell. The rate at which a given solute crosses the bilayer barrier is usually expressed in terms of a permeability coefficient (P), which by convention is defined as the amount of solute crossing a square centimeter of membrane in 1 s down a unit concentration gradient. A simplified equation for the permeability coefficient is $P = J/\Delta C$, where J is the flux in $\text{mol cm}^{-2} \text{s}^{-1}$, and ΔC is the difference in concentration driving the flux in mol cm^{-3} . The units are then cm s^{-1} . A typical measurement of the permeability coefficient of water is 10^{-3}s^{-1} , whereas the permeability of an ion such as potassium is $10^{-11} \text{cm s}^{-1}$, which is eight orders of magnitude lower. A more intuitive way to think about permeability is in terms of the half-time of decay of a gradient. For instance, water permeation across liposome membranes has a half-time measured in milliseconds, while the decay of a potassium gradient in the same system is measured in hours.

Solute have two mechanisms for crossing a lipid bilayer barrier. The simplest mechanism is referred to as solubility-diffusion, in which the solute dissolves in the hydrocarbon phase and diffuses to the other side where it dissolves in the opposite bulk phase. Small neutral molecules, like water and gas molecules, pass through the membrane barrier by this process. The other mechanism involves transient or permanent transmembrane defects. For instance, membranes would be virtually impermeable to ionized solutes such as potassium ions due to the Born energy required for an ion to move from a high dielectric polar solvent like water to a low dielectric phase such as the nonpolar

interior of a lipid bilayer, which is composed of hydrocarbon chains. However, ions can penetrate the lipid bilayer by passing through transient defects that constantly appear and disappear in the bilayer. The protein channels in biological membranes overcome the Born energy barrier by providing a permanent high dielectric pathway through the hydrocarbon chains.

Selective permeability to solutes is an essential property of cell membranes today, and must also have been important to the first forms of cellular life. It is likely that primitive cell membranes were composed of short chain amphiphilic molecules available in the prebiotic environment, which would be much more permeable than the evolved membranes of cells today. Therefore, the function of membranes in the first forms of life would be to maintain large polymers within a compartment so that they could interact, while allowing access to nutrient solute molecules such as amino acids.

Cross-References

- [Amino Acid](#)
- [Lipid Bilayer](#)
- [Membrane](#)

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Peroxisome

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A peroxisome is a membrane-enclosed ► [organelle](#) present in almost all eukaryotic cells, whose

function is to produce hydrogen peroxide (H_2O_2) from the reduction of O_2 by various hydrogen donors. They participate in the metabolism of fatty acids and many other metabolites. The hydrogen peroxide produced in the peroxisome is degraded to H_2O and O_2 by the enzyme catalase. Peroxisomes are bound by a single membrane that separates their contents from the cytosol and contains membrane proteins involved in different functions (transport, proliferation). Peroxisomes originate in the cell by incorporating their proteins and lipids from the cytoplasm, eventually becoming a membrane-enclosed entity that can enlarge and divide in synchrony with the cell. Peroxisomes are absent in prokaryotic organisms.

Cross-References

- [Eukaryote](#)
- [Organelle](#)

Perseverance

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Mars · Rover · Mars sample return ·
Exploration Astrobiology

Definition

Perseverance is the name of the rover of the → NASA mission to → Mars named → MARS 2020. The mission has been launched on July 28, 2020, by an Atlas V rocket. The rover landed safely, at the surface of Mars in Jezero Crater, February 18, 2021. The rover is designed to perform scientific research and to collect Martian samples to be sent to Earth in the next decade. It is equipped with seven science instruments, one demonstrator to produce locally molecular

oxygen (O_2), and a system to collect, seal, and store sample tubes. Additionally, → Ingenuity, a small helicopter was released from the body then tested to demonstrate the feasibility of flying within the Martian rarefied atmosphere.

History

In July 2013, a science definition team for the next mission to Mars, set up by NASA, issued the science objectives and exploration priorities for the next NASA robotic mission to Mars (Mustard et al. 2013). The launch date target was set for 2020.

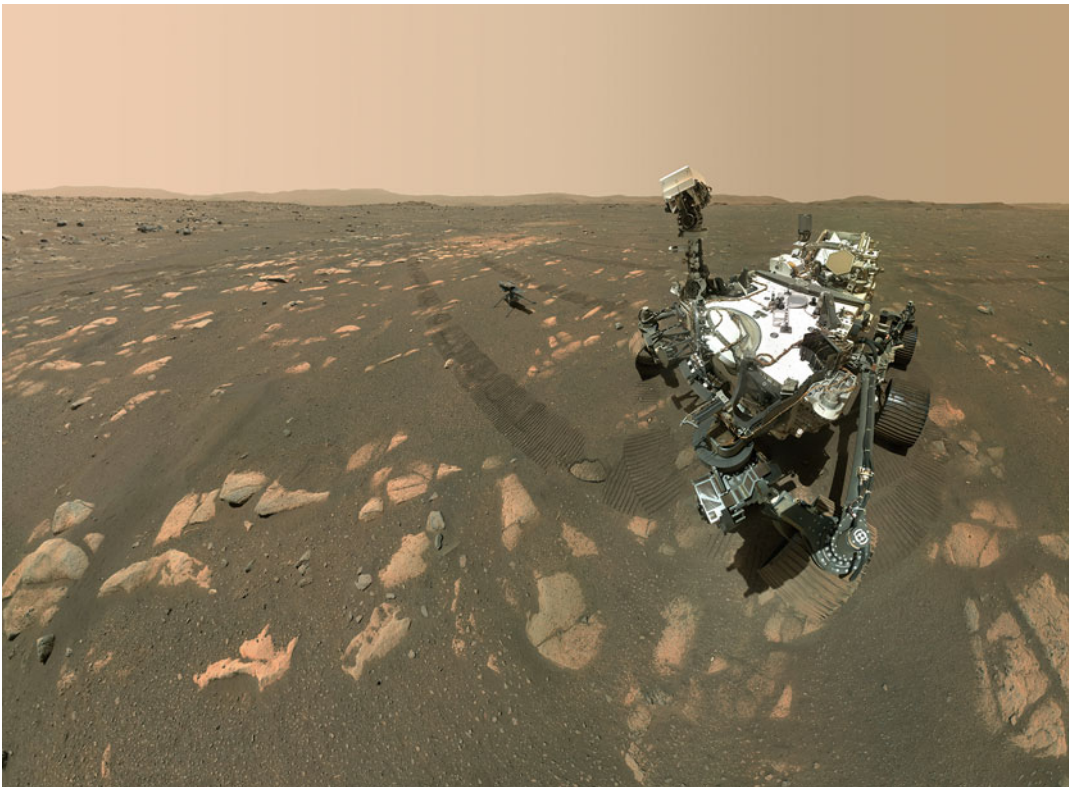
September 24, 2013, NASA issued an Announcement of Opportunity (AO) for the instruments of the science payload of the new Martian rover which will be similar to →

Curiosity. The AO was open as usual to foreign contributors as long as they are sponsored by their national institutions.

NASA received 58 proposals and announced by July 31, 2014, the seven selected instruments. The development of the composite spacecraft including the sky crane and the rover is based on the heritage of Curiosity, while the instrumentation is essentially new.

Overview

Perseverance is a six wheel vehicle weighting 1025 kilograms on Earth (Fig. 1). The vehicle is roughly 3 m long and 2.7 m wide. It is equipped with a 2.1 m long robotic arm holding a 45-kilogram turret at the end. It has also a mast carrying several instruments and cameras, topping



Perseverance, Fig. 1 NASA's Perseverance Mars rover selfie with the Ingenuity helicopter, seen here about 3.9 m from the rover in this image taken April 6, 2021, by WATSON the camera of SHERLOC. Credit NASA/JPL-Caltech/MSSS

at 2.2 m. The energy, about a continuous 110 W flow, is provided by a Multi-Mission Radioisotopic Thermo-electric Generator (MMRTG) based on Plutonium 138 decay.

The science goals of Mars 2020 as described in the MEPAG report (Mustard et al. 2013) are split in four high level objectives: (i) to explore ancient environments of Mars to decipher the geological history of the planet; (ii) to evaluate the potential for eventual biosignatures in selected geological context; (iii) to collect relevant samples of Martian soil and atmosphere to be sent to Earth by future missions; and (iv) to prepare for future human exploration of the planet.

To fulfill these goals, the 59 kg scientific payload comprises seven instruments.

Mastcam Z (Bell et al. 2021) is a set of two cameras, focusable and zoomable to provide multispectral, stereo, and panoramic images of the environment. They are mounted on the remote sensing mast, at around 2 m above the Martian surface. Through a set of filters on wheels it produces broad band red/green/blue and narrowband 400–1000 nm images. The instrument lead is from the Arizona State University.

SuperCam (Maurice et al. 2021) based on the heritage of the ChemCam instrument is a suite of five techniques to analyze rocks and soil. The observation are performed through Laser-Induced Breakdown Spectroscopy (LIBS), Time-Resolved Raman and Luminescence (TRR/L), both sharing the same laser lamp, visible, and near-infrared spectroscopy (VISIR), high-resolution color imaging (RMI), and acoustic recording (MIC). The instruments operate at remote distances, primarily 2–7 m for LIBS, TRR/L, and up to the infinite for VISIR and RMI, while providing data and images at sub-mm to mm scales. SuperCam is mounted on the top of the remote sensing mast. This instrument is provided by a consortium led by Los Alamos National Laboratory (USA) with “Institut de Recherche en Astronomie et Planétologie” (France) and University of Valladolid (Spain).

Radar Imager for Mars Subsurface Exploration (RIMFAX), (Hamran et al. 2020) is a Ground Penetrating Radar to image subsurface structure, and to provide information regarding subsurface composition. The instrument is a Frequency Modulated Continuous Wave (FMCW) radar, which transmits a signal swept through a range of frequencies between 150 and 1200 MHz. The full bandwidth (effective center frequency 675 MHz) is used for shallow imaging down to several meters. Imaging deeper structures uses a reduced bandwidth of the lower frequencies, centered on the frequency 375 MHz. The instrument is built under the direction of the University of Oslo (Norway).

Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC), (Barthia et al. 2021) is a Raman spectrometer and a camera mounted on the robotic arm. The Spectrometer produces spatially resolved chemical maps using fluorescence and Raman spectroscopy coupled to microscopic images (10.1 $\mu\text{m}/\text{pixel}$). The camera (WATSON) obtains color images from microscopic scales (13 $\mu\text{m}/\text{pixel}$) to infinity. SHERLOC Spectroscopy is based on a pulsed deep UV neon-copper laser (248.6 nm), giving a 100 μm spot on a target at a working distance of 48 mm. Fluorescence emissions from organics, and Raman scattered photons from organics and minerals, are analyzed with a single diffractive grating spectrograph with a spectral range of 250 to 370 nm. Because the fluorescence and Raman regions are naturally separated the Raman region 250 to 273 nm and the fluorescence region 274 to 370 nm are acquired simultaneously. The instrument is provided by the Jet Propulsion Laboratory (USA).

Planetary Instrument for X-Ray Lithochemistry (PIXL) (Allwood et al. 2020) is a microfocus X-ray spectrometer placed on the robotic arm. It provides within seconds the composition in major and minor rock-forming elements as well as some trace elements. The diameter of the X-ray beam is 120 μm . On several hours, the instrument can collect several thousand points of measurement, providing an elemental

map of a rock surface, correlated to the image acquired by the PIXL camera. The instrument is provided by the Jet Propulsion Laboratory.

Mars Environmental Dynamics Analyzer (MEDA) (Rodriguez-Manfredi 2021) is a set of meteorological sensors. Placed on the mast of the rover, it comprises a wind sensor, a barometer, a relative humidity sensor, and a set of five thermocouples to measure atmospheric temperature at about 1.5 m and 0.5 m above the surface. Some thermopiles characterize the thermal IR brightness temperatures of the surface and of the lower atmosphere. MEDA monitors also the optical atmospheric properties to determine bulk aerosol physical parameters. The instrument is provided by Centro de Astrobiologia, (Spain).

Mars Oxygen ISRU Experiment (MOXIE) (Hecht et al. 2021) verifies that it is possible to produce molecular oxygen dissociating atmospheric carbon dioxide. This technological demonstrator is based on solid oxide electrolysis of heated CO₂. The anode is producing almost pure oxygen while the cathode is concentrating the carbon monoxide (by-product of the method) and other atmospheric gases. The production could deliver up to 6 g/h of 98% pure molecular oxygen. The instrument is provided by the Massachusetts Institute of Technology (USA).

Finally the rover is equipped with a complex and sophisticated sampling and caching system (Moeller et al. 2021) to take samples, to preserve, and to store them in dedicated sample tubes and finally deliver them on the ground, at the appropriate time and location, to be retrieved by a future European Fetch Rover. Perseverance is the actual first leg of the International → Mars sample return program.

Because it is landing on Mars, searching for biosignatures and preparing a restricted sample Earth return, the rover and its payload have to follow stringent rules to be in agreement with the → Planetary Protection Policy addicted by COSPAR and adopted by the USA.

In addition, perseverance is carrying a small helicopter, →Ingenuity to demonstrate the possibility to fly in the tenuous atmosphere of Mars and explore how this kind of device can help either for the robotic or future manned exploration of the red planet.

Cross-References

- Curiosity
- Ingenuity
- Mars 2020
- Mars
- Planetary Protection

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Petrifaction

► [Fossils \(from Antiquity to the Eighteenth Century\)](#)

PFS

► [Venus Express](#)

pH

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[Hydrogen ion concentration index](#)

Definition

pH describes the activity of hydronium ions (H_3O^+ , or more precisely the hydrated form of the proton H^+ in solution) in aqueous solution. pH characterizes the acidity or basicity of aqueous solutions. It is formally defined by the relation:

$$\text{pH} = -\log_{10} a_{\text{H}}$$

in which a_{H} is the activity of the solvated hydronium ion. The pH of an acidic solution is less than 7, and the pH of basic solution is greater than 7 at 25 °C, but pH values change as a function of temperature.

Cross-References

► [Hydrogen](#)

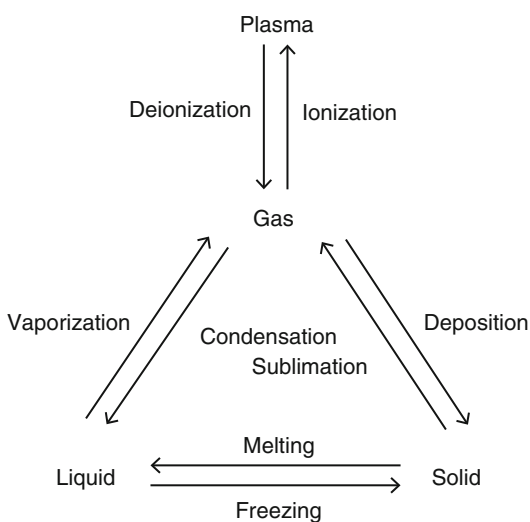
Phase Transition

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Matter in the universe generally exists in one of four phases (states in which matter has essentially uniform physical properties): plasma, gas, liquid, and solid. The transition between each phase has an associated name (Fig. 1). Transitions can also occur within the solid phase.

The transition of matter between phases may be exergonic or endergonic. The change in energy is due to the change in interactions and ordering of the atoms or molecules and the associated changes of entropy and/or enthalpy (e.g., upon the freezing



Phase Transition, Fig. 1 The four phases of matter and the transitions between them

of a liquid phase, in which the components are highly mobile (with higher entropy), to a solid phase in which the components are in relatively fixed positions (with lower entropy)).

When a phase change occurs at a constant temperature, the energy required to cause the phase change (in the case where such a change is not spontaneous or energetically favorable), or the energy liberated (in the case where a phase change is spontaneous) is referred to as the latent heat. The value of this quantity is specific to the type of material in question (i.e., the latent heat of water is different than the latent heat of lead).

Cross-References

- [Endergonic](#)
- [Enthalpy](#)
- [Entropy](#)
- [Exergonic](#)
- [Free Energy](#)
- [Latent Heat](#)
- [Triple Point](#)
- [Water](#)
- [Water in the Solar System](#)
- [Water in the Universe](#)
- [Water, Solvent of Life](#)

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Phase, Orbital

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Definition

For an object in a periodic orbit, the phase is the fraction of period that has passed since the time

$t = 0$. Mathematically, the location of $t = 0$ can be any arbitrary point on an orbit; however, in Keplerian orbits, the point of ► [periastron](#) is considered as the location of $t = 0$. Usually, the phase is measured from the most recent periastron passage, but sometimes the phase will include an integer count for the number of orbital cycles since a fiducial periastron passage. For a circular orbit, the usual convention is to define phase zero as the time of maximum radial velocity of recession for the more massive component.

Cross-References

- [Periastron](#)

Phenetics

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[Numerical taxonomy](#)

Definition

Taxonomical analysis aimed at classifying organisms with respect to their ► [phenotype](#). It considers the overall similarities in observable/measurable characters – such as morphology or metabolic traits – among organisms or biological taxa regardless of their phylogenetic or evolutionary relationships. Phenetic techniques include various forms of clustering. They measure a – usually large – number of variables, analyze them by mathematical and statistical means to reduce them to a manageable level, and generally produce two- or three-dimensional graphs where different clusters of phenotypes are located.

Cross-References

- [Phenotype](#)
- [Phylogeny](#)
- [Taxonomy](#)

Phenotype

Susanna Manrubia

Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Keywords

Adaptation · Environment · Genotype · Morphology · Natural selection · Survival

Definition

The phenotype of an organism is the collection of all its observable characteristics, such as morphological traits, physiology, or behavioral properties. The phenotype arises from the interaction of the total genetic inheritance of each organism with the ► [environment](#) where it develops and grows, and might change during its life due to aging processes or environmental changes. In its turn, the phenotype determines how suited an organism is to survive and reproduce in a given environment. In the case of a virus, the phenotype refers mainly to the effects it causes in the infected host. The phenotype of a molecule consists of its structure and chemical function.

Overview

The relationship between ► [genotype](#) and phenotype is essential to understand how biological evolution proceeds. The distinction between the hereditary and developmental pathways as causally separated processes dates back to 1911 (Johannsen 1911): the genome is inherited,

while the phenotype is its final expression under the environmental conditions specific to an organism. While innovations in biological evolution result from unintentional changes (► [mutations](#)) at the genomic level, ► [natural selection](#) can only act on the phenotype. Therefore, phenotypic variation is a prerequisite for evolution by natural selection.

The genotype-phenotype map is a many-to-many relationship, and as such it is only partly deterministic. One genotype might produce different phenotypes, since not all inherited possibilities are expressed. Plants growing in different watering conditions, for instance, are able to adjust their size and the shape of their leaves. Another example is that of certain proteins – fully functional in their native folded state – that become infectious agents (► [prions](#)) when mis-folded. Even identical human twins differ in their fingerprints, and behave distinctly as a result of nurture. The environment-dependent expression of genotype (a one-to-many relationship) is called phenotypic plasticity (De Witt and Scheiner 2004). On the other hand, the construction of an organism from genotype to phenotype displays a great amount of redundancy (a many-to-one relationship). Redundancy is an essential property conferring robustness when organisms face endogenous or exogenous change, fluctuations, or randomness. The neutral theory of molecular evolution (Kimura 1983) analyzes the important role of a huge number of mutations present in the genotype that do not have an effect on phenotype (beyond changing the genomic sequence) but strongly affect the population structure and its intrinsic diversity, and thus its ability to adapt to new environments. The extent to which changes in genotype do not affect phenotype is called genetic canalization (Rendel 1967; Jen 2005).

The concept of extended phenotype (Dawkins 1982) refers to all the effects a gene can have upon the world which influence its chances of ► [survival](#), thus extending beyond the genome-carrying individual organism. Examples are dams constructed by beavers, the elaborately woven nests of weaver birds, or the behavior a parasite can induce upon an infected host.

Cross-References

- [Adaptation](#)
- [Environment](#)
- [Evolution, Biological](#)
- [Evolution, In Vitro](#)
- [Genotype](#)
- [Mutation](#)
- [Natural Selection](#)
- [Prion](#)
- [Selection](#)
- [Species](#)
- [Survival](#)

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Phenyl Cyanide

- [Benzonitrile \(C₆H₅CN\)](#)

Phenylalanine

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Phenylalanine is one of the 20 protein ► [amino acids](#) whose chemical structure is NH₂—CH

(CH₂C₆H₅)—COOH. Its three-letter symbol is Phe, and one-letter symbol is F. Its molecular weight of 165.19, and its isoelectric point (pI) is 5.48. It shows poorer water solubility than most of the other amino acids. Since its side chain is a benzyl group (—CH₂C₆H₅), it is grouped as an aromatic amino acid together with tyrosine and tryptophan. ► [Proteins](#) present a UV absorbance at 280 nm because of the UV-absorbing aromatic rings present in these amino acids. Phenylalanine has recently been detected in extracts from Antarctic carbonaceous chondrites.

Cross-References

- [Amino Acid](#)
- [Protein](#)

Philae Lander

Hervé Cottin
Univ Paris Est Creteil and Université de Paris, CNRS, LISA, Créteil, France

Keywords

Lander · Rosetta · Comet · 67P/Churyumov-Gerasimenko

Definition

Philae is the lander of the ESA Rosetta mission, which landed and bounced on the nucleus of comet 67P/Churyumov-Gerasimenko on November 12, 2014.

Overview

Philae is the first automated vehicle that landed on the nucleus of a comet. It is part of the European mission ROSETTA. Its overall mass is 98 kg including a scientific payload of 27 kg.

The name of the lander follows the name of a Nile island where an obelisk was found, whose association with the Rosetta stone helped Champollion to understand the meaning of hieroglyphs.

On November 12, 2014, the Philae lander was released from its mother spacecraft at a distance of about 3 AU from the Sun and 20 km from the surface of comet 67P/Churyumov-Gerasimenko to land after 7 h of free fall. The landing site (called Agilkia) was a relatively smooth terrain on the smaller lobe of comet 67P. Contact with the nucleus was reported at 15:34 UTC. However, it turned out that the lander did not anchor at the surface and bounced twice on the comet before making it to its final landing site after 2 h hovering above the nucleus in its low gravity environment. There, not sufficiently illuminated by the Sun, it could rely only on its primary battery to achieve its first science measurements sequence. After 64 h of operations at the comet's surface, Philae went into safe mode due to lack of power. For a while, hopes remained that it could wake up again and proceed to new measurements when the comet is closer to the Sun, with a better orientation to provide sufficient energy to the solar panels of Philae. Some very limited communication could indeed be established from June 13 to July 9, 2015, showing that the lander had sufficient illumination to reboot out of the safe mode. However, the communication was too sporadic to allow any operation of the lander for science. Later, no communication could be established, and the reason for the poor transmission quality between the spacecraft and the lander is still unclear. Finally, close to the end of the Rosetta mission, a picture of Philae was taken from the Rosetta spacecraft on September 2, 2016. It showed Philae on its side, underneath a cliff. Its final site has been called Abydos.

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Comet](#)
- [Comet \(Nucleus\)](#)
- [Rosetta Spacecraft](#)

Phobos

Harald Hoffmann

DLR, Institute of Planetary Research, Berlin, Germany

Definition

Phobos is the inner of the two Martian satellites that were discovered by Asaph Hall in 1877. It is in nearly circular synchronous (Phobos's; length of day and orbital period are identical) orbit around ► [Mars](#) with an average distance of 9375 km to the center of the ► [planet](#) and an orbital period of 0.32 days (Jacobson 2010). Phobos measures $26.8 \times 22.4 \times 18.4$ km; it has a bulk density of about 1.9 g/cm^3 . The heavily cratered surface indicates an old formation age. Two hypotheses are actually discussed to explain the origin of Phobos: capture of a D-type ► [Asteroid](#) or reaccrction of Martian ejecta.

Cross-References

- [Asteroid](#)
- [Deimos](#)
- [Mars](#)
- [Phobos-Grunt](#)
- [Planet](#)
- [Satellite or Moon](#)

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Phobos Soil

- [Phobos-Grunt](#)

Phobos-Grunt

Michel Cabane

LATMOS/IPSL B102/T45-46, Université Pierre et Marie Curie UPMC-Paris 6, Paris, France

Keywords

Asteroid · Carbonaceous chondrite · In situ · Mars · Mars Express · Phobos · Satellite

Synonyms

Phobos soil

Definition

Phobos-Grunt is a mission to ► [Phobos](#), one of the two small satellites of ► [Mars](#); it was developed by the Russian agency ► [Roskosmos](#), with the participation of other countries to the science payload. Launch occurred in Baikonur, on November 8, 2011, for an arrival end-2012, and a landing on Phobos mid-2013; the payload consisted in Phobos-Grunt and ► [YingHuo-1](#), a Chinese satellite, intended to study Mars and Phobos. One of the goals of Phobos-Grunt was to proceed to in situ soil analyses, to help understand the composition of Phobos (structure, mineralogy, organic matter), hence its origin. About 200 g of soil samples should have been sent from Phobos to Earth, for a landing in 2014. Unfortunately, due to some concerns in the cruise stage, the probe was unable to leave its elliptical orbit around the Earth, and to begin its cruise to Mars and Phobos. After orbiting for 2 months, it disintegrated while entering Earth dense layers of the atmosphere, and the debris fell in Pacific Ocean. The idea of a return to Phobos exists, this reflight should mainly utilize spare models of the experiments that were on the previous probe.

Overview

Due to its low ► [albedo](#) and spectral characteristics (Murchie and Erard 1996; Simonelli et al.

1997), Phobos could be identified as a captured ► [asteroid](#), with a composition close to the organic-bearing carbonaceous chondrites (Rivkin et al. 2002); nevertheless, its low apparent density (1.9 g/cm^3) (Avanesov et al. 1991) leads to think that it could contain water ice (Christensen et al. 1977) or have a “rubble pile” structure (Murchie and Erard 1996). This possible porosity (25–35%) could also be explained by an origin at the moment of Mars’ formation, or as the result of an asteroidal impact on Mars. Phobos’s surface is covered by impact craters: near the rim of the huge crater Stickney, for example, “blue” material indicates material that possibly originates at depth (Fig. 1).

Twenty years after the USSR’s Phobos 1 and 2 missions, Roskosmos developed Phobos-Grunt (P-G), to be launched in 2011 (Zelenyi et al. 2010). It will carry the Chinese satellite Yinghuo-1, devoted to Mars study, and it will land on Phobos in April 2013 (Figs. 2 and 3).

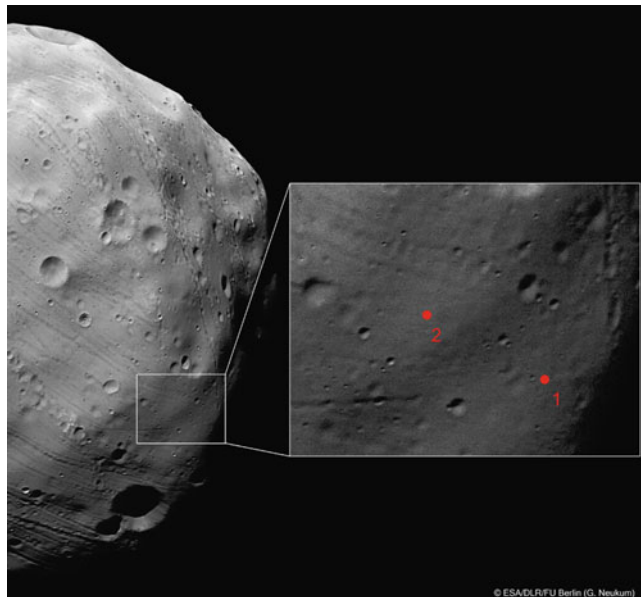
The in situ science payload of the P-G lander (Zelenyi et al. 2010) resembles those of MSL and ► [Exomars](#). Its 40 kg includes, among others, cameras, radar, and seismometer to understand Phobos structure, and classical in situ instruments searching for elementary and mineralogical composition (Mossbauer, APX, IR, γ and n spectrometers, laser ablation mass spectrometer). The Gas Analytical Package will proceed to analyze soil samples, delivered by the P-G manipulator arm, possibly using a drill. Heating and pyrolysis of these samples, followed by analysis of evolved gases (► [GC-MS](#) and IR laser spectroscopy), will detect the presence of any water ice (Christensen et al. 1977) and the structural gases of the minerals (H_2O , CO_2 , etc.). Using the same techniques, this instrument will be able to search for ► [noble gases](#), ► [organic molecules](#) (nature, ► [isotopic ratios](#)) present in the ground, to be compared to the ones present in ► [meteorites](#) (Rivkin et al. 2002), to give clues on the origin and history of Phobos. Once landed, P-G will also sample the ground and bring to Earth (arrival July 2014; Galimov 2010) about 200 g of material, in a devoted container (see Fig. 3: small brown sphere on top of P-G) for further analyses.

Phobos-Grunt,

Fig. 1 Crater Stickney, at right, as observed from 5800 km by NASA probe Mars Reconnaissance Orbiter (March 2008; resolution: 5.8 m/pixel). (Credit: NASA/JPL/University of Arizona <http://hirise.lpl.arizona.edu/phobos.php>)

**Phobos-Grunt,**

Fig. 2 Possible landing sites for Phobos-Grunt, as observed by ESA probe Mars Express (March 2010; resolution 4.4 m/pixel). (Credit ESA/DLR/FU Berlin – G. Neukum http://www.esa.int/images/5_h7915_Phobos_LandingSites_H.jpg)



P

The experiment Living Interplanetary Flight Experiment (LIFE) proposed by a US nonprofit association (the Planetary Society) will sit in the Phobos sample return capsule. Two titanium containers specially designed by the Russian Institute for Medico-Biological Problems will house terrestrial organisms (like seeds) and microorganisms. Pure culture of known resistant microorganisms strains from the three

domains of life (Archaea, Bacteria, and Eukarya) will sit along a sample of a terrestrial natural soil. All this samples will be tested for survival upon their recovery with the Phobos samples and subsequently analyzed. The containers will mimic rock and this will be an attempt to evaluate the possibility of panspermia while those organisms will experience a 34-month round trip to Mars.

Phobos-Grunt,

Fig. 3 Mock-up (scale 1/1) of Phobos-Grunt lander (Moscow, November 2006). (Credit: CNES photo <http://smc.cnes.fr/PHOBOS/Fr/>)

**Cross-References**

- [Albedo](#)
- [Asteroid](#)
- [Carbonaceous Chondrite](#)
- [ExoMars](#)
- [GC/MS](#)
- [Mars Express](#)
- [Mars Science Laboratory](#)
- [Panspermia](#)
- [Phobos](#)

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Phoebe

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Saturn's satellite Phoebe was discovered in 1899 by William Henry Pickering; it has been for a century the outermost known satellite of ► [Saturn](#). It orbits at about 13 million kilometers (or 215 Saturnian radii) from Saturn; its orbit is highly inclined and is retrograde, which suggests that Phoebe was captured, rather than having been formed together with Saturn. It may have

originated as a Kuiper Belt Object. Phoebe was first observed by Voyager 2 in 1981 and then extensively explored by the ► [Cassini](#) orbiter. Its diameter is 220 km and its density is 1.6 g/cm³. Phoebe might be the source of a tenuous external Saturnian ring, and might also be responsible for feeding the dark side of ► [Iapetus](#) with dark material.

Cross-References

- [Iapetus](#)
- [Kuiper Belt](#)
- [Saturn](#)
- [Voyager, Spacecraft](#)

Phoenix

Michel Viso
Innovaxiom, Paris, CX, France

Definition

Phoenix was launched for its cruise to Mars from Cape Canaveral by a Delta II rocket on August 4, 2007. The soft landing in the north polar region occurred on May 25, 2008. The five science instruments, provided by US institutions with contributions from the Max Plank Institute (Germany) and the Canadian Space Agency (Canada), examined water ice under the surface, checking if this place could support life. A meteorological station provided data on the atmosphere and the water cycle. After 5 months of operation, the power declined as the illumination by the sun decreased. The last brief signal was received on November 2, 2008. In early 2010, attempts to communicate with Phoenix failed. The hardware was not designed to survive the cold and ice-coating load of an arctic Martian winter. One of the main results is the hypothesis of the presence of carbonate and perchlorate as well as the evidence of subsurface ► [ice](#).

Phosphaethyne (HCP)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[HCP](#); [Methinophosphide](#)

Definition

Phosphaethyne is, with PN, PH₃, and the radical CP, one of the few molecules detected outside the Earth that contain phosphorus, an element that plays a crucial role in biochemistry (being part of the structural framework of DNA and RNA and being used to transport cellular energy). HCP is similar in many ways to hydrogen cyanide, HCN, as phosphorus is below nitrogen in the Periodic Table. In the laboratory, phosphaethyne is a reactive species that spontaneously and rapidly polymerizes.

History

Phosphaethyne has been detected by Agúndez et al. (2007) in the carbon-rich circumstellar envelope of the evolved star IRC +10216 (CW Leo).

Cross-References

- [Molecules in Space](#)
- [Phosphorus Monoxide \(PO\)](#)

References and Further Reading

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Phosphates

Francis Albarède

Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

Phosphates are minerals containing the tetrahedral PO_4^{3-} group, the most abundant of which is apatite $\text{Ca}_{10}(\text{PO}_4)_6(\text{X})_2$, where X is OH, F, Cl, or CO_3 . Apatite is the main repository of phosphate in the Earth's mantle and the crust, and is used by both vertebrates and invertebrates to build solid parts (skeletons). In natural waters, the phosphate anion is an essential nutrient entering nucleic acids, phospholipids, and the universal energy currency adenosine triphosphate (ATP). Surface waters are depleted in phosphate by organic productivity. At depth, phosphate strongly correlates with nitrate and the remarkably constant C:N:P proportions of phytoplankton (105:15:1) are known as the Redfield ratio. ► [Mid-ocean ridges](#) and sediments are net P sinks, whereas continents are the dominant source of oceanic phosphate.

Cross-References

- [Mid-Ocean Ridge](#)
- [Nucleic Acids](#)
- [Phosphates on Mars](#)

Phosphates on Mars

Daniela Tirsch¹ and Alessandro Airo²

¹German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

²Fachbereich Geowissenschaften, Institut für Geologische Wissenschaften Tektonik und Sedimentäre Geologie, Freie Universität Berlin, Berlin, Germany

Definition

Phosphates are the salts and esters of phosphoric acid (H_3PO_4). Since phosphate is a essential

nutrient for life on Earth and part of the backbone of DNA, its occurrence is important for estimating the ► [habitability on Mars](#). Phosphates can be derived from minerals (e.g., apatite $\text{Ca}_5[(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})]$) through the weathering of igneous rocks. Calcium-phosphate minerals have a high solubility in acidic water. Measurements done by the Mars Pathfinder Rover and the Mars Exploration Rover indicate that the Martian soil is enriched in phosphorus relative to the rock.

Cross-References

- [Habitability of the Solar System](#)
- [Mars](#)
- [Mineral](#)
- [Sulfates, Extraterrestrial](#)

Phosphine

Matthew A. Pasek

University of South Florida, Tampa, FL, USA

Synonyms

[Hydrogen phosphide](#); [Phosphorus hydride](#)

Definition

Phosphine, PH_3 , is a toxic, phosphorus gas at standard temperature and pressure, boiling at 185 K and freezing below 135 K. Relative to phosphate, the redox state of the phosphorus atom in phosphine is reduced to -3 . Phosphine is the most abundant, naturally occurring volatile phosphorus species, and has been detected in the atmospheres of the gas giants Jupiter and Saturn, in the atmospheric envelopes of giant stars, and as a trace constituent in the atmosphere of the Earth. Its terrestrial origin may be linked to microbial activity or to anthropogenic sources; hence, phosphine plays a small role in the phosphorus biogeochemical cycle. At low

temperatures (below 70–80 K), it can be trapped as a clathrate in water ice.

Phosphite

Matthew A. Pasek
University of South Florida, Tampa,
FL, USA

Synonyms

[H-phosphonate](#); [Phosphonate](#)

Definition

Phosphite (HPO_3^{2-}) is the anion of phosphorous acid (H_3PO_3), an oxide of phosphorus in which the phosphorus has a +3 valence state. In contrast to orthophosphate dissolved in solution, in phosphite one hydrogen atom is directly bound to the central P atom, instead of being bound through an O atom. Phosphite is more soluble in ocean water than phosphate. Oxidation of phosphite yields phosphate and, under certain conditions, also pyrophosphate and larger polyphosphates. Phosphite on the Earth may have originated from corrosion of iron-rich meteorites or from reduction of phosphate by lightning strikes or other high-energy events, and may have comprised some portion of the total phosphorus in the early Archean oceans.

Cross-References

- ▶ [Phosphates](#)
- ▶ [Phosphoric Acid](#)
- ▶ [Pyrophosphate](#)

Phosphonate

- ▶ [Phosphite](#)

Phosphoric Acid

Matthew A. Pasek
University of South Florida, Tampa,
FL, USA

Synonyms

[Orthophosphate](#)

Definition

Phosphoric acid is a triprotic acid with a formula of H_3PO_4 . Its pK_a s are about 2, 7, and 12.5 at 25 C. Heating of phosphoric acid results in dehydration leading to pyrophosphoric acid and larger polyphosphoric acid polymers.

Cross-References

- ▶ [Diphosphate](#)
- ▶ [Phosphine](#)
- ▶ [Phosphite](#)

Phosphorus Chemistry

Víctor M. Rivilla
Centro de Astrobiología (CSIC/INTA), Madrid,
Spain
Osservatorio Astrofisico di Arcetri, INAF,
Florence, Italy

Keywords

Phosphorus · Star formation · Comets ·
Prebiotic chemistry

Definition

Phosphorus (P) is a key element for the development of life. However, its low cosmic abundance compared to the other biogenic elements (carbon,

oxygen, nitrogen, and sulfur) has significantly limited our knowledge about its chemistry in the interstellar medium. Thanks to recent advances in the instrumentation of ground-based radiotelescopes and spatial missions, we have attained a much better understanding about the formation of P-bearing molecules in star-forming regions and Solar System objects. The study the inheritance of the reservoir of P during the process of star and planet formation is essential to understand how P became prebiotically available at the dawn of our planet, allowing the origin of life.

Overview

Phosphorus (hereafter P) is a key biogenic element for the development of life. This is because compounds containing P, and in particular phosphates, are unique in forming large biomolecules, thanks to their extreme structural stability and functional reactivity. Phosphorus is one of the crucial components of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), phospholipids (the structural components of cellular membranes), and the adenosine triphosphate (ATP) molecule, which stores the chemical energy within cells. Moreover, P-compounds are also key catalysts and chemical buffers for the formation of nucleotides (Powner et al. 2009). However, while the P abundance in living organisms is relatively high, e.g., $P/H \sim 10^{-3}$ in bacteria, (Fagerbakke et al. 1996), the abundance of P in the Universe is several orders of magnitude lower: $P/H \sim 3 \times 10^{-7}$ (Asplund et al. 2009). This makes P one of the major limiting nutrients for the development of life, and raises the question of how the reservoir of P can become biologically available on planets, and in particular how became on the early Earth. To answer these questions, multiple efforts in the last years have tried to understand the chemistry of P in the molecular cradles of stars and planets, and also in comets, which are considered to be representative of the pristine Solar System material, and might have delivered key

prebiotic chemicals to the primitive Earth (Chyba and Sagan 1992).

P is generated in the interior of massive stars and it is injected into the interstellar medium (ISM) through supernova explosions (Koo et al. 2013). The low number of these stars helps to explain the relatively low cosmic abundance of P relative to other biogenic elements. Moreover, since P is a relatively heavy element (atomic mass of 31 Da), it is expected to be depleted on the surfaces of interstellar dust grains in the dense and cold ISM (Turner et al. 1990). Thus, the detection of P-bearing species in the gas phase of the ISM is challenging. Historically, this has limited the number of P-bearing molecules identified in space. However, in the recent years, thanks to the improvement of sensitivity of current ground-based telescopes and space spacecrafts, a plethora of new detections of P-bearing species has been possible, allowing us to significantly improve our understanding about the chemistry of interstellar and cometary P.

Basic Methodology

The search of P-bearing species in different astronomical sources of the ISM can be done using rotational spectroscopy, mainly at (sub)millimeter wavelengths, using single-dish radiotelescopes such as the IRAM 30 m telescope or the Atacama Pathfinder Experiment (APEX), and interferometric arrays such as the Atacama Large Millimeter/submillimeter Array (ALMA), and the Northern Extended Millimeter Array (NOEMA). The analysis of the observed spectra, which can be done assuming Local Thermodynamic Equilibrium (LTE) or non-LTE **conditions**, provides the molecular abundances of the P-bearing species, and also their excitation conditions.

In the case of comets, although molecular studies using rotational spectroscopy from ground-based radiotelescopes are also possible, the in-situ mass spectroscopy obtained by the European Space Agency (ESA) mission Rosetta have provided unprecedented details

about the molecular reservoir of the comet 67P/Churyumov-Gerasimenko.

The outcome of the observations (see details in the section below) has been compared with newly developed theoretical chemical models (e.g., Rivilla et al. 2016; Jiménez-Serra et al. 2018), with the goal of understanding how P-bearing molecules are formed in the natal environment of stars and planets, and how they might be transferred to planetary system objects like comets and our own Earth.

Key Research Findings

While the ion P^+ was early discovered in several diffuse clouds (Jura and York 1978), no P-bearing species have been detected so far towards these regions despite deep observational searches (Chantzios et al. 2020). In the circumstellar envelopes of evolved stars, several P-bearing species have been identified (PN, PO, CP, HCP, C_2P , and PH_3 ; e.g., Guelin et al. 1990; Agúndez et al. 2007; Tenenbaum et al. 2007; Halfen et al. 2008; Agúndez et al. 2014). However, detections in star-forming regions have been more elusive, with only two species detected so far. PN was identified towards a handful of sources in the late 1980s (Turner and Bally 1987), and more recently towards large samples of massive star-forming regions (Fontani et al. 2016; Fontani et al. 2019), and molecular clouds in the center of our Galaxy (Rivilla et al. 2018), and also towards the birth environment of Solar-like protostars (Lefloch et al. 2016; Bergner et al. 2019). After several unsuccessful efforts (e.g., Fontani et al. 2016), PO was detected towards both massive (Rivilla et al. 2016; Bernal et al. 2021) and low-mass star-forming regions (Lefloch et al. 2016; Bergner et al. 2019), and towards a molecular cloud in the Galactic Center (Rivilla et al. 2018). These detections, based on single-dish observations, showed that P is less depleted on the dust grains of star-forming regions than previously thought, with a depletion factor around 100. Both P-bearing species have very low excitation

temperatures ($T_{\text{ex}} < 20$ K; Rivilla et al. 2018; Fontani et al. 2019; Bergner et al. 2019), which indicates that they are sub-thermally excited. The non-LTE effects on the derived molecular column densities have been considered using available collisional coefficients, and no significant deviations with respect to the LTE analyses have been found (Bergner et al. 2019; Rivilla et al. 2020). Remarkably, PO is more abundant than PN in all the astronomical sources where both species have been detected so far, within a factor ~ 2 –8. Several works have found that the spectral profile of PN is similar to that of a typical shock-tracer such as SiO (Lefloch et al. 2016; Fontani et al. 2019), which suggests that shocks are an important agent on the interstellar chemistry of P, as suggested by Aota and Aikawa (2012). This idea was also supported by the results from a survey of molecular clouds in the center of the Galaxy, in which PN was only detected in those clouds whose chemistry is dominated by shocks (Rivilla et al. 2018). This work also found a clear correlation between the column density of PN and that of SiO, result that has been confirmed by additional observations towards a large sample of massive star-forming region in the galactic disk (Fontani et al. 2019). The first interferometric maps of the emission of P-bearing molecules in a star-forming region (Rivilla et al. 2020) have shown that PN and PO arises from several spots associated with post-shocked low-velocity gas in the cavity walls of a protostellar bipolar outflow, rather than from high-velocity and directly shocked gas in the outflow. As already indicated by previous single-dish observations, PO is more abundant than PN, with an increasing trend of the PO/PN ratio with the distance to the protostar. These observations favor a formation scenario in which the formation and PO/PN are governed not only by shocks, as previously proposed, but also by UV radiation from the protostar. While shocks are needed to sputter P from the surface of dust grains, photochemistry in the gas phase induced by UV photons efficiently forms PO and PN in the illuminated cavity walls, in agreement with the chemical models by Jiménez-Serra et al. (2018).

Regarding the detection of P-bearing molecules in our Solar System, phosphine (PH_3) has been observed in the atmospheres of Jupiter and Saturn (Bregman et al. 1975; Ridgway et al. 1976). P has been identified in meteoritic material in the form of the mineral schreibersite (Pasek and Lauretta 2005) and phosphoric acids (Schwartz 2006). More recently, the measurements of the ESA Rosetta mission claimed the presence of P in the comet 67P/Churyumov–Gerasimenko (Altwegg et al. 2016), which is predominantly in the form of PO (Rivilla et al. 2020). The P/O ratio derived in 67P is $(0.5\text{--}2.7) \times 10^{-4}$, close to the Solar value of 5.8×10^{-4} , which indicates that P is only slightly depleted in the cometary material. As found in star-forming regions, PO is more abundant than PN, by at least a factor of 10. Since it is thought that the chemical composition of the 67P comet is presolar, PO, among other volatiles, was already in the cometary ices prior to the birth of the Sun. Therefore, the cometary chemical budget was inherited from the natal environment of the Solar System, which is thought to be a clustered environment that likely also included massive stars (Adams et al. 2010). The predominance of PO as main carrier of P both in both star-forming regions and Solar-like objects such as the comet 67P, confirms this chemical thread during the whole process of star formation.

Since comets may have delivered a significant amount of prebiotic material to the early Earth (Chyba and Sagan 1992), the P reservoir measured in 67P (mainly in the form of PO), along with those in other comets, could have contributed to the prebiotically available P reservoir during the dawn of our planet. This can help to solve the known as the “phosphate problem” about the availability of inorganic phosphate on the early Earth. The most common form of P on our planet is mainly found in apatite minerals, which have high insolubility, and whose P was not available for prebiotic processes. To solve this scarcity of prebiotic P, alternative (extraterrestrial) sources of P have been proposed: cometary material (Rivilla et al. 2020), and also the water-soluble schreibersite, $(\text{Fe,Ni})_3\text{P}$, the major carrier of P in iron meteorites (Pasek 2008). Moreover, recent theoretical works have also explored the possible

injection of meteoritic P in rocky planets, including our Earth (Douglas et al. 2019).

Future Directions

The detection of new P-bearing species in the gas of star- and planet-forming regions (e.g., PH_3 , CP, PS) will significantly help us to constrain much better the chemistry of this key biogenic element in the ISM. Since P is cosmically low-abundant, these detections will surely require very deep observations of the current, and likely, the next generation of radiotelescopes. Moreover, more detections of PO towards a large sample of sources will help us to evaluate if the ratio $\text{PO/PN} > 1$ found in a handful of regions is ubiquitous in the Universe. As well, the study of the spatial distribution of the emission of P-bearing species with interferometers (e.g., ALMA) towards more sources will allow us to attain a much better knowledge about the possible physical mechanisms (e.g., shocks, photochemistry) that are responsible of the formation and destruction of P-bearing species in the ISM. In this regard, the further development of the few theoretical chemical models devoted to P will be absolutely needed. New plausible chemical routes should be explored, and their associated reaction rates should be derived theoretically and/or measured directly in the laboratory. Moreover, the study of spectroscopy of new P-bearing species might also allow its future detections in the ISM, completing our picture of the interstellar chemistry of P.

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Abundances](#)
- [Abundances of Elements](#)
- [ALMA](#)
- [ATP](#)
- [Circumstellar Chemistry](#)
- [Dense Cloud](#)
- [Diffuse Cloud](#)
- [Hot Core](#)

- [Hot Corino](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Phosphates](#)
- [Phosphine](#)
- [Phosphorus Monoxide \(PO\)](#)
- [Pyrophosphate](#)
- [Radio Astronomy](#)
- [Silicon Monoxide \(SiO\)](#)
- [Spectral Line](#)
- [Spectroscopy](#)
- [Star Formation, Theory](#)

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Phosphorus Hydride

- [Phosphine](#)

Phosphorus Monoxide (PO)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[PO](#)

Definition

Phosphorus monoxide is an unusual oxidized form of phosphorus, recently detected in the envelope expelled by an evolved star (the most common phosphorus oxides on Earth are P_4O_6 and P_4O_{10}). PO is, with HCP, PN, PH_3 , and CP, one of the few molecular species outside the Earth containing phosphorus, an element that plays a central role in biochemistry. The P—O bond is present in adenosine diphosphate (ADP) and adenosine triphosphate ([▶ ATP](#)).

History

Tenenbaum et al. (2007) detected phosphorus monoxide in the circumstellar shell of the oxygen-rich supergiant star VY Canis Majoris.

Cross-References

- ▶ [ATP](#)
- ▶ [Molecules in Space](#)

References and Further Reading

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Photoattachment

- ▶ [Radiative Attachment](#)

Photoautotroph

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Photosynthetic organism](#)

Definition

Photoautotrophs are organisms that obtain cellular [▶ energy](#) from radiation and assimilate CO_2 as a source of carbon. They differ from photoheterotrophs that produce ATP using solar energy but obtain carbon for biosynthesis from reduced organic compounds. The [▶ photosynthesis](#) reaction center of photoautotrophic organisms contains chlorophyll, a pigment responsible for the transduction of radiation into cellular energy. Photoautotrophs can be divided in two groups, anoxygenic and oxygenic, depending on the number of reaction centers in their photosynthetic apparatus and on their ability to use water as a source of reducing power and generating oxygen as a by-product. Anoxygenic photoautotrophs are dependent on environmental reducing power to assimilate CO_2 . From an ecological point of view, life on Earth has been considered to be dependent on photoautotrophy; however, the recent discovery of underground strict chemolithoautotrophs is challenging this concept.

Cross-References

- ▶ [Anoxygenic Photosynthesis](#)
- ▶ [Bioenergetics](#)

- Carbon Dioxide
- Chlorophylls
- Cyanobacteria
- Energy
- Energy Conservation
- Green Bacteria
- Oxygenic Photosynthesis
- Photosynthesis
- Photosynthetic Pigments

Photobiology

Petra Rettberg

Institute of Aerospace Medicine, German
Aerospace Center (DLR), Cologne, Germany

Keywords

Bioluminescence · Chronobiology ·
Environmental photobiology · Infrared
radiation · Nonionizing radiation ·
Photosynthesis · Photocarcinogenesis ·
Photomedicine · Ultraviolet radiation · Visible
radiation

Definition

Photobiology is the scientific discipline studying the effects of nonionizing radiation on biological systems – specifically ultraviolet, visible, and infrared radiation, either from the sun or from artificial sources.

Overview

Photobiological responses are the result of chemical and/or physical changes induced in biological systems by nonionizing radiation. The radiation spectrum covered by the discipline photobiology ranges from ultraviolet radiation with wavelengths from 10 to 400 nm to visible light from 400 to 750 nm to the infrared radiation from 750 nm to 300 mm.

The research topics in photobiology are very broad: Photobiology at the molecular and cellular level deals with photochemical reactions after the absorption of nonionizing radiation and the following biological responses in cells, e.g., enzymatic repair of UV radiation-induced DNA damage or the induction of the synthesis of photoprotecting compounds. Another research field is the investigation of bioluminescence, the production of light by biochemical cellular reactions in some bacteria, invertebrates, and vertebrates. Organisms had developed the ability to produce bioluminescence for signaling and communication purposes. In biotechnology, bioluminescence is used as a reporter signal for genetic engineering. Photosynthesis, the process of utilizing solar radiation and carbon dioxide for the synthesis of organic compounds in plants, algae, and some species of bacteria, is another important field of photobiological research. At the organism level, chronobiology examines periodic phenomena in living organisms and their adaptation to solar-related rhythms. Photocarcinogenesis research aims at the discovery of the complex simultaneous and sequential biochemical events in higher organisms that ultimately lead to the occurrence of skin cancer, in many cases several years after exposure. In photomedicine, the application of light with respect to health and disease is studied and used for therapy. Photomedical aspects can be found in various fields of medicine including dermatology, surgery, dentistry, optical diagnostics, cardiology, and oncology. Effects of solar radiation on ecosystem level are monitored and examined in environmental photobiology. In astrobiology, the early Earth's UV climate with wavelengths down to 200 nm penetrating the atmosphere to the Earth's surface was found to be a major driving force for biological evolution. Based on photobiological laboratory experiments in planetary and space simulation facilities and in space experiments in low Earth orbit like those performed in ESA's EXPOSE facilities on the International Space Station (ISS), the habitability of other planets, such as, Mars, with respect to a UV climate different from today's Earth is estimated.

Cross-References

- ▶ [Biological Evolution](#)
- ▶ [Darwin's Conception of the Origins of Life](#)
- ▶ [DNA Damage](#)
- ▶ [Expose](#)
- ▶ [Extreme Ultraviolet Light](#)
- ▶ [Faint Young Sun Paradox](#)
- ▶ [International Space Station](#)
- ▶ [Ionizing Radiation, Biological Effects](#)
- ▶ [Life in the Solar System \(History\)](#)
- ▶ [Photochemistry](#)
- ▶ [Photochemistry, Atmospheric](#)
- ▶ [Photosynthesis](#)
- ▶ [Radiation Biology](#)
- ▶ [Solar UV Radiation, Biological Effects](#)
- ▶ [UV Climate](#)
- ▶ [UV Radiation](#)
- ▶ [UV Radiation, Biological Effects](#)

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Photochemical Hazes

Benjamin Charnay
LESIA, Observatoire de Paris, Université PSL,
CNRS, Sorbonne Université, Université de Paris,
Meudon, France

Keywords

Aerosols · Photochemistry · Organics · Radiative effects · Venus · Titan · Pluto · Early Earth · Exoplanets

Definition

Solid particles produced by photochemistry in planetary atmospheres.

Overview

Clouds and hazes are present in every atmosphere of the Solar System and they are expected to be common in exoplanetary atmospheres. For the planetary science community, clouds refer to condensates that grow from an atmospheric species when the partial pressure of the vapor exceeds its saturation vapor pressure (Marley et al. 2013). “Hazes” generally refer to particles produced from chemistry in the atmosphere that results in the formation of involatile solids. Hazes produced from photochemical reactions are called photochemical hazes. Photochemical haze formation is initiated by the production of haze precursors (radicals or ions) from the photolysis of simple molecules (CH_4 , N_2 , CO , SO_2 , ...). Neutral or ion chemistry results in the formation of macromolecules that will further grow to aerosols through coagulation and through chemistry.

Photochemical Hazes in the Solar System

Earth

On Earth, a stratospheric aerosol layer (called the Junge layer) is present between the tropopause and 30 km. It is sustained by natural emission of OCS and by volcanic injection of SO_2 , whose photolysis leads to the formation of sulfuric acid (H_2SO_4) aerosols.

In the troposphere over large cities, photochemical hazes called photochemical smog are produced by the photolysis of nitrogen oxides (NO and NO_2), which react with volatile organic compounds, forming organic aerosols. The combustion of fossil fuel is the main source of these nitrogen oxides and organic molecules. Photochemical smog represents a major health issue.

Despite these sources of photochemical hazes, Earth's atmosphere globally remains clear and haze-free. This is mostly due to the high fraction

of O_2 , which leads to the formation of OH radicals. The latter limit the formation of organic hazes by oxidizing organic molecules (e.g., CH_4). Before 2.4 Ga, Earth's atmosphere was much more reduced and O_2 was absent or just in very low amounts. Methane produced by methanogens may have reached high levels in the Archean atmosphere (3.8–2.5 Ga), potentially with a CH_4/CO_2 ratio exceeding 0.2. Under such conditions, photochemical models and lab experiments predict the formation of photochemical organic haze, similar as on Titan (Trainer et al. 2006). The early Earth, in particular at the end of the Archean, may have been covered by organic hazes (Zerkle et al. 2012).

Venus

Venus is covered by thick layers of sulfuric acid clouds and hazes. The photolysis of SO_2 in the upper atmosphere initiates chemical cycles which convert SO_2 into H_2SO_4 and S_8 . These compounds condensate into sulfuric acid and sulfur aerosols. Sulfuric acid aerosols above 60 km can be considered as photochemical haze, since they form from the recently photochemically produced H_2SO_4 . Aerosols below 60 km are considered as clouds since they form from the global and long-term tropospheric H_2SO_4 .

Titan

Titan is the archetype of hazy world. CH_4 and N_2 in Titan's upper atmosphere are photolyzed by UV photons or ionized by charged particles from Saturn's magnetosphere. The orbiter Cassini revealed the unexpected and fundamental role of ion-neutral chemistry leading to the formation of massive molecules, including benzene and polycyclic aromatic hydrocarbon, in Titan's ionosphere (Waite et al. 2007, Lavvas et al. 2013). Neutral chemistry initiated by photochemistry likely dominates the growth of particles below ~800 km. The large thermally driven pole-to-pole Hadley-like circulation, coupled with particle microphysics, produces a detached layer of haze particles above Titan's stratosphere (Rannou et al. 2002, Lavvas et al. 2009). The tropospheric methane cycle with cloud

condensation/precipitation tends to eliminate hazes, which deposit at the surface and may be the major constituent of Titan's dunes. Hazes also have a major impact on the radiative budget of Titan's atmosphere. Absorption of solar radiation by hazes produces a stratospheric thermal inversion and a cooling of the surface by an anti-greenhouse effect (McKay et al. 1991).

Pluto

The New Horizon probe revealed photochemical hazes in Pluto's atmosphere, similar as on Titan (Gladstone et al. 2016). These hazes are likely produced from the photolysis of CH_4 and N_2 by solar far-UV and with also a contribution from interplanetary Lyman- α emission. A difference compared with Titan is the larger abundance of atmospheric CO, which may change the composition and optical properties of hazes. Pluto's hazes dominate the atmospheric radiative balance from the ground to an altitude of 700 km (Zhang et al. 2017). They explain the observed thermal profile, colder than expected.

Giant Planets

All giant planets in the Solar System have hazes in their atmosphere. Their formation is likely initiated by UV photolysis and by energetic magnetospheric particles in the auroral regions. The high concentration of UV-absorbing hazes at high latitudes on Jupiter and Saturn suggests a primary formation by auroral energy deposition coupled with a confinement within the polar vortex.

Photochemical Hazes on Exoplanets

Most of exoplanets seem to be cloudy or hazy (Sing et al. 2016). Their presence is suggested by flat transit spectra with reduced molecular absorption bands and Mie slope in the visible. These are either condensate clouds or photochemical hazes. It is currently difficult to distinguish them and they represent a major issue for the characterization of exoplanetary atmospheres. Lab experiments suggest that photochemical hazes could form for a large range of temperature and atmospheric composition, but with significant variations in the production rate (Hörst et al.

2018). Hazes with sub-micrometric sizes (as on Titan) are expected to be optically thinner in the infrared. Future observations by JWST and ARIEL in the infrared may allow to characterize the optical properties of hazes and the chemical composition of hazy planets.

Astrobiological Interest

Lab experiments using plasma chambers or UV sources are particularly useful to understand the formation, composition, and properties of photochemical hazes. The particles produced by such experiments are called tholins. Analysis of tholins formed under Titan-like conditions revealed that they contain numerous prebiotic molecules, including amino acids and nucleotide bases (Hörst et al. 2012). The hydrolysis of tholins naturally released such prebiotic molecules (Poch et al. 2012). Photochemical organic hazes have therefore a major astrobiological interest and may have contributed to the prebiotic chemistry leading to life on Earth.

Cross-References

- [Atmosphere, Temperature Inversion](#)
- [Mie Scattering](#)
- [Stratosphere](#)
- [Venus Clouds](#)

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Photochemistry

Christopher R. Arumainayagam
Wellesley College, Wellesley, MA, USA

Keywords

Electronic excitation · Prebiotic molecules ·
Molecular panspermia · Interstellar ice ·
Venus · Radiation chemistry

Definition

Photochemistry is defined as chemical processes initiated by photon-induced electronic excitation, not involving ionization. Energetic processing of interstellar ice mantles and planetary atmospheres via photochemistry is a critical mechanism in the extraterrestrial synthesis of prebiotic molecules. Molecular panspermia posits that space-synthesized prebiotic molecules (e.g., amino acids and sugars) were delivered to Earth by comets, kick-starting life.

Word range of Entry: approx. 2200 words excl. References, as agreed with the Editors-in-Chief

Overview

Photochemistry, which involves nonionizing radiation, is defined as “the branch of chemistry which relates to the interactions between matter and photons of visible (700–400 nm) or ultraviolet (UV-A region (400–315 nm), UV-B (315–280 nm), and UV-C (280–100 nm)) light and the subsequent physical and chemical processes which occur from the electronically excited state, formed by photon absorption” (Wardle 2009). According to a recent review, “Interstellar ice photochemistry is an efficient pathway to chemical complexity in space. It is a source of prebiotic amino acids and sugars, and maybe the original source of enantiomeric excess on the nascent Earth”(Öberg 2016). Condensed-phase photochemistry occurs not only on ice mantles of interstellar (sub)micron-size grains (Herbst 2017; Arumainayagam et al. 2019; Sandford et al. 2020), but also on ices of extrasolar and solar planets (e.g., Mars), dwarf planets (e.g., Pluto), moons (e.g., Europa), asteroids (e.g., Ceres), and comets (e.g., 67P/Churyumov–Gerasimenko). Gases surrounding these ices also undergo photochemistry, likely contributing to the synthesis of prebiotic molecules. Gas-phase photochemistry may also occur in circumstellar envelopes associated with the last phase of stellar evolution. Interestingly, the ultraviolet irradiation of interstellar ice analogs containing H₂O, CH₃OH, and NH₃ leads to the production of ribose, the central molecular subunit of RNA (Meinert et al. 2016). The idea that organic building blocks of life originate in outer space is the fundamental assumption of molecular panspermia, which posits that endogenous delivery of prebiotic molecules kick-started abiogenesis on Earth.

In contrast to thermal chemistry, which involves the ground electronic state, photochemistry concerns electronically excited states (Arumainayagam et al. 2021). The electronically excited molecule may decay via primary *photophysical* and/or *photochemical* processes such as (1) luminescence (fluorescence or phosphorescence): $A^* \rightarrow A + h\nu$, (2) radiationless decay: $A^* + M \rightarrow A + M^*$, (3) quenching: $A^* + B \rightarrow A + B$, (4) photodissociation: $A^* \rightarrow B + C$, (5) photoisomerization: $A^* \rightarrow B$, (6) electron transfer: $A^* + B \rightarrow A^+ + B^-$,

(7) excitation transfer or sensitization: $A^* + B \rightarrow A + B^*$, (8) bimolecular reaction: $A^* + B \rightarrow C + D$, (9) H-abstraction reaction: $A^* + RH \rightarrow AH + R$, and (10) ion-pair formation: $AB^* \rightarrow A^+ + B^-$. None of these processes involve the production of low-energy electrons, a signature characteristic of radiation chemistry. Reactions attributable solely to photochemistry are limited to those initiated by photons associated with far (deep)-UV (4.1–6.2 eV) (300–200 nm), near-UV (3.1–4.1 eV) (400–300 nm), and occasionally visible (1.8–3.1 eV) light. We focus on photodissociation to produce radicals because current astrochemical simulations do not invoke photosensitization, abstraction reactions, photoaddition, or photocyclization. Depending on the shape of the excited state potential energy curves, photodissociation of a diatomic molecule may occur via (1) a bound upper state, (2) an unbound upper state, (3) predissociation, (4) indirect photodissociation, or (5) spontaneous radiative dissociation (Arumainayagam et al. 2021). In addition to photochemistry, vacuum ultraviolet (VUV) (6.2–12.4 eV) and extreme ultraviolet (EUV) (10.0–124 eV) light may initiate radiation chemistry, which involves “chemical changes produced by the absorption of radiation of sufficiently high energy to produce ionization”(Woods 1998).

Several core principles govern photochemistry (Arumainayagam et al. 2021). According to the Grotthuss-Draper law of photochemistry, only the light absorbed is effective in promoting photochemistry. This law may appear self-evident, but note that in stimulated emission, a molecule emits radiation that it had not previously absorbed. Most photochemical reactions obey the Bunsen-Roscoe law, according to which a photochemical effect is directly proportional to the total energy dose, irrespective of the time required to deliver that dose. This law may not apply to high photon flux experiments involving multiphoton processes. In other words, photochemical effects, in contrast to some radiation chemistry outcomes, depend on the photon fluence (photons per unit area, integrated over time) but not on the flux (photons per unit area per unit time). The Bunsen-Roscoe law is assumed valid for ice processing when extrapolating laboratory simulations (flux $\sim 10^{14}$ photons/cm²/sec) to dark, dense

molecular clouds (flux $\sim 10^4$ photons/cm²/sec). According to the Stark-Einstein law, a single molecule absorbs only one photon in the primary step of a photochemical reaction. Multiphoton processes typically occur in laboratory settings involving lasers with high incident photon fluxes (Arumainayagam et al. 2021).

Electronic excitation ($A + h\nu \rightarrow A^*$), the fundamental first step in photochemistry, is governed by spin and electric dipole transition selection rules, the latter of which are obtained from group theory symmetry arguments (Arumainayagam et al. 2021). The selection rules given below are best defined for gas-phase species. Strongly allowed transitions for gaseous diatomic molecules depend upon the couplings among different angular momentum quantum numbers and whether the quantization is best treated in space-fixed or molecule-fixed coordinates. For the so-called pure Hund's case (a), transitions of linear molecules involve the following restrictions on angular momentum quantum numbers: (1) $\Delta A = 0, \pm 1$ (A is the quantum number that specifies the total electronic orbital angular momentum along the molecular z-axis); (2) $\Delta S = 0$ (S is the total spin angular momentum); and (3) $\Delta Q = 0, \pm 1$ (Q is the quantum number that specifies the total orbital angular momentum along the molecular z-axis). Electronic transitions in diatomic molecules are subject to additional restrictions resulting from their high degree of symmetry, as detailed elsewhere (Atkins and Friedman 2011; Bernath 2015). In molecular orbital parlance, $\sigma^* \leftarrow \sigma$ and $\pi^* \leftarrow \pi$ transitions are allowed but not $\pi^* \leftarrow \sigma$ or $\sigma^* \leftarrow \pi$. While the typical cross section for allowed electronic transitions is 10^{-17} – 10^{-18} cm², the nominally forbidden $\pi^* \leftarrow n$ transitions, involving excitation of non-bonding electrons to π^* orbitals in species such as carbonyls, have significantly lower cross sections. Solvent interactions cause $\pi^* \leftarrow \pi$ and $\pi^* \leftarrow n$ transitions to “redshift” and “blueshift,” respectively (Arumainayagam et al. 2021).

In the gas phase, photon-induced processes are said to be spin-allowed when the spin multiplicity does not change (e.g., singlet to singlet and triplet to triplet transitions) (Arumainayagam et al. 2021). For example, photon-induced gas-phase

reactions of ammonia include spin-allowed (e.g., $\text{NH}_3 + h\nu \rightarrow \text{NH}(a^1\Delta) + \text{H}_2$) and disallowed (e.g., $\text{NH}_3 + h\nu \rightarrow \text{NH}(X^3\Sigma^-) + \text{H}_2$) processes. Because spin-orbit coupling is proportional to the fourth power of the atomic number, spin-forbidden transitions (e.g., singlet to triplet) become more likely for metal-containing heavy molecules in which the spin and orbital angular momenta are more strongly coupled. In contrast to the gas phase, spin-forbidden photon-induced transitions are allowed in the condensed phase (Bondybey et al. 1996).

Photochemistry in the condensed phase may differ from that in the gas phase because the collective behavior of molecules in close proximity influences the absorption process and the fate of the excited species (Arumainayagam et al. 2021). Because solvation reduces electronic state energies by different amounts, the absorption spectrum changes, causing spectra to be typically blue-shifted in the condensed phase. The solid O₂ absorption band, which peaks at ~ 7.0 eV, is attributed to the absorption of the (O₂)₂ dimer (Mason et al. 2006). This phenomenon is exclusive to the condensed phase. Absorption intensities may also change because interaction with neighboring molecules invalidates selection rules. In addition, quenching/collisional deactivation of the electronically excited state in the condensed phase is more likely than in the gas phase (Arumainayagam et al. 2021). Photochemistry yields in the condensed phase are diminished because of the so-called “cage effect,” which allows two photofragments of a molecule to be trapped and undergo numerous collisions before escaping the cage (Arumainayagam et al. 2021). Condensed-phase photochemistry is influenced by the formation of excitons, which are localized electronically excited states associated with generating a negative electron and a positive hole (absence of an electron in the valence band) bound by Coulombic attraction (Arumainayagam et al. 2021). In contrast to gas-phase photochemistry, condensed-phase photochemistry may be altered by the formation of supra-molecular excited collisional complexes (e.g., excimers (**excited dimer**) or exciplexes (**excited complexes**)) whose lifetime is longer than those of the corresponding ground-state complexes (Arumainayagam et al. 2021).

Photochemistry in space is initiated by three nonionizing (typically <10 eV) photon sources (Arumainayagam et al. 2021): (1) the interstellar radiation field (ISRF), permeating all of space except within dark, dense molecular clouds, plays a vital role in the photochemistry occurring in the outer layers of interstellar clouds, protoplanetary disks, and circumstellar envelopes (extended atmospheres of older stars, such as asymptotic giant branch (AGB) stars), (2) protostellar (stars in the act of formation before the so-called main sequence of hydrogen burning in their interiors) and stellar blackbody radiation lead to photochemistry in protoplanetary disks and planetary objects, and (3) secondary UV radiation, produced by primary cosmic rays exciting the Lyman and Werner band systems of molecular hydrogen, initiates chemical reactions within cold starless cores.

Photochemistry in the gas phase occurs in the following extraterrestrial locations (Arumainayagam et al. 2021):

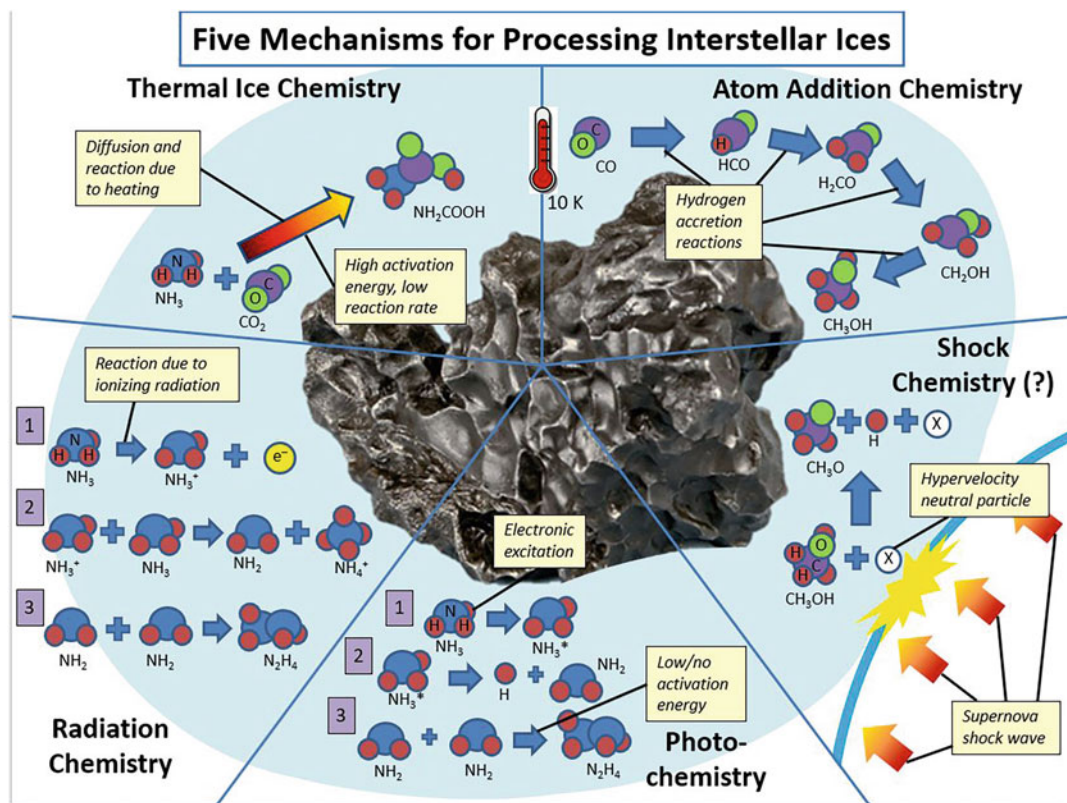
1. Protoplanetary disks (e.g., the production of cyanides has been attributed to the interaction of UV light hydrogen cyanide (HCN) (Du et al. 2015).
2. Planets (e.g., photochemistry of methane likely occurs in Mars' atmosphere (Taysum and Palmer 2020))
3. Moons (e.g., photodissociation of N_2 in Titan's atmosphere leads to the production of nitriles (Iino et al. 2020) and vinyl cyanide, a potential precursor of cell membranes/vesicle structures (Palmer et al. 2017).
4. Circumstellar envelopes (e.g., photochemistry in these planetary nebulae (when these objects were first discovered in 1784, they were mistakenly associated with planets) facilitates the production of complex molecules that possibly include polycyclic aromatic hydrocarbons (PAHs consist of concatenated aromatic rings) (Zhen et al. 2018), which may provide ingredients for a new stellar cycle)

Gas-phase photochemistry is studied using techniques such as flash photolysis, microwave

discharge flows, mass spectrometry, synchrotron radiation, plasma dissociation, Laval expansion, crossed molecular beam techniques, velocity map imaging, and computational chemistry (Arumainayagam et al. 2021).

Condensed-phase photochemistry by UV light leading to the production of radicals is one of five postulated mechanisms (Fig. 1) for the processing of interstellar ~ 0.01 μm -thick ice mantles surrounding the micron-sized dust grains found in dark, dense molecular clouds (Arumainayagam et al. 2021). The photochemistry induced by UV light produces both light and heavy radicals. While facile light radical diffusion is possible at ~ 10 K (Oba et al. 2018), (possibly leading to the atom addition chemistry shown in Fig. 1), the gradual warm-up from ~ 10 K in cold cores to ~ 100 K in hot cores/hot corinos allows for heavy radical diffusion (Arumainayagam et al. 2021). The subsequent barrierless radical-radical reactions produce complex organic molecules (COMs), which likely lead to the synthesis of precursors of biologically relevant molecules. Condensed-phase photochemistry may also occur in protoplanetary disks, the planetary birthplaces that evolve from hot cores/corinos (Arumainayagam et al. 2021). Another example of condensed-phase photochemistry is chemical synthesis in the icy bodies of the outer solar system initiated by solar photons (Kulikov et al. 2019). For example, solar photons are thought to contribute to the condensed-phase synthesis of tholins, the hydrolysis of which may lead to the production of amino acids and nucleobases on Pluto (Cruikshank et al. 2019).

Energetic processing of cosmic ices via photochemistry is thought to be a dominant mechanism for the extraterrestrial synthesis of prebiotic molecules (Arumainayagam et al. 2021). According to a 2019 PNAS publication, "Meteorites were carriers of prebiotic organic molecules to the early Earth; thus, the detection of extraterrestrial sugars in meteorites implies the possibility that extraterrestrial sugars may have contributed to forming functional biopolymers like RNA" (Furukawa et al. 2019).



Photochemistry, Fig. 1 Nonenergetic and energetic processing of interstellar ice. (Reproduced from Ref. (Arumainayagam et al. 2019) with permission from the Royal Society of Chemistry)

Basic Methodology

Surface science techniques are typically used to analyze condensed-phase photochemistry relevant to astrobiology. Such experiments are usually conducted using nanoscale thin films of multilayer adsorbates under ultrahigh vacuum (UHV) conditions ($P \sim 10^{-9}$ torr). Photon-stimulated desorption (PSD) experiments, conducted *during* irradiation, have yielded vital information relevant to initial photon-induced processes. In addition, analyzing the products *following* < 10 eV photon irradiation has provided new insights into photochemistry. The surface science techniques temperature-programmed desorption (TPD), reflection absorption infrared spectroscopy (RAIRS), X-ray photoelectron spectroscopy (XPS), and high-resolution electron energy loss spectroscopy (HREELS) are particularly useful for postirradiation analysis. Microwave-discharge

hydrogen-flow lamps (MDHLs) used in “photochemistry” experiments typically initiate both photochemistry and radiation chemistry in cosmic ice analogs. In contrast to MDHL sources, irradiation with deuterium lamps (3.1–7.8 eV), tungsten halogen lamps (1.1–3.9 eV), or xenon arc lamps (0.5–6.2 eV) typically induces only photochemistry. Laser sources can generate tunable coherent narrow-bandwidth UV radiation by employing resonant four-wave mixing. Synchrotron radiation sources (e.g., NSRRC in Taiwan, DESIRS beamline at SOLEIL in France) produce continuous intense photon emission.

Key Research Findings

1. Photochemistry of (a) interstellar ices, near star-forming regions, likely leads to the extra-terrestrial synthesis of prebiotic molecules.

2. Because the ionization threshold is lower in the condensed phase than in the gas phase, most “photochemistry” studies of astrochemistry likely involve radiation chemistry.

Future Directions

The newly deployed James Webb Space Telescope (JWST) should provide new insights into the mechanisms (e.g., photochemistry) responsible for the extraterrestrial synthesis of prebiotic molecules. There is a critical need for more wavelength-dependent condensed-phase astrochemically relevant photochemistry studies, of which there have been only a few.

Cross-References

- [Circumstellar Chemistry](#)
- [Cosmic Rays](#)
- [Comet](#)
- [Complex Organic Molecules](#)
- [Hot Core](#)
- [Hot Corino](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Photodissociation](#)
- [Photoionization](#)
- [Photolysis](#)
- [Pluto](#)
- [Prebiotic Chemistry](#)
- [Protoplanetary Disk](#)
- [Ultraviolet Radiation](#)
- [Vacuum Ultraviolet](#)

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Photochemistry, Atmospheric

Melissa G. Trainer

NASA Goddard Space Flight Center Code 699,
Greenbelt, MD, USA

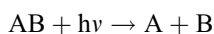
Definition

Atmospheric photochemistry is the study of light initiated chemical reactions which occur in the atmospheres of planetary bodies. These reactions play an important role in climate, and likely contributed to prebiotic organic synthesis.

Overview

Planetary atmospheric photochemistry occurs when incident radiation contains enough energy to dissociate bonds within the atmospheric molecules. Bond energies in atmospheric molecules are on the order of 10^2 – 10^3 kJ mol⁻¹, and thus bond dissociation requires photons in the ultraviolet and visible region of the electromagnetic spectrum. A photochemical reaction occurs when the absorption of light triggers an electronic transition within the molecule, activating the reaction. Products of photo dissociation are typically highly reactive radicals.

A photochemical reaction is represented by the following general equation:



where $h\nu$ represents the energy of the photon. This reaction is characterized by a first-order rate

constant (known as a “J-value”), and the rate of photochemical dissociation is expressed as:

$$\text{Rate (molecules cm}^{-3}\text{s}^{-1}) = -J(AB).$$

The J-value is dependent upon the absorption spectrum of the molecule, the available light in the atmosphere, and the quantum yield for dissociation once the molecule is electronically excited by light absorption. The quantum yield is the ratio of the number of molecules dissociated to the number of photons absorbed, a dimensionless parameter ranging from 0 to 1. The lifetime (τ) of a particular molecule with respect to photolysis loss is given by $1/J$, and this value allows for comparison between photolysis and other possible loss processes, such as transport.

To calculate a J-value at any point in the atmosphere for any particular molecule, the following summation is used over the wavelength (λ) range of interest:

$$J \text{ (s}^{-1}) = \sum_{\lambda} I(\lambda) \sigma(\lambda) \varphi(\lambda) d\lambda$$

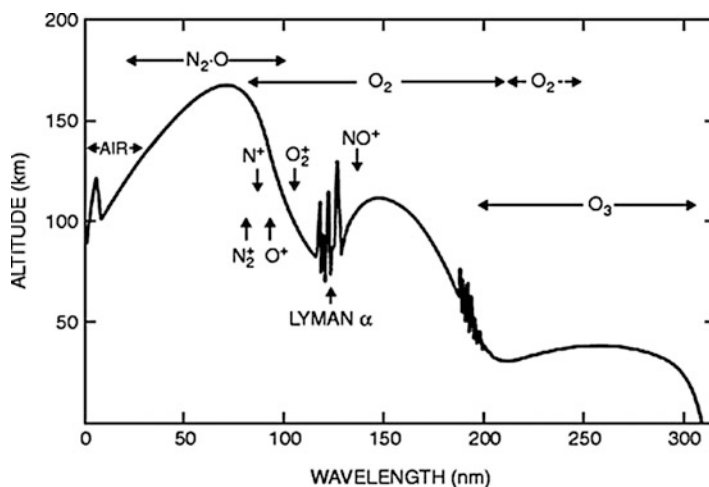
where $I(\lambda)$ is the available light (photons cm⁻² s⁻¹), $\sigma(\lambda)$ is the absorption cross section of the molecule (cm² molecule⁻¹), and $\varphi(\lambda)$ is the quantum yield. The photon flux is a property of the planet, determined by the incident angle of sunlight, flux at the top of the atmosphere, and the amount of light absorbed above the point of interest. Both the absorption cross section and quantum yield are properties of the molecule.

The dependence on the photon flux leads to a strong dependence on altitude, which contributes to the vertical distribution of gases within an atmosphere and serves to attenuate the light that reaches the planet's surface. Figure 1 shows the penetration depth of ultraviolet solar radiation into the Earth's atmosphere and relevant absorbing molecules. On Earth, the highest energy ultraviolet radiation is effectively absorbed by O₂ and O₃ before reaching the surface, protecting life from this damaging radiation.

Atmospheric photochemistry on the current Earth, early Earth, and other planets is of interest because of the effects photochemical processes can have on planetary environments. These

Photochemistry, Atmospheric,

Fig. 1 Depth of penetration of ultraviolet radiation in the Earth's atmosphere. The altitudes correspond to an attenuation of $1/e$. The principle absorbers are indicated. (Adapted from Brasseur and Solomon 2005)



include the chemical composition of the atmosphere, the attenuation of sunlight reaching the surface, the radiative balance of the planet, the oxidative capacity of the atmosphere, the production and delivery of organic molecules to the surface, and the generation of radiatively shielding hazes and pollution.

Cross-References

► [Atmosphere, Organic Synthesis](#)

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Photodesorption

Karin I. Öberg
Center for Astrophysics, Harvard-Smithsonian,
Cambridge, MA, USA

Keywords

Interstellar dust · Snow line

Synonyms

[Photoevaporation](#); [Photosputtering](#)

Definition

A photodesorption event occurs when the absorption of a UV (or X-ray) photon by a molecule condensed on a surface results in its desorption (direct photodesorption), in the “kick-out” of a nearby molecule (indirect photodesorption), or in dissociation followed by recombination and desorption (photochemical desorption). In space, photodesorption can regulate the locations of “snow-lines,” the transition regions where the dominant phase of volatiles changes from gas to ice (particularly in protoplanetary disks). Photodesorption from ices and other surfaces that mimic interstellar grain compositions is characterized experimentally to determine molecule-specific desorption efficiencies and mechanisms.

Overview

In dense and cold regions in space, atoms and molecules freeze out on interstellar grains, forming icy mantles that continue to evolve chemically. Photodesorption connects the surface/ice chemistry with the gas phase in regions that are too cold for efficient thermal ice evaporation. In

the presence of strong radiation fields, photodesorption will affect the location of “snowlines,” i.e., the molecule-specific transition regions where ice desorption overtakes freeze-out. In less exposed regions, where the ice phase dominates, low-level photodesorption can maintain a small fraction of molecules in the gas phase. This is important because it potentially enables the use of gas-phase spectroscopic observations as a probe of ice compositions.

Ice photodesorption efficiencies are measured experimentally in ultrahigh vacuum chambers, where interstellar ice equivalents are irradiated with broadband or monochromatic UV/X-ray sources and desorption rates are measured using a quartz balance, infrared spectroscopy, or mass spectrometry, or a combination of two or more of these techniques. These experiments can also be used to characterize the desorption process based on how the photodesorption rate responds to radiation at different fluxes and frequencies, and based on the effects of ice thickness, temperature, and morphology on the desorption efficiency. Experiments on photodesorption off metal surfaces have a long history (Avouris and Walkup 1989), while investigations of ice photodesorption date back to the mid-1990s (Westley et al. 1995).

Measured far-UV photodesorption efficiencies are high for some small molecules such as CO, N₂, O₂, CH₄, and CO₂, of the order 10⁻²–10⁻³ desorbed molecules per incident UV photon, somewhat lower for water ice, and substantial lower for most organic ices, including CH₃OH and CH₃CN (Öberg et al. 2009a, b; Bertin et al. 2012; Zhen and Linnartz 2014; Cruz-Diaz et al. 2016; Dupuy et al. 2017; Cruz-Diaz et al. 2018; Basalgète et al. 2021b; Fillion et al. 2021). Derived desorption mechanisms are ice specific. Simple ices that only present nondissociative excitations mainly desorb through the excitation of a subsurface molecule, followed by the kick-out of a surface molecule. CO and N₂ are in this category when exposed to a typical interstellar radiation field (Bertin et al. 2012). In contrast, many other astrophysically important ices, including O₂, H₂O, and CO₂, and most organic ices, only

have strong dissociative transitions in the far-UV and photodesorption proceeds differently: Following absorption of a photon, the dissociation fragments either desorb directly or recombine and desorb, or kick out a surface molecule (Andersson and van Dishoeck 2008; Hama et al. 2010). The number of active layers is generally larger for dissociative photodesorption because of the dynamics involved.

Extreme UV and X-ray photons may ionize as well as dissociate molecules resulting in the photodesorption of molecular ions. X-ray photodesorption efficiencies are generally less well constrained than far-UV photodesorption efficiencies, but there is some experimental evidence that they may be important for desorbing organic ices in star- and planet-forming environments (Andrade et al. 2010; Dupuy et al. 2018; Basalgète et al. 2021a).

Photodesorption efficiencies are included in astrochemical models of clouds, protostars, and protoplanetary disks to determine the division of molecules between the gas phase and the grain surfaces. Since the gas phase and grain surface chemical reactions are different, this is important to predict the chemical evolution during most stages of star and planet formation.

Cross-References

- [Interstellar Ices](#)
- [Snow Line](#)
- [Solar Nebula](#)

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Photodestruction

► [Photodissociation](#)

Photodetachment

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Photodetachment is the chemical process whereby an electron is removed from an ► [anion](#) (e.g., CN[−]) by absorption of a photon.

Cross-References

► [Anion](#)

Photodissociation

Steven B. Charnley
Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Photodestruction](#)

Definition

Photodissociation is the chemical process whereby a molecule is broken apart by absorption of a photon. Specific processes include direct photodissociation, ► [predissociation](#), coupled-

states photodissociation, and spontaneous radiative photodissociation.

Cross-References

► [Photolysis](#)

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Photodissociation Region

Mark G. Wolfire¹ and Michael J. Kaufman²

¹Astronomy Department, University of Maryland, College Park, MD, USA

²Department of Physics and Astronomy, San José State University, San Jose, CA, USA

Keywords

Interstellar medium (ISM) · Molecular cloud · Star formation · Thermal process

Synonyms

[PDR](#); [Photon dominated region](#)

Definition

A photodissociation region (PDR) is an interstellar gas phase in which far-ultraviolet (FUV; $6\text{ eV} < h\nu < 13.6\text{ eV}$, where eV is the energy of the radiation in electron volts) radiation plays a role in the heating and/or chemistry (Tielens and Hollenbach 1985a). These regions include the diffuse atomic ► [interstellar medium](#), and the surfaces of interstellar molecular clouds exposed to the interstellar radiation field and to intense radiation from nearby OB stars. Note that in the following article we use the standard astronomical

notation of square brackets (e.g., [CII]) indicating “forbidden” transitions, that is, transitions from a metastable state. Likewise, the ionization state of an atom is indicated by a Roman numeral, so that I indicates the neutral atom, II is once ionized, and so on (e.g., HII for ionized hydrogen).

Overview

The FUV range of energies is responsible for dissociating molecules and dominates the heating process in photodissociation regions (PDRs). The upper bound of this range is the energy required to ionize hydrogen, and thus PDRs are neutral hydrogen regions (in contrast, astronomers refer to plasmas of electrons and ionized hydrogen as ► [HII regions](#)). The FUV field is often measured in units of the Draine (Draine 1978) interstellar radiation field, equal to ~ 1.7 times the Habing (Habing 1968) local interstellar FUV field ($1.6 \times 10^{-3}\text{ erg cm}^{-2}\text{ s}^{-1}$ or $\sim 10^8\text{ photons cm}^{-2}\text{ s}^{-1}$). A common notation is that G_0 is the radiation field in units of the Habing field, and field strengths that are typically encountered range between $G_0 \sim 1.7$ for the interstellar field and $G_0 \sim 10^5$ for the Orion nebular PDR.

PDRs are found where FUV radiation from OB stars or the general interstellar radiation field shines on molecular clouds. The FUV radiation can affect the chemistry for visual extinctions up to $A_V \sim 8$ by maintaining in atomic form that oxygen that is not tied up in CO. The relation between extinction and hydrogen nucleus ► [column density](#) is $N = 1.9 \times 10^{21} A_V / Z' \text{ cm}^{-2}$ where Z' is the dust abundance relative to the abundance in the local galaxy. The mean extinction in giant ► [molecular clouds](#) is also $A_V \sim 8$ (Solomon et al. 1987), so much of the mass in molecular gas is in PDRs. PDRs are also found in the diffuse medium in cold ($T \sim 100\text{ K}$) and warm ($T \sim 8000\text{ K}$) neutral hydrogen clouds (see ► [Interstellar Medium](#)). The same physics that applies in the molecular cloud surfaces (Kaufman et al. 2006; Abel et al. 2005; Le Petit et al. 2006) also applies in the diffuse atomic interstellar medium (Wolfire et al. 2003; Shaw et al. 2006; Wolfire et al. 2008) but with weaker FUV field ($G_0 \sim 1\text{--}10$) and lower

hydrogen nucleus column densities ($N \sim 10^{19} - 10^{21} \text{ cm}^{-2}$). PDRs are also present in the neutral interstellar medium in starburst galaxies (Kaufman et al. 1999) and in galaxies with active galactic nuclei (Meijerink et al. 2007).

Structure

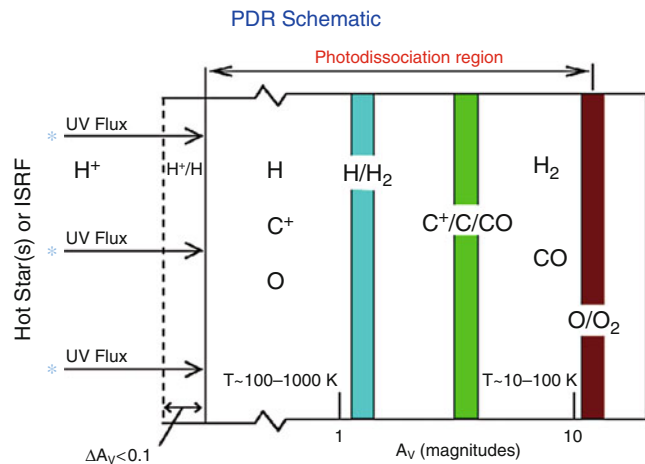
A PDR can be divided into various chemical regimes as a function of ► [optical depth](#) from the cloud surface (Sternberg and Dalgarno 1995). In the outer portions, the gas is mainly neutral atomic H, He, O, and C^+ (see Fig. 1, where ISRF is the interstellar radiation field and transition regions are indicated in color). Incident FUV radiation is absorbed by dust and large carbon molecules – ► [polycyclic aromatic hydrocarbons](#) (PAHs) – and mostly results in excitation of PAHs and grain heating. However, as much as 0.1–1% of the absorbed FUV is converted to energetic photoelectrons that are ejected from PAHs and grains and heat the gas. The gas generally attains a higher temperature ($T \sim 100\text{--}5000 \text{ K}$) than the grains ($T \sim 10\text{--}50 \text{ K}$) because of the much less effective cooling of the gas (predominantly via $[\text{CII}] 158 \mu\text{m}$ and $[\text{OI}] 63 \mu\text{m}$ ► [line emission](#)) relative to the dust continuum cooling. On the surfaces of molecular clouds, the warm gas leads to intense emission of the $[\text{CII}] 158 \mu\text{m}$ line and the $[\text{OI}] 63$ and $145 \mu\text{m}$ lines, as well as infrared (IR) dust continuum and near-infrared emission features (at 3.3, 6.2, 7.7, 8.6, and $11.3 \mu\text{m}$) believed to arise from PAHs.

Additional diagnostic line emission is provided by $[\text{SiII}] 35 \mu\text{m}$ and $[\text{FeII}] 26 \mu\text{m}$ (Si^+ and Fe^+), which can be used to estimate elemental abundances (Kaufman et al. 2006).

At extinctions $A_V > 1$ atomic hydrogen is converted to molecular hydrogen on grain surfaces and molecular H_2 vibrational transitions are produced. The grain photoelectric heating process still dominates, balanced by C^+ and O^0 fine-structure line cooling. In this region, the gas is mainly H_2 , but the carbon is in the form of C^+ and not CO. Since CO is often used as a tracer of molecular gas, this regime has been called “dark gas” (i.e., no CO emission; Grenier et al. 2005; Wolfire et al. 2010; this has nothing to do with dark matter or dark energy). The dark gas may increase the molecular mass of galactic clouds by $\sim 30\%$ relative to estimates based on the CO emission alone and could increase the molecular mass by a factor of ~ 30 in low-metallicity (low abundance of elements heavier than helium) galaxies such as the Small Magellanic Cloud (Leroy et al. 2007). Deeper in PDRs ($A_V > 2\text{--}3$), the transition of C^+ to C to CO occurs, and the CO rotational and $[\text{CI}] 370$ and $609 \mu\text{m}$ lines originate. In the deepest layers, grain photoelectric heating or cosmic-ray heating dominates depending on the strength of the incident field, balanced by cooling from rotational transitions of CO. The chemistry of oxygen and carbon not locked in CO is affected by the FUV radiation to cloud depths of $A_V \sim 5\text{--}10$.

Photodissociation

Region, Fig. 1 Typical structure of PDR chemical zones as a function of extinction A_V into a cloud illuminated by an FUV radiation field



Heating

Detailed investigations of the grain photoelectric heating process have been presented by Bakes and Tielens (1994) and Weingartner and Draine (2001). An FUV photon is absorbed by a dust grain that can eject a hot electron into the gas. The electron kinetic energy is a function of the accumulated charge on the grain since the electron must overcome the Coulomb barrier of the accumulated charges. The grain charge is found by balancing the ► [photoionization](#) rate with the recombination rate. The calculated heating efficiency from Bakes and Tielens (1994) is shown in Fig. 2.

Figure 2 shows that as grains become positively charged and hence the electron density n_e in the gas increases, the heating efficiency drops. For typical conditions in the neutral diffuse ISM (Wolfire et al. 2003) ($G_0 \sim 1.7$, $n_e/n \sim 1.6 \times 10^{-4}$, $n \sim 30 \text{ cm}^{-3}$, $T \sim 85 \text{ K}$, where n is the hydrogen nucleus volume density; i.e., n includes both atomic and molecular hydrogen), grains are mainly neutral, and the photoelectric heating efficiency is near maximum. In contrast, for the photodissociation region in Orion (Tielens and Hollenbach 1985b) ($n \sim 2 \times 10^5 \text{ cm}^{-3}$, $G_0 \sim 1 \times 10^5$, and $T \sim 550 \text{ K}$), grains are highly charged, and the heating efficiency is a factor of 10 lower.

Note, however, that the efficiency shown in Fig. 2 is integrated over the grain size distribution from large grains, $\sim 0.1 \text{ }\mu\text{m}$, to large molecules,

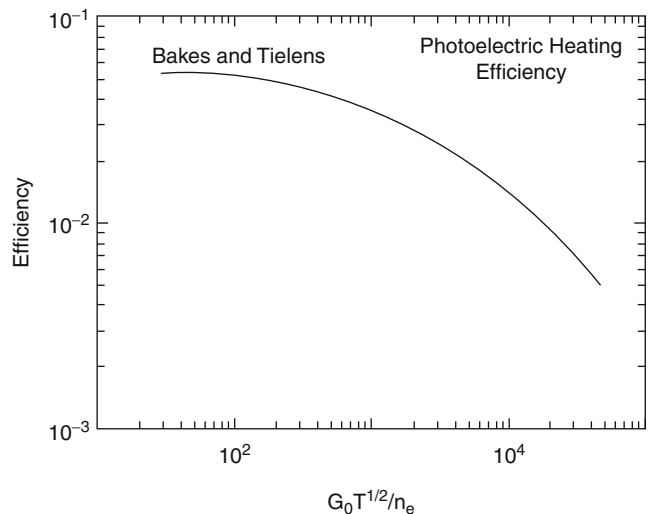
$\sim 5 \text{ }\text{\AA}$, with a distribution in radius $n(a) \propto a^{-3.5}$. Bakes and Tielens (1994) found that $\sim 1/2$ of the heating comes from the smallest grain sizes. The efficient heating from small grains is mainly for two reasons. First, the yield increases as the grain size decreases. The yield is the fraction of electrons that reach the grain surface that are ejected from the grain. In a large grain, the electron energy is lost to infrared continuum radiation, but in a small grain, a greater fraction can reach the surface to be ejected.

Second, the ionization-to-recombination ratio is proportional to a^2 so that larger grains become charged and their heating efficiency drops. The smallest population of grains is almost certainly PAHs (polycyclic aromatic hydrocarbons; Allamandola et al. 1985; Leger and Puget 1984). The simplest PAH is benzene with six carbon atoms in a ring; larger PAHs are composed of multiple rings.

In addition to photoelectric heating from grains, various other heating processes could contribute depending on the incident field strength and depth into the cloud. At large ► [optical depth](#), heating from cosmic-ray ionization could become important. The primary ionization rate per hydrogen nucleus is approximately $\zeta_{\text{xp}} \sim 1.8 \times 10^{-17} \text{ s}^{-1}$ with each ionization producing a primary electron of mean energy 35 eV. The primary electrons can produce secondary ionizations, molecular dissociation, atomic and molecular excitation, or gas

Photodissociation

Region, Fig. 2 Grain photoelectric heating efficiency from Bakes and Tielens (1994), where T is temperature, n_e is electron density and G_0 measures the radiation field (see text)



heating, with yields depending on the electron and molecular abundances (Dalgarno et al. 1999). Additional heating processes at large optical depth may include IR dust continuum pumping of [OI] 63 μm followed by collisional de-excitation and gas-dust interactions (Tielens and Hollenbach 1985a).

At small $\blacktriangleright$ **optical depth**, the heating is dominated by grain photoelectric heating, while photoionization of CI and photodissociation of H_2 contributes about 1% to the heating (Tielens and Hollenbach 1985a).

Cooling

At $A_V < 3$, the gas cools mainly by collisional excitation by H and H_2 of fine-structure transitions, followed by radiative de-excitation. Dominant cooling lines include [CII] 158 μm , [OI] 63 μm , and [CI] 610 μm . Along with the cooling transitions, weaker lines can be used as diagnostics of the gas density, temperature, and incident FUV fields. These include [OI] 145 μm , [CI] 370 μm , [SiII] 35 μm , [FeII] 26 μm , and the H_2 rotational transitions 0–0 S (0) 28 μm , 0–0 S(1) 17 μm , and 0–0 S(2) 12 μm . Deeper into the cloud, CO rotational transitions dominate the gas cooling.

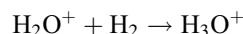
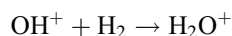
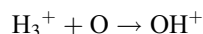
Chemistry

Formation and Destruction of H_2

In steady state, photodissociation of molecular hydrogen is balanced by formation on dust grains. An H_2 molecule in the ground state can absorb a FUV photon ($\lambda < 1108 \text{ \AA}$) and be excited to the first or second electronic level. About 10% of the pumped molecules de-excite to the vibrational continuum thereby dissociating the molecule. The remainder land in bound excited states resulting in a UV emission line and an IR vibrational cascade. PDR computational codes have been constructed including detailed H_2 models that account for self-shielding in individual pumping lines as well as the infrared line emission produced in the fluorescent cascade (Draine and Bertoldi 1996; Sternberg and Dalgarno 1989; Black and van Dishoeck 1987). For $G_0/n < 0.025$, H_2 self-shielding dominates over dust shielding, and the H/H_2 transition is drawn to the cloud surface (Burton et al. 1990).

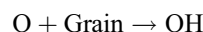
Formation and Destruction of CO

The formation of CO follows that of H_2 and OH as one goes deeper into the cloud. In the gas phase, the formation of OH is initiated by the cosmic-ray ionization of H_2 (van Dishoeck and Black 1986; see also $\blacktriangleright$ **Interstellar Chemical Processes**). Reactions with H_2 and O lead to

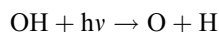


Dissociative recombination of H_3O^+ leads directly to OH or to H_2O (which is then photodissociated to form OH).

Hollenbach et al. (2009) has suggested that for typical cosmic-ray ionization rates, formation of OH on grain surfaces can exceed the gas phase production. In this case, the OH abundance is determined by equating the formation of OH on grain surfaces

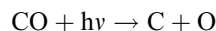
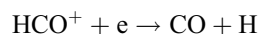
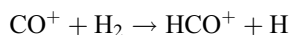
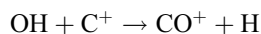


to the FUV photodissociation of OH



where $h\nu$ represents a photon.

Once OH is formed, the chemistry proceeds as follows (van Dishoeck and Black 1988):



The first reaction dominates the formation of CO^+ ; the second reaction dominates the destruction of CO^+ and the formation of HCO^+ ; the third reaction dominates the destruction of HCO^+ and

the formation of CO; the last reaction dominates the destruction of CO. As a result, every CO^+ that is formed by the first reaction results in a formation of a CO by the third reaction. The H_2 absorption lines in the FUV overlap with several of the CO dissociating transitions, and thus the H_2 can shield the CO at larger optical depth. The shielding factor is tabulated for a range of H_2 and CO columns in Visser et al. (2009). An expression for the depth at which the CO ($J = 1-0$) line becomes optically thick, $N(\text{CO}) \sim 2 \times 10^{16} \text{ cm}^{-2}$, is given by Wolfire et al. (2010).

Since the heating rates and the depth to the transition regions depend on G_0/n , we expect regions with the same ratio of G_0/n to have similar structure.

Electron Abundance

The electron abundance is important in setting the grain photoelectric heating rate and in setting the abundance of various atomic and molecular ions that are neutralized or destroyed by recombination. At low A_V ($<2-3$), electrons are mainly provided by the photoionization of C to C^+ and by photoionization of He by soft X-rays. Essentially, all the C is in the form of C^+ yielding an electron abundance $n_e/n \sim n_{\text{C}^+}/n \sim 1.6 \times 10^{-4}$, the value of the gas phase carbon abundance in the ► [interstellar medium](#) (Sofia et al. 2004). The charge exchange of metal cations with PAH—can effectively compete with gas phase recombination, and the inclusion of PAHs in the chemical network can significantly decrease the optical depth to the C^+/C transition and increase the neutral abundances of species such as C^0 , Si^0 , Mg^0 , Fe^0 , and S^0 (Wolfire et al. 2008; Bakes and Tielens 1998). Deeper into the cloud, electrons are provided mainly by cosmic-ray ionization of H and He.

Model Example

A sample model calculation is presented in Wolfire et al. (2010).

Observations

The bright HII region M17 and associated PDR are shown in Fig. 3. The image is taken with the

Spitzer IRAC instrument and is dominated by PAH emission. The PAH emission lies between the ionized gas at the center and molecular gas to the upper left and right. Shown in Fig. 4 is a strip map in [CII] $158 \mu\text{m}$ emission taken along the line shown in Fig. 3. The [CII] line emission peaks at the PDR but also seems to have a tail of emission in the molecular gas, perhaps indicating FUV penetration in a clumpy medium. We also show in Fig. 5 a Spitzer IRS spectrum near the ionized/neutral interface showing bright PAH emission but also H_2 pure rotational lines and fine-structure lines from ionized gas.

Future Directions

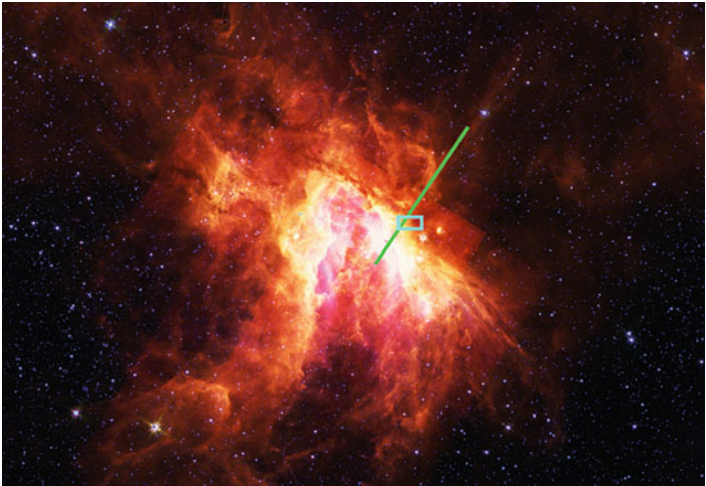
The basic PDR model seems to provide good fits to many observations, especially for bright PDRs. There are, however, a few emerging problems in which more detailed modeling is required or laboratory measurements are needed to constrain the theory.

Turbulence

We know that atomic and molecular clouds are turbulent with a log-normal probability density distribution (Goodman et al. 2009; Vazquez-Semadeni 1994). The chemical rates are proportional to the gas density squared, and thus the rates can be quite different in the extreme densities. In general, the dynamic time to transport molecular material out of the cloud interior to the atomic surface, or to transport atomic material from the surface inward, is longer than the chemical equilibrium times (Wolfire et al. 2010), but there are cases for low G_0 or strong H_2 self-shielding when the time-dependent chemistry can be important (Glover and Mac Low 2007). An additional problem is that the FUV penetration depends on column density that can be different in the high-density and low-density regions. Some initial work has been done to investigate turbulent PDRs, but much more can be done in the areas of time-dependent chemistry, turbulent structure, and line emission.

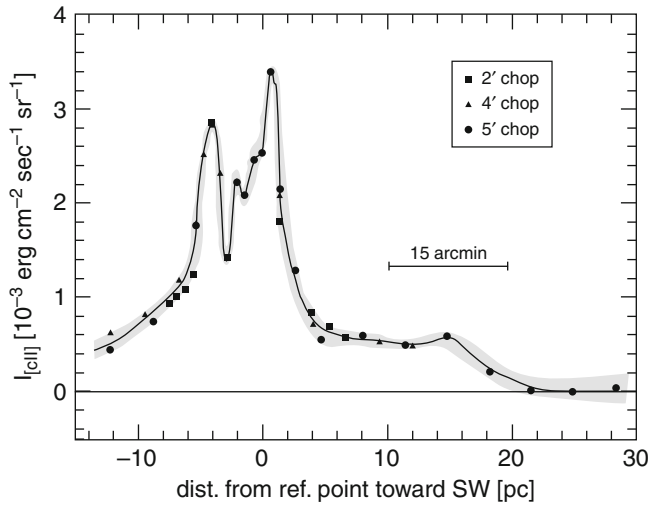
Photodissociation

Region, Fig. 3 Spitzer IRAC observations of the M17 HII region and PDR. The *green line* is about 10 arcmin in length and crosses the M17SW PDR, and shows the direction of the [CII] strip map shown in Fig. 4. The *box* shows the location of the Spitzer IRS spectrum shown in Fig. 5



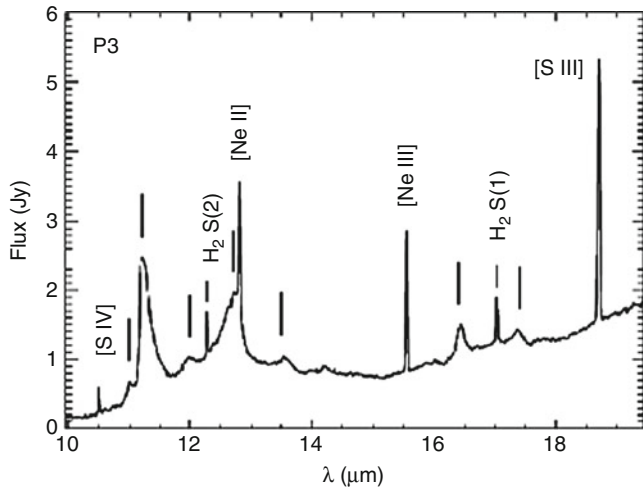
Photodissociation

Region, Fig. 4 Strip map of [CII] 158 μm emission in M17SW PDR from Stutzki et al. (1988)



Photodissociation

Region, Fig. 5 Spitzer IRS observations of the PDR M17SW showing flux versus wavelength, from Povich et al. (2007). Vertical solid lines show the location of the PAH features



XDRs

Another type of region that is of increasing importance is called an XDR (Meijerink et al. 2007), in which hard X-ray radiation ($h\nu > 1$ keV) dominates the heating and chemistry. The most luminous XDRs are associated with black holes in galactic nuclei in which the X-ray emission penetrates the surrounding molecular clouds. XDRs are expected to have large hydrogen nucleus column densities ($N > 10^{22}$ cm $^{-2}$) and high volume densities ($n > 10^5$ cm $^{-3}$), and we expect to see highly excited molecules such as CO with rotational transitions up to $J = 30$ – 29 (~ 87 μ m; Spaans and Meijerink 2008). Spectrometers on board Herschel and the aircraft SOFIA will open new spectral windows in order to observe the highly excited molecular gas in XDRs.

Cross-References

- Column Density
- Extinction, Interstellar or Atmospheric
- Herschel, William
- HII Region
- Interstellar Dust
- Molecular Cloud
- Optical Depth
- Photodissociation
- Photoionization
- Polycyclic Aromatic Hydrocarbon
- Turbulence, Interstellar

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Photoevaporation

► [Photodesorption](#)

Photoevaporation of Protoplanetary Disks

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

The physical process in which radiation from a young ► [protostar](#) causes the removal of gas from its circumstellar disk is called photoevaporation. Energetic stellar radiation, comprising mainly extreme ultraviolet (EUV; wavelengths from 121 nm down to 10 nm) and far ultraviolet (FUV; 200–122 nm) photons and X-rays, heats the surface layers of the gaseous disk, producing thermal pressure gradients that permit the gas to escape the gravitational potential of the disk in an expanding ► [hydrodynamic flow](#).

Cross-References

► [Protostars](#)

Photoferrotrophy

Casey Bryce and Andreas Kappler
Geomicrobiology, Center for Applied Geoscience, University of Tübingen, Tübingen, Germany

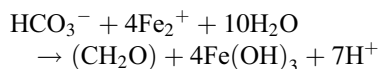
Keywords

Ferruginous habitats · Phototrophic iron oxidation · Iron cycling · Photosynthesis

Synonyms

Anoxygenic phototrophic Fe(II) oxidation

Chemical Formula



Definition

The process by which photosynthetic microorganisms fix CO_2 into organic matter using light as an energy source and reduced iron, Fe(II), as a source of electrons.

History

The existence of microbes which could conduct photoferrotrophy was first proposed almost a decade before any bacteria capable of this metabolism were discovered. Hartman (1984) had looked at Archean and Proterozoic banded iron formations which were previously proposed to have formed when oxygen produced by cyanobacteria reacted with reduced iron (Fe(II)) in the Earth's early, oxygen-poor, ferruginous oceans (Cloud 1973). He suggested instead that these deposits were formed by photosynthetic microorganisms which harvested energy by anaerobic photosynthesis, and could use the abundant Fe(II) in the anoxic oceans as an electron donor. This process would provide a mechanism by which Fe(II) could be oxidized and Fe(III) oxyhydroxide minerals precipitated even in the absence of oxygen. Nine years later, the first anoxygenic phototrophic Fe(II)-oxidizing bacteria were discovered (Widdel et al. 1993).

Overview

It is now well accepted that photoferrotrophs could have dominated the Earth's oceans prior to the oxygenation of the atmosphere (Kappler et al.

2005), and they are still widespread in anoxic aquatic and terrestrial habitats today. Most photoferrotrophs isolated so far come from marine or freshwater sediments, or small terrestrial aquatic habitats such as iron-rich ditches or streams. They are typically of low abundance in sediments, probably due to limitations imposed by their requirement for light (Laufer et al. 2016). They can make significant contributions to Fe(II) oxidation in the anoxic and ferruginous water column of stratified lakes. For example a photoferrotroph was enriched from the water column of ferruginous Lake La Cruz in Spain and shown to contribute to Fe(II) oxidation in situ (Walter et al. 2014). Even when iron(II) is low, photoferrotrophs can still have a significant effect on the biogeochemistry of stratified lakes due to rapid recycling of Fe(II) by Fe(III) reduction in a so-called cryptic cycle. For example, they are thought to account for up to 10% of total carbon fixation in Lake Cadagno which is meromictic but low in iron due to rapid re-cycling between microbial Fe(II) oxidation and microbial Fe(III) reduction (Berg et al. 2016). Despite their apparent importance in these stratified lakes, *Chlorobium phaeoferrooxidans* which was isolated from Lake Kivu in East Africa, is currently the only isolate to originate from a ferruginous water column (Crowe et al. 2017).

All current isolates are either purple sulfur bacteria (class Gammaproteobacteria), non-sulfur bacteria (class Alphaproteobacteria), or green sulfur bacteria. The most well-studied purple bacteria isolates are *Rhodospseudomonas palustris* TIE-1 and *Rhodobacter ferrooxidans* SW2, which are both isolated from iron-rich ditches. Marine photoferrotrophs from the purple bacteria have also been isolated. All green sulfur bacteria isolates belong to the genus *Chlorobium*. The most well-studied of these is *Chlorobium ferrooxidans* strain KoFox (Heising et al. 1999), which exists only in co-culture with a heterotrophic bacterium and is from freshwater. The only marine photoferrotroph from the green sulfur bacteria which has been isolated is *Chlorobium* sp. strain N1, isolated from coastal marine sediments (Laufer et al. 2017).

Most studies with photoferrotrophs involve using aqueous Fe(II) as an iron source, but these organisms can also oxidize Fe(II)-bearing minerals such as magnetite (Byrne et al. 2015) or even use electrons from electrodes (Bose et al. 2014). During Fe(II) oxidation, Fe(III) oxyhydroxides form which are typically closely associated with the cells, forming cell-mineral aggregates (Schaedler et al. 2009). However, mineral formation inside the cells is not observed in organisms which are true photoferrotrophs, i.e., can be maintained indefinitely with just CO₂, Fe(II) and light and do not require any additional electron donors to be added. The mechanism by which photoferrotrophs avoid encrustation by minerals which form quickly when Fe(III) forms at circumneutral pH is still undefined but may be related to the formation of a low pH microenvironment observed around the cells (Hegler et al. 2010) or, more speculatively, the production of Fe(III)-complexing ligands (Croal et al. 2004; Kappler and Newman 2004). *Chlorobium phaeoferrooxidans* is the only isolated photoferrotroph which does not form cell-mineral aggregates (Crowe et al. 2017; Thompson et al. 2017).

Cross-References

- [Anaerobic Photosynthesis](#)
- [Banded Iron Formation](#)
- [Iron Oxidation](#)
- [Oxygenation of the Earth's Atmosphere](#)

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Photoionization

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

Photoionization is the chemical process in which absorption of a photon by a neutral molecule produces a positive ion (cation) and a free electron.

Photolysis

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Photodissociation](#)

Definition

Photolysis is a chemical reaction in which a chemical compound is broken down (dissociated) by the absorption of electromagnetic radiation (photons).

Cross-References

- ▶ [Interstellar Chemical Processes](#)
- ▶ [Photodissociation Region](#)

Photon

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Definition

A photon is an elementary particle that is the basic unit (quantum) of light and of all other forms of ▶ [electromagnetic radiation](#). The photon has no rest mass and no charge and by definition travels at the speed of light. It is characterized by very few parameters: its energy and its polarization state. Its energy E is directly related to the frequency ν of the electromagnetic wave it is associated with, through the relation $E = h\nu$, where h is the Planck constant.

As regards fundamental interactions, the photon is the quantum of the electromagnetic field. This means that it mediates the interaction between charged particles, that is, the electromagnetic force.

Photons belong to the broad family of bosons, which are described as the carriers of the various fundamental interactions and are a necessary consequence of physical laws having particular symmetries at every point in space-time. Because it is made of bosons, a collection of photons can present very specific properties, one of the best known being the laser or ▶ [maser](#) effect.

Photons exhibit wave-particle duality. In other words, they exhibit properties of both waves and particles. For example, a single photon follows the same path as the optical beam and can be refracted or reflected just as the electromagnetic waves which are solutions of Maxwell's equations, but it can also act as a particle, for instance, when extracting an electron from a metal (photoelectric effect).

Cross-References

- ▶ [Electromagnetic Radiation](#)
- ▶ [Electromagnetic Spectrum](#)

Photon Dominated Region

- ▶ [Photodissociation Region](#)

Photosphere

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The photosphere corresponds to the apparent visible surface of a star and especially of the Sun. It is a very thin shell where most of the light a star radiates is produced. Its thickness is less than one thousandth of the star's radius. Its temperature, which is typically between 3000 and 40,000 K, is one of the fundamental parameters characterizing a stellar type.

Cross-References

- [Effective Temperature](#)
- [Hertzprung-Russell Diagram](#)
- [Stars](#)

Photospattering

- [Photodesorption](#)

Photosynthesis

Francisco Montero
Department of Biochemistry and Molecular
Biology I, Facultad de Ciencias Químicas,
Universidad Complutense de Madrid, Madrid,
Spain

Keywords

Photobiology · Photosynthetic antennae ·
Photosynthetic generation of protonmotive
force · Photosynthetic pigments · Reaction
center

Definition

Photosynthesis is the metabolic process by means of which organisms capture light in order to carry out an ► [endergonic](#) synthesis of organic molecules. In a general sense, photosynthesis can be considered as the primary event in the process of converting the energy associated to photons into a gradient of electrochemical potential of protons across some biological membranes, that is to say, into a ► [protonmotive force](#).

Overview

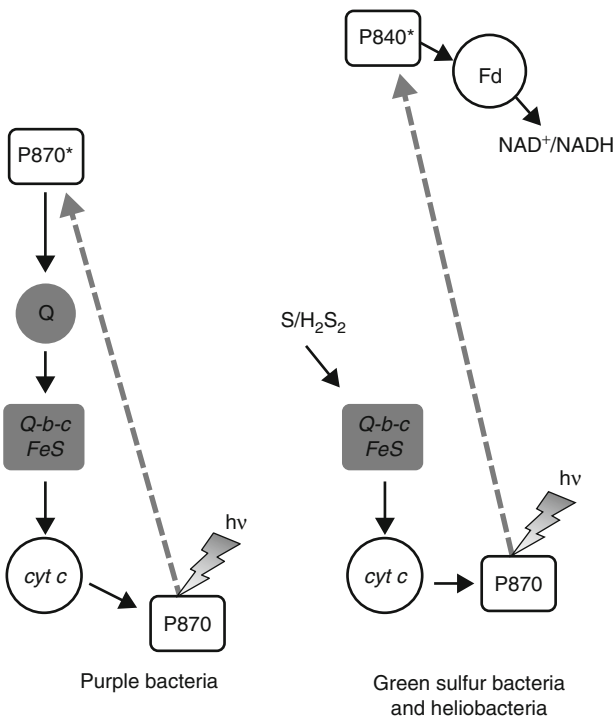
Although initially photosynthesis was used to describe the events by means of which the energy of visible light was transduced in the synthesis of sugars from carbonic anhydride in plants and cyanobacteria, the phenomenon is more general, and in all the cases the primary events are not associated with such a synthesis, but with the translocation of protons across biological membranes as the thylakoid membrane of the chloroplast in plants or the cytoplasmic membrane in photosynthetic bacteria. The different photosynthetic mechanisms can be classified into three classes:

1. Direct coupling between absorption of photons and translocation of protons, the simplest mechanism of phototransduction. One example is bacteriorhodopsin, a family of monomeric membrane proteins with a prosthetic group (retinal) that suffers a conformational change as a consequence of the absorption of light. This causes a change in the pK of several residues of the protein amino acids, leading to the exclusion of protons and then to the origination of a protonmotive force. The reentry of protons through the ► [ATP synthase](#) yields ATP. In 1971, bacteriorhodopsin from halophilic archaea was shown to function as a light-driven ► [proton pump](#). In 2000, a new type of rhodopsins, proteorhodopsins, was found in marine bacteria. These proteins are present in most of the phototrophic microorganisms living in ocean surface waters.

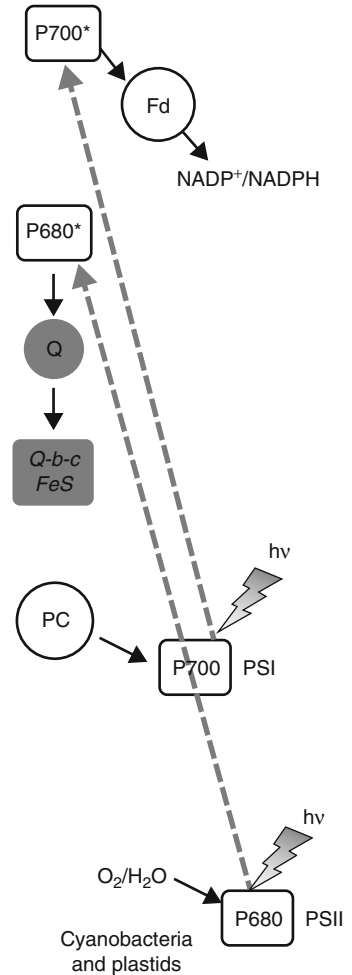
2. Cyclic ► **electron transport**. This is the case of many purple bacteria as *Rhodobacter sphaeroides* (see Fig. 1a). A dimmer of bacteriochlorophyll whose maximum of absorption is at 870 nm (P_{870}) absorbs electromagnetic radiation and, in its excited state, has a very negative ► **redox potential**. As a consequence,

an electron from the dimmer can be transferred to another spatial closed molecule, as bacteriopheophytin. Eventually, the electron comes back to the dimmer of bacteriochlorophyll through a non-hemo Fe and a ubiquinone (UQ) molecule. In the transport of electrons, a bc_1 complex, similar to complex III in the

a Anoxygenic photosynthesis



b Oxygenic photosynthesis



Photosynthesis, Fig. 1 Examples of anoxygenic and oxygenic photosynthetic electron transport chains. **(a)** In purple bacteria (*left*) and green sulfur bacteria and heliobacteria (*right*), only one photosystem is operative. After excitation by photons, the bacteriochlorophyll of the reaction center (P_{870} or P_{840}) releases an electron to a cyclic (*left*) or a linear (*right*) transport chain. In the second case, an external electron donor (usually H_2S) reestablishes the fundamental state in P_{840} . **(b)** In cyanobacteria and plastids, two photosystems act in series allowing the

transport of electrons from water to $NADP^+$. The position of the different components is approximate to their reduction potential. *Arrows* indicate electron transfer and *broken arrows*, excitation by photons; *boxes* indicate the bacteriochlorophyll (or the chlorophyll) of the reaction centers; *gray boxes* indicate a multimeric electron transport complex; *circles* indicate small electron carriers; *gray circles* indicate the quinone pool. *PS I* photosystem I, *PS II* photosystem II, *cyt* cytochrome, *Fd* ferredoxin, *PC* plastocyanin

respiratory chain, is also implicated. As a consequence of this cyclic electron transport, a net exclusion of protons from the cytoplasm of the bacteria takes place, and a protonmotive force is generated. In this kind of photosynthesis, no direct reducing power is produced. In order to get this, a reverse transport of electrons coupled with the reentry of protons is needed. Moreover, the reentry of protons drives the synthesis of ATP by means of an ATP synthase. A main conclusion of these facts is the universality of mechanisms of the transduction processes in bioenergetics and a closely related evolutionary history of these mechanisms.

3. Noncyclic electron transport. In these systems electrons flow from an initial donor to a final acceptor, eventually producing reduction power, usually NAD(P)H. In plants and cyanobacteria, the initial donor of electrons is a water molecule (see Fig. 1b). The water-splitting reaction (water photolysis) as a consequence of the absorption of electromagnetic radiation is one of the most intriguing mechanisms in the biosphere. The releasing of molecular oxygen as a consequence of water oxidation (i.e., ► [oxygenic photosynthesis](#)) has had a dramatic effect on the evolution of the chemical composition of the Earth atmosphere, from an early anoxic planet to the current oxygen-rich atmosphere. A molecule of chlorophyll (named as P_{680}) in the excited state reaches a very negative oxidoreduction potential, leading one electron to a molecule of pheophytin, resulting in a chlorophyll with a positive charge. The pair chl^+/chl has a very positive redox potential ($\sim +1200$ mV), being able to accept one electron from the water molecules. All these processes take place in the named Photosystem II, a purple bacteria-like photosynthetic center. On the other hand, other chlorophyll (P_{700}), integrated in the Photosystem I (green sulfur bacteria-like photosynthetic center), in its excited state as a consequence of absorption of light, releases one electron that through a successive transport across different molecules, including ferredoxin, eventually reduces a molecule of $NADP^+$. The P_{700}^+ so produced captures the

electron originated in the Photosystem II, which is transported sequentially through plastoquinones, *bf* complex (very similar in molecular organization to complex III in mitochondria), and plastocyanin. The main contribution to the protonmotive force is originated in the *bf* complex. Thus, in these organisms, two different photosystems are working in series.

While in cyanobacteria the photosynthetic systems are localized in the cytoplasmic membrane, in plants all the processes take place in the chloroplast, in a highly organized internal membrane named thylakoid. As a consequence of the photosynthetic processes, protons are released to the interior of the thylakoid generating the protonmotive force, and by means of an ATP synthase, the transit of the internal protons to the stroma (space between the external membrane of the chloroplast and the thylakoid) yields ATP. Both the ATP so produced and the NADPH resulting from the noncyclic transport of electrons are necessary for the fixation of the carbonic dioxide and its conversion in different metabolites. These processes classically, and incorrectly, have been known as *light-independent reactions*.

Other microorganisms, as green sulfur bacteria and heliobacteria, also show a noncyclic electron transfer in their photosystems (Fig. 1a). However, there are two main differences with respect to the photosynthetic chains of cyanobacteria (and chloroplasts): they possess only one photosystem, and the initial electron donor usually is hydrogen sulfide instead of water. Oxygen is not a by-product of these photosynthetic chains, hence the name of anoxygenic photosynthesis. The organization of the photosystems of green sulfur bacteria is closely related to Photosystem I of cyanobacteria and chloroplasts. In the same way, Photosystem II is related to photosystems of purple bacteria.

Although the mechanism described above takes place in the reaction centers, the excitation of these centers does not occur by a direct absorption of light by such centers, but by the transfer of the excitation from other molecules grouped in complexes known as antennae, and is composed

of many molecules of chlorophylls and carotenoids. Except haloarchaea, all the other photosynthetic systems have antennae. The existence of these complexes of antennae has several advantages. On one hand, the turnover time of the photosynthetic center is about 100 s^{-1} , whereas the capacity of absorption of light for this center, even under very bright sunlight, is only one ► **photon** every second. This means that without other source of excitation, the photosynthetic center will be for most of the time not working. Antennae supplies continuously excitation to the reaction center, and so the kinetic impediment mentioned above is overcome. On the other hand, the molecule components of the reaction center only absorb radiation of certain ► **wavelength**, usually near the red. That means that photons with less wavelength would be discarded. The existence of the antennae avoids this problem, harvesting photons of lower wavelength and transferring the excitation to the reaction center by means of several mechanisms, mainly by resonance and by excitons. The structural organization of the antennae around the reaction center is very precise in order to get the optimization of the excitation transfer processes.

Regarding the origin and evolution of photosynthetic electron transport chains, several models have been proposed. Since oxygenic photosynthesis is the main source of molecular oxygen known, the study of the changes in atmospheric composition throughout the geological time is a key evidence to date the origin of Photosystem II, most probably by molecular evolution from an ancestral form similar to purple bacteria photosystems. In any case, the origin of the water-oxidizing ability remains obscure. Some authors propose that the two photosystem chains arose by fusion of gene repertoires from anoxygenic photosynthetic bacteria and the late emergence of a water-splitting enzyme. On the other hand, others postulate the existence of an ancestral cyanobacteria-like microorganism encoding both photosystem types and with the ability of expressing them differentially. This model postulates the loss of the switching ability or one or the other photosystem to explain the

origin of the oxygenic or the anoxygenic photosynthesis, respectively.

Basic Methodology

Spectroscopic techniques, mainly absorption and fluorescence spectra, have been one of the main methodologies in the study of photosynthetic mechanisms. For example, a loss of absorbance (bleaching) at a certain wavelength indicates the loss of an electron of a molecule absorbing at this wavelength. On the other hand, fluorescence has been a very useful technique for evaluating the order of the transmission of the excitation as well as the kinetic details of the processes.

Details about the chain of reaction involved in the transfer of electrons have been obtained by using similar techniques as those used for the respiratory chains, for example, using some specific inhibitors of the electron transport complexes.

The structural determination of photosynthetic systems, mainly through X-ray diffraction, has been decisive in order to know precisely the mechanism of the different events that take place in the photosystems. Unfortunately, many of them have a very large size, and the preparation of crystals is difficult. At present, only a few reaction centers and antennae of some bacteria are known at atomic resolution.

Key Research Findings

- The influence of light in the consume of CO_2 and in the liberation of O_2 by the plant was first described by Jean Senebier in 1796.
- In the middle of the twentieth century, Cornelius Bernardus van Niel demonstrated that photosynthesis is a light-dependent redox reaction. In this reaction an oxidable compound (not necessarily water) reduces CO_2 to yield sugars.
- The existence of two photosynthetic systems working in parallel was derived from the so-called *red drop* or Emerson effect. This author studied the evolution of O_2 by algae

illuminated at different wavelengths. In the range from 400 to 680 nm, O₂ evolved very effectively, but at higher wavelength, the production of O₂ decreased sharply, but this production was reestablished if the system was illuminating with a non-saturating light at 650 nm.

- Determination of the structure of the reaction center of photosystems, as well as of the antennae, by X-ray diffraction. The seminal works were developed on purple bacteria photosystems by several authors (Johann Deisenhofer, Robert Huber, and Hartmut Michel).

Applications

- Artificial photosynthesis
- Agriculture and the new challenges for photosynthesis research

Future Directions

- Structural determination at atomic resolution of reaction centers and antennae systems of cyanobacteria and plants. Although some details of this are known, further studies are necessary in order to understand completely the mechanisms of actuation.
- Artificial photosynthesis. This tries to merge some aspects of photosynthesis, as the conversion of sunlight, water, and CO₂ into sugars and O₂, or to produce a protonmotive force, by using artificial membranes.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [ATP Synthase](#)
- [Bioenergetics](#)
- [Electron Transport](#)
- [Endergonic](#)
- [Oxidizing Atmosphere](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Oxygenic Photosynthesis](#)
- [Photoautotroph](#)

- [Photobiology](#)
- [Photochemistry](#)
- [Photosynthetic Pigments](#)
- [Phototroph](#)
- [Proton Motive Force](#)
- [Proton Pump](#)
- [Redox Potential](#)
- [Wavelength](#)

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Photosynthetic Eukaryotes

► [Algae](#)

Photosynthetic Organism

- ### ► [Photoautotroph](#)
- ### ► [Phototroph](#)

Photosynthetic Pigments

Francisco Montero
Department of Biochemistry and Molecular
Biology I, Facultad de Ciencias Químicas,
Universidad Complutense de Madrid, Madrid,
Spain

Keywords

Carotenoids · Chlorophyll · Photosynthesis

Synonyms

[Pigment molecules](#)

Definition

Photosynthetic pigments are the molecules responsible for absorbing electromagnetic

radiation, for transferring the energy of the absorbed photons to the reaction center, and for photochemical conversion in the photosynthetic systems of organisms capable of photosynthesis.

Overview

Photosynthetic pigments derive their name from the fact they can absorb visible light (from Lat. pi (n)g(ere) – to paint + ment(um)). The molecules of photosynthetic pigments are quite ubiquitous and are always composed of chlorophylls and carotenoids. Chlorophylls consist of a porphyrin ring, which is bounded to an ion Mg^{2+} , attached to a phytol chain. Chlorophylls form part of reaction centers – where the photochemical conversion takes place – and antennas, or light-harvesting complexes, i.e., collectors of electromagnetic radiation, whereas carotenoids are found only in the antennas. Both types of molecules are found in “quasi-crystalline” structures in photosynthetic systems, associated with protein molecules that form part of biological membranes, either the cytoplasmic membranes of photosynthetic bacteria or thylakoid membranes inside plant chloroplasts. Chlorophylls found in bacteria are called bacteriochlorophylls. Photosynthetic systems also contain another pigment, pheophytin (bacteriopheophytin in bacteria), which plays a crucial role in the transfer of electrons in photosynthetic systems. Moreover, other pigments can be found in particular photosynthetic systems, such as xanthophylls in plants.

The oxidation-reduction potential of reaction center chlorophylls in an excited state as a consequence of the absorption of a photon can become very negative, which promotes the transfer of electrons to neighboring molecules, usually pheophytins. This is the primary photochemical reaction that takes place in reaction centers.

There is one class of pigment that exists only in halobacteria, called bacteriorhodopsin. It is composed of a protein attached to a retinal prosthetic group, which is responsible for the absorption of light photons, leading to a conformational change

in the protein, which results in the expulsion of the protons from the cell.

Cross-References

- [Bacteriochlorophyll](#)
- [Chlorophylls](#)
- [Chloroplast](#)
- [Photochemistry](#)
- [Photosynthesis](#)

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Phototroph

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Synonyms

[Photosynthetic organism](#)

Definition

Phototroph is an organism that can use visible light as a primary ► [energy](#) source for metabolism, a process known as ► [photosynthesis](#). Phototrophs contrast with ► [chemotrophs](#), which obtain energy from the oxidation of organic compounds. Most phototrophs are autotrophs, also known as photoautotrophs, making use of the

energy obtained from photosynthesis to assimilate carbon dioxide (CO₂). Photoheterotrophs produce ATP using solar energy, but their source of carbon for biosynthesis is reduced organic compounds. From an ecological point of view, it has been considered that life on Earth is dependent on photoautotrophy, although the recent discovery of submarine strict chemolithoautotrophs is challenging this concept. Phototrophic organisms contain pigments that allow the use of light as an energy source.

Cross-References

- [Anoxygenic Photosynthesis](#)
- [Bioenergetics](#)
- [Carbon Dioxide](#)
- [Chemotroph](#)
- [Chlorophylls](#)
- [Chloroplast](#)
- [Cyanobacteria](#)
- [Energy](#)
- [Energy Conservation](#)
- [Halophile](#)
- [Oxygenic Photosynthesis](#)
- [Photosynthesis](#)

Phyllosilicates, Extraterrestrial

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Keywords

Hydrated minerals · Mars

Synonyms

[Clay minerals](#); [Micas](#); [Sheet silica](#)

Definition

Term for hydrated minerals that consist of parallel sheets of silicate SiO_4 tetrahedra.

Overview

Phyllosilicates are usually built as alteration products of olivine- or magnesium-rich ► [rocks](#), often associated with hydrothermal weathering. They can also result from the transformation of primary ► [minerals](#) (e.g., feldspar). Their formation is controlled by bedrock composition, climate factors (temperature, pH-value, accessibility of liquid ► [water](#)), topography, time, and kinetics of mineral reaction. During the weathering process, OH groups are incorporated into the crystal lattice, leading to the hydration of these minerals. Thus, their existence is an indicator for the long-term availability of liquid water at the time of mineralization. Depending on their tetrahedral structure, phyllosilicates are grouped in dual- and triple-layer phyllosilicates. The silicate sheets are interleaved with layers of other elements. A typical characteristic of clay minerals, which constitute a subgroup of phyllosilicates, is their ability to expand and shrink in response to the reversible adsorption of water molecules.

Extraterrestrial phyllosilicates do not differ from terrestrial ones except for the abundance of individual mineral types. Typical phyllosilicates found on ► [Mars](#) are, for example, ► [kaolinite](#) ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), smectite (e.g., montmorillonite $((\text{Na}, \text{Ca})_{0.33}(\text{Al}, \text{Mg})_2(\text{Si}_4\text{O}_{10})(\text{OH})_2 \cdot n\text{H}_2\text{O})$), and chlorite (e.g., chamosite $((\text{Fe}^{2+}, \text{Mg}, \text{Fe}^{3+})_5\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH}, \text{O})_8)$). The bulk of the Martian phyllosilicates were probably built in a nonacidic aqueous alteration regime in ► [Noachian](#) times, which has been proposed to be termed the phyllosian period (Bibring et al. 2006). The various formation hypotheses include sedimentation and aqueous alteration in fluvial channels and standing bodies of water (e.g., Story et al. 2010), impact-induced hydrothermalism (e.g., Schwenzer and Kring 2009; Marzo et al. 2010), subsurface alteration

by hydrothermal groundwater circulation (Ehlmann et al. 2011), and pedogenesis (e.g., Le Deit et al. 2012).

Cross-References

- [Carbonate, Extraterrestrial](#)
- [Mars](#)
- [Mineral](#)
- [Noachian](#)
- [Rock](#)
- [Sulfates, Extraterrestrial](#)
- [Water](#)

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Phylogenetic Tree

David Moreira

Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris,
France

Keywords

Chronogram · Cladogram · Homology ·
Phylogram

Synonyms

Evolutionary tree; Tree of life; Universal tree of life

Definition

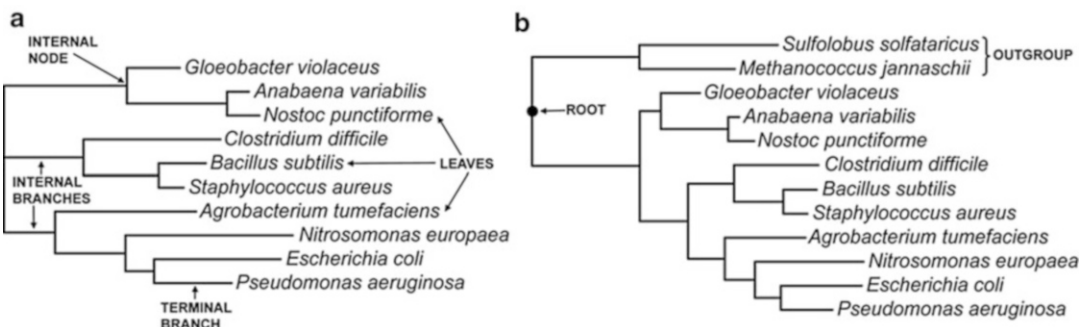
Phylogenetic trees, often called evolutionary trees, are tree-like diagrams depicting the evolutionary relationships among organisms or other entities (such as gene sequences) that derive from a **common ancestor**. Phylogenetic trees are usually drawn as bifurcating diagrams, so that technically they can be defined as noncircular connected graphs. They are composed of nodes and branches (or edges). Both branches and nodes can be internal or external. An internal node corresponds to the last common ancestor of all branches and nodes arising

from it (therefore, internal nodes are also called ancestral nodes). External or terminal nodes, also called leaves, represent the entities from which the tree was inferred. Phylogenetic trees can be rooted or unrooted (Fig. 1). In general, rooting a tree requires the use of an outgroup organism or sequence, which allows constructing directed or polarized trees (i.e., trees in which the order of changes occurring in the species or sequences can be inferred).

Overview

Phylogenetic trees are inferred using different kinds of information, in particular morphological and molecular characters. The aim of these trees is to provide an accurate representation of the evolutionary relationship between organisms or sequences using the evolutionary information contained in the characters. This information can be treated using different methods (such as distance, maximum parsimony, and maximum likelihood ones) to estimate the degree of relatedness of the units (e.g., organisms or sequences) for which the phylogenetic tree is constructed. Once the tree is constructed, it can be represented in different ways, which include: (1) cladograms, which only represent the branching pattern without drawing branch lengths proportional to the divergence between organisms or sequences; (2) phylograms, which show branch lengths proportional to the divergence (number of changes in

P



Phylogenetic Tree, Fig. 1 Phylogenetic tree of bacterial species based on ribosomal RNA sequence comparison. (a) Unrooted tree showing different elements of the tree;

(b) the same tree but rooted using two sequences of archaeal species as outgroup

the characters used) between organisms or sequences; and (3) chronograms, which have branch lengths that are proportional to the time of divergence between organisms or sequences. In addition, all these representations can be rooted or unrooted. Rooted phylogenetic trees are directed or polarized trees containing a node that corresponds to the most recent ancestor of all the leaves of the tree. This node is usually identified by using an outgroup, namely, an organism or sequence (or a set of them) that is known not to be part of the group for which the phylogenetic tree is constructed (i.e., the ingroup) but that have characters that are homologous to those used for the tree construction. Rooting the tree allows inferring the order of emergence of the different branches in the tree, as well as the order of evolutionary change in the states of the characters used to construct the tree. In contrast, unrooted trees do not specify the ancestry but just provide information about the relatedness among the branches.

The universal tree of life, also known as “the tree of life,” depicts the phylogenetic relationships among all living beings. It can be reconstructed using markers that are present in all species. The most famous version of the tree of life is based on the analysis of small subunit ribosomal RNA sequences which led to the classification of living beings into the three domains of life: Bacteria, Archaea, and Eucarya.

Cross-References

- [Common Ancestor](#)
- [Domain \(Taxonomy\)](#)
- [Evolution, Biological](#)
- [Homology](#)
- [Last Common Ancestor](#)
- [Phylogeny](#)
- [Prokaryote](#)
- [Sequence](#)

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Phylogenetics

- [Phylogeny](#)

Phylogeny

David Moreira

Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris, France

Keywords

Distance methods · Homology · Maximum likelihood · Maximum parsimony

Synonyms

[Phylogenetics](#)

Definition

Phylogeny concerns the study of the evolutionary relationships among organisms or among ► [sequences](#) of biological macromolecules (DNA, RNA, or proteins) using information from morphological, structural, developmental, or molecular markers (the latter commonly called molecular phylogeny). Phylogeny implies that the organisms or sequences analyzed derive from a ► [common ancestor](#) (i.e., the common descent principle) and that evolution proceeds through a branching process. This means that species evolve and separate into different branches or disappear (extinction). The representation of this process can be done using ► [phylogenetic trees](#). Phylogeny has become the basis of modern ► [taxonomy](#),

commonly called “phylogenetic systematics,” so that the different taxa should represent monophyletic groups inferred by phylogenetic analysis.

Overview

Phylogenetic analysis is based on the comparison of characters found in the different entities (e.g., species or gene sequences) for which a phylogenetic tree is constructed. An essential requisite for a proper phylogenetic reconstruction is that those characters have to be homologous (namely, to have been inherited from a common ancestor) and they have to be variable. This means that they can exist in different forms, which are called character states (e.g., the four nucleotides A, T, C, and G for a site in a DNA sequence or the different morphologies of organisms). The information (called “phylogenetic signal”) that is analyzed by the phylogenetic approach is contained in the particular configuration of states of the characters examined. These characters are compared among the different organisms or sequences in order to estimate their degree of relatedness, which can be measured in different ways (see the section “[Basic Methodology](#)” below).

Basic Methodology

The simplest method of phylogenetic inference is the [phenetic](#) approach based on the construction of distance matrices based on overall similarity between the entities studied compared two by two (the simplest distance is the p-distance or the number of characters with different character states divided by the total number of characters, and it can be expressed as a percentage of similarity). More sophisticated methods include maximum parsimony, maximum likelihood, and Bayesian inference. These are called discrete data methods because they examine each character separately and look for the phylogenetic tree that best accommodates the corresponding information. Maximum parsimony, a method inspired by the cladistic approach, is intended to find the phylogenetic tree that minimizes the number of

changes required to explain the distribution of character states found in the set of organisms or sequences studied. Maximum likelihood and Bayesian inference require a model of character evolution (or substitution model), that is, a series of rules about the probabilities of change from a given character state to the other possible states. Using this kind of models, maximum likelihood estimates the probability for each character of the distribution of character states found in the set of organisms or sequences studied and tries to find the phylogenetic tree with maximum global probability for the entire set of characters analyzed. Bayesian inference has a similar basis, but it also evaluates the probability of the character data set for a given phylogenetic tree.

Distance methods are much faster than discrete data methods but they are much less informative: Their outcome is only a phylogenetic tree whereas the other methods also provide information about the evolution of the different characters along the tree. The only way to assure that the best phylogenetic tree has been found using the discrete data methods is to test all the possible trees to choose the most parsimonious or the most likely one. However, this is possible in practice only for data sets containing a very small amount of species or sequences. In fact, for a data set of size 10, there are 2,027,025 possible different bifurcating trees, and the number is of $\sim 2 \times 10^{20}$ different trees for 20 species. The latter are impossible to treat in a reasonable time using the complex parsimony or likelihood calculations. Therefore, different techniques of non-exhaustive exploration, called heuristic search methods, have been developed to search the tree space of all possible trees. Nevertheless, they do not assure retrieving the best tree.

Phylogenetic analysis can be biased by a series of data and methodological problems that have been characterized in the last decades. Stochastic errors arise when all character states have not changed following the same evolutionary pattern. This problem is particularly critical when a small number of characters are used for phylogenetic analysis. Therefore, there is a tendency to utilize as much characters as possible (the “total evidence” approach), though this can induce other

types of problems (the systematic biases) which can be exacerbated by the addition of increasing number of characters, especially when they are analyzed using models that do not describe correctly the evolutionary process. Convergent evolution is a well-known source of error that can lead to the inference of incorrect phylogenies. For example, parasitic species often have simple morphologies because they lose organs that are unnecessary since many functions are provided by their hosts. Therefore, parasites of different evolutionary origins may be artificially grouped together in phylogenies because of their convergent similarity. Molecular phylogeny can also be affected by convergence problems. For example, hyperthermophilic prokaryotes tend to have ribosomal RNA (rRNA) sequences rich in G and C nucleobases because they are more stable at high temperatures. Phylogenetic trees reconstructed using rRNA sequences analyzed with inadequate models can group hyperthermophiles of different origins just because their sequences may appear to be similar due to their high GC content. This type of compositional bias is a clear example of systematic error in molecular phylogeny because the artefactual result becomes stronger as more and more sequence data are used. This is also the case with fast-evolving species or sequences, which are affected by the so-called long-branch attraction artifact: the tendency to group fast-evolving entities irrespective of their true evolutionary relationships.

Key Research Findings

The findings of the application of phylogenetic analysis to the study of biological evolution and diversity have been numerous and very important, beginning with the recognition during the eighteenth and nineteenth centuries that many animal and plant fossils could be affiliated to groups still existing, or the discovery that contemporary birds are the descendants of an ancient dinosaur ancestor. However, it is thanks to the development of molecular phylogeny based on the analysis of DNA and protein sequences that the most radical

changes in our view of biological evolution have been possible. In particular, the first phylogenies based on the comparison of the rRNA gene sequences led to the discovery in the late 1970s that all living beings can be classified into three major groups or domains, Eukaryotes, Bacteria, and Archaea, the latter being unknown to the scientific community until then (Woese and Fox 1977). Molecular phylogeny has also demonstrated the endosymbiotic origin of mitochondria and chloroplasts from bacterial ancestors (alphaproteobacteria and cyanobacteria, respectively), as well as the importance of horizontal or ► [lateral gene transfer](#) in microbial evolution.

Applications

The applications of phylogenetic analysis are extremely diverse, from very basic to applied ones. It is the tool of choice to address a variety of evolutionary questions, not only the inference of the evolutionary relationships between species but also the evolution of genes (including gene duplications, horizontal gene transfer, etc.) and biogeography. Phylogeny has also a large spectrum of medical applications, including epidemiology studies and forensic medicine.

Future Directions

Phylogeny is a very active field of research in evolutionary biology. Particular effort is now devoted to take advantage of the huge amount of molecular data that are made available by the sequencing of complete genomes or large scale metagenome projects. This has launched a new field called phylogenomics, which is promoting active investigation to improve algorithms and models to cope with very big data sets.

Cross-References

- [Biodiversity](#)
- [Bioinformatics](#)
- [Common Ancestor](#)
- [Domain \(Taxonomy\)](#)

- [Evolution, Biological](#)
- [Homology](#)
- [Lateral Gene Transfer](#)
- [Phenetics](#)
- [Phylogenetic Tree](#)
- [Sequence](#)
- [Taxonomy](#)

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Phylotype

David Moreira and Purificación López-García
Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris, France

Synonyms

[Environmental sequence](#); [Operational taxonomic unit](#); OTU

Definition

In microbiology, a phylotype is an environmental DNA sequence or group of sequences sharing more than an arbitrarily chosen level of similarity of a particular gene marker. The most widely used phylogenetic marker is the small subunit ribosomal RNA gene. Two prokaryotic sequences are generally considered as belonging to the same phylotype when they are more than 97–98% identical (for eukaryotes, the values generally used are in the 98–99% nucleotide identity range). In prokaryotic microbiology, phylotypes, often referred to as Operational Taxonomic Units (OTUs), are a proxy for ► [species](#).

Cross-References

- [Phylogeny](#)
- [Species](#)
- [Taxonomy](#)

Phylum

David Moreira and Purificación López-García
Unité d'Ecologie, Systématique et Evolution
CNRS UMR8079, Université Paris-Sud 11, Paris, France

Synonyms

[Division](#)

Definition

Plural, phyla. A phylum is a high-order taxonomic category in the hierarchical biological classification system. Situated below the domain and kingdom levels, it is above the taxonomic level of class. The term Division is used as synonym, particularly in botany. In prokaryotic microbiology, although the term phylum is preferred for taxa including cultivated members, the expression “Candidate Division” is used for clusters of environmental sequences that, phylogenetically, constitute groups equivalent to phyla for described species.

History

The term was coined in 1876 to mean a “division of the plant or animal kingdom” by the French naturalist Georges Dagobert, Baron Cuvier (1769–1832), from the Greek phylon “race, stock,” related to phyle “tribe, clan,” and phylein “bring forth.”

Cross-References

- [Taxonomy](#)

Physical Adsorption

► Physisorption

Physicalism

Physicalism Malaterre

Institut d'Histoire et Philosophie des Sciences et Techniques (IHPST), Université Paris 1-Panthéon Sorbonne, Paris, France

Keywords

Materialism · Metaphysics · Physical theory · Physicalism · Supervenience

Synonyms

[Materialism](#)

Definition

Physicalism is the metaphysical thesis that everything is physical. According to this thesis, everything in the world, including chemical, biological, mental, and social entities and processes, is constituted by or results from physical entities and processes. In analytic philosophy, one might say that physicalism is the claim that everything supervenes on, or is necessitated by, the physical.

Overview

Physicalism is sometimes taken as synonymous to ► [“materialism”](#). Historically though, the word had a different meaning as it used to be associated with a particular linguistic thesis of positivist philosophers of the Vienna Circle. It is now generally understood as a metaphysical claim about the nature of the world emphasizing a connection to physics and the physical sciences (and no longer

solely to matter, as was initially the case with “materialism”). According to physicalism then, everything that exists is physical.

As such, this claim blends three types of questions, each of which is controversial on its own: What does it mean to say that *everything* satisfies a given condition? What does it mean for something to say that it satisfies the condition of being *physical*? And, is it *true* that everything is physical?

One answer to the first question is to appeal to the notion of supervenience. Accordingly, “everything is physical” is taken to mean that “everything supervenes on the physical,” or, in other words with the language of modal logic, that “no two possible worlds can be identical in their physical properties yet differ in some of their other properties such as their chemical, biological, mental or social properties” (e.g., Davidson 1970; Lewis 1986; Stalnaker 1996).

One way to answer the second question is to link the notion of a physical property to that of a physical theory. Accordingly, a “property is physical” is taken to mean that this property belongs to (or supervenes on) the type of properties that physical theory tells us about (e.g., Smart 1978; Chalmers 1996; Stoljar 2001).

Different answers to both questions are possible as they remain much controversial (as exemplified by the debate about nonreductive physicalism and emergence).

As to the truth question of physicalism, much debate arises in philosophy of mind: in particular, the existence of qualia (i.e., the felt qualities of experience) that would be distinct from the physical is considered as one of the most serious challenges to physicalism (e.g., Chalmers 1996), whereas the argument of the causal closure of the world (i.e., intuitively the idea that every cause is a physical cause) is usually taken as establishing physicalism (e.g., Kim 1993).

Cross-References

- [Chance and Randomness](#)
- [Materialism](#)
- [Reductionism](#)
- [Vitalism](#)

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Physisorption

Steven B. Charnley
Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Physical adsorption](#)

Definition

Physisorption involves van der Waals interactions between an adsorbed atom or molecule and the molecules present in a solid surface, such as that of an interstellar grain. This weak bonding contrasts with the strong, covalent bonding of [chemisorption](#).

Cross-References

- [Chemisorption](#)
- [Interstellar Dust](#)

Phytoplankton

Zoe V. Finkel¹ and Andrew J. Irwin²

¹Department of Oceanography,
Dalhousie University, Halifax, NS, Canada

²Department of Mathematics and Statistics,
Dalhousie University, Halifax, NS, Canada

Keywords

Algae · Phytoplankton · Primary production · Biogeochemistry · Climate change

Synonyms

[Algae](#); [Microalgae](#)

Definition

The term plankton comes from the Greek meaning to drift or wander and was introduced in 1887 by Victor Hensen to refer to biological matter that drifts in bodies of water (Mills 1989). The term phytoplankton refers to the photosynthetic species of the plankton community. Phytoplankton are a genetically diverse set of organisms that include the prokaryotic cyanobacteria and many eukaryotic groups (Hackett et al. 2007; Simon et al. 2009).

Overview

Evolutionary History

Microfossil and molecular clock evidence indicates that prokaryotes originated in the Archean and eukaryotes in the Proterozoic (Betts et al. 2018). Determining when these groups first became photosynthetic, first became planktonic, and whether they originally inhabited fresh or marine environments is extremely challenging. Analyses of extant cyanobacterial genomes indicate that photosynthesis may have been acquired relatively late in the evolution of cyanobacteria, perhaps not long before the rise of oxygen ~2.3 billion years ago (Soo et al. 2017), and the

currently dominant oceanic picocyanobacteria, *Prochlorococcus* and *Synechococcus*, did not emerge until the Cryogenian, ~850 to 635 million years ago (Sánchez-Baracaldo 2015). While the photosynthetic eukaryotic lineages trace their origins to the Proterozoic, the dominant eukaryotic phytoplankton groups in the ocean today, namely, the diatoms, dinoflagellates, and coccolithophores, arose in the Mesozoic (Falkowski et al. 2004; Katz et al. 2004). Dinoflagellates and coccolithophores exhibit their highest levels of morphological diversity in the Mesozoic, while the diatoms reach their highest diversity in the later part of the Cenozoic.

Diversity

The global estimate of marine phytoplankton richness based on microscopy ranges from 3444 to 4375 species in marine waters to about 14,000 in freshwaters (Sournia et al. 1991). A majority of the described marine species are dinoflagellates and diatoms, with a smaller number of haptophytes and green algae (Sournia et al. 1991; Simon et al. 2009). Recent molecular analyses are providing new insight into the diversity of phytoplankton. A study based on the DNA sequence of the V9 region of the 18S ribosome estimates the diversity of marine eukaryotic plankton (both photosynthetic and non-photosynthetic members) at ~150,000 operational taxonomic units (OTUs) (de Vargas et al. 2015). The highest levels of diversity are associated with the smallest size fraction examined, cells with diameters between 0.8 and 5 μm . The picoplankton include photosynthetic, mixotrophic, and heterotrophic members such as parasites and symbiotic hosts. While some taxonomic groups of phytoplankton are strictly photoautotrophs (depending strictly on light for energy), many of the eukaryotic groups are mixotrophic (meaning they acquire energy through a combination of photosynthesis and heterotrophic nutrition) (Stoecker et al. 2017).

Phytoplankton Functional Groupings and Their Biogeography

Phytoplankton species are often grouped into a modest number of clusters based on their

ecological or biogeochemical role, termed phytoplankton functional types. The major marine phytoplankton groupings are described below. In some cases, there is overlap between evolutionary history (taxonomic group), cell size, and ecological and biogeochemical function. Biogeochemically, while all phytoplankton species use N and P, only some use Si (primarily the diatoms), and only a few can fix N_2 into reduced nitrogen (cyanobacteria). The stoichiometry of both the macro- and trace elements requirements (especially Fe) and ability to acquire resources vary across many of these groups. Differences in elemental requirements and ability to acquire resources are important determinants of the biogeography of phytoplankton functional groups.

Cell Size

Phytoplankton cell size influences competitive ability for resources, sinking rate, grazing susceptibility, and ecological and biogeochemical function (Finkel et al. 2010). Traditionally ecological and biogeochemical studies have divided the phytoplankton into three size classes (Sieburth et al. 1978): the picoplankton (0.2 to about 2–3 μm (10^{-6} m) in cell diameter), the nanoplankton (2–20 μm), and the microplankton (20–200 μm). Commonly, picophytoplankton communities are dominated by picocyanobacteria, while diatoms and dinoflagellates often constitute the largest fraction of the microplankton communities. Generally small cells thrive in stable and lower nutrient conditions, and larger cells predominate in environments with episodic and higher nutrient concentrations. Furthermore, larger phytoplankton are associated with higher trophic (fish yield) and carbon export efficiency (but see Richardson and Jackson (2007)).

Cyanobacteria

Cyanobacteria are often divided into two functional groupings: the (1) non-nitrogen-fixing picocyanobacteria and (2) nitrogen-fixing cyanobacteria. The dominant non-nitrogen-fixing picocyanobacteria in the ocean are dominated by two genera: *Prochlorococcus* and *Synechococcus* (see Partensky et al. 1999). Both are solitary coccoid species, but they differ in size and

pigment composition. *Prochlorococcus* is smaller than *Synechococcus*, 0.6 versus 0.9 μm in diameter, and uses divinyl chlorophyll a/b versus phycobilisomes. These differences in cell size and pigment composition influence their competitive ability under different nutrient and light regimes. *Prochlorococcus* often dominates phytoplankton biomass in much of the oligotrophic open ocean and can be found both in surface waters and deeper in the euphotic zone. *Synechococcus* is common in the surface of the oligotrophic ocean and increases in abundance and biomass in areas with episodic and higher nutrient inputs. *Prochlorococcus* has a more restricted geographic distribution and is found at a narrower range of salinities and warmer temperature than *Synechococcus*.

Nitrogen-fixing cyanobacteria convert N_2 into ammonia, providing a biologically useful source of fixed nitrogen to aquatic ecosystems that stimulates photosynthetic carbon fixation and export into the deep sea. Nitrogen fixation is catalyzed by the enzyme nitrogenase that is inactivated by oxygen. Many photosynthetic nitrogen-fixing organisms isolate nitrogenase in a specialized cell, termed a heterocyst, which isolates nitrogenase from oxygen. There are several single-celled, nitrogen-fixing cyanobacteria and non-heterocystous colonial species that segregate nitrogen fixation and oxygenic photosynthesis over time or across the cell or colony. Common open-ocean marine nitrogen-fixing cyanobacteria include the non-heterocystous colonial *Trichodesmium*, the single-celled *Crocosphaera watsonii*, and the photo-heterotrophic (does not use CO_2 as a C source) haptophyte symbiont UCYN-A (Martínez-Pérez et al. 2016). Common heterocystous forms include the free-living genera *Nodularia* and *Anabaena* and the diatom symbiont *Richelia intracellularis* (Sohm et al. 2011). *Nodularia* and *Anabaena* are typically found in cooler, more brackish, coastal regions, such as the Baltic Sea. In oligotrophic oceans, diatom diazotroph (can grow without external source of fixed N) associations (DDAs) provide biologically available nitrogen to diatom hosts (Villareal 1994). Common diatom hosts include *Hemiaulus* and

Rhizosolenia with the nitrogen-fixing symbiont *Richelia*. DDAs are especially well documented in the western tropical North Atlantic near the Amazon river plume but may be much more widely distributed (Subramaniam et al. 2008).

Picoeukaryotes

The photosynthetic picoeukaryotes are taxonomically diverse, many (but not all) species are flagellated (phytoflagellates), and many are mixotrophs. Many of the picoeukaryotes contain only a single mitochondrion, Golgi apparatus, and chloroplast. Photosynthetic picoeukaryotes can reach densities between 10^3 and 10^5 cells per milliliter in surface waters (see Massana 2011) and tend to reach their largest relative abundances in moderately oligotrophic to mesotrophic conditions. Traditionally the picoeukaryotes are difficult to identify by light microscope, but molecular methods provide new insight into their spatial and temporal controls. Prasinophyceae, Pelagophyceae, Bolidophyceae, and Pinguiphyceae are common groups of photosynthetic picoeukaryotes found in the ocean.

Calcifying Coccolithophores

Coccolithophores, most notably the nanoplankton *Emiliania huxleyi*, which forms large blooms, produce inorganic carbon as well as organic carbon. Coccolithophores are covered in calcite scales (termed liths), which may affect predation rates and light harvesting. Their production (Monteiro et al. 2016) has a direct effect on alkalinity, dissolved inorganic carbon, and pH. Some species of coccolithophores are particularly sensitive to changes in pH and may be strongly affected by ocean acidification (Riebesell et al. 1993). The downward flux of liths made of CaCO_3 removes carbon from the surface ocean and augments the biological pump of organic carbon.

Silicifying Phytoplankton

Diatoms are a dominant group of phytoplankton, responsible for almost half of all marine primary production. They range in size from 2 to several 1000s of micrometers in diameter (Finkel et al. 2005). Despite this diversity, they are best known for their species, which grow rapidly, are strong

competitors for nutrients, and form large, intense blooms. Diatoms play an important role in supporting fish production and in the export of carbon into the deep sea (Tréguer et al. 2017). Notably, diatoms have an obligate requirement for silicon to form a rigid frustule as part of their cell wall. Small differences in frustule structure are diagnostic of individual species. Although diatoms are the ecologically dominant silicifying phytoplankton group, several other phytoplankton groups incorporate Si, for example, silicoflagellates construct a skeleton of fused Si bars and rods. Some of the cyanobacteria have been shown to have a requirement for a trace amount of Si.

Dinoflagellates

Dinoflagellates are a diverse group with intermediate- to large-sized species and incorporate autotrophs, heterotrophs, and a large number of mixotrophs. Morphologically, they are characterized by two flagella and, for many species, the presence of an armored cell wall composed of chemically resistant organic plates called theca. Dinoflagellates generally have slower growth rates than diatoms (Tang 1996) and tend to be found in higher abundance in warmer, stratified waters.

Biogeochemical and Ecological Significance of the Phytoplankton

Phytoplankton perform approximately half of the photosynthesis on Earth: 45–50 Pg C per year (Falkowski et al. 1998). Photosynthesis splits water molecules, releasing O₂ into the atmosphere, and converts inorganic dissolved carbon and nutrients into biomass. As a consequence, phytoplankton influence the biogeochemistry of the Earth and fuel aquatic and marine food webs. Although total phytoplankton productivity is approximately the same as land plants, the total biomass of phytoplankton is a tiny fraction of land plant biomass, so carbon flows from inorganic forms through phytoplankton and into other pools relatively quickly. Most of the organic carbon fixed and oxygen evolved by phytoplankton is quickly respired by grazers or the microbial decomposers, reversing the process of

photosynthesis. A small fraction of the organic carbon is transferred to long-lived organisms such as fish and marine mammals. Another small fraction is exported from the pelagic (surface sunlit) zone into the deep ocean and sediments. Carbon exported to the deep ocean and sediments is effectively removed from interactions with the atmosphere for thousands to many millions of years, respectively. It is this long-term export of carbon into the deep ocean and sediment that regulates atmospheric CO₂ and O₂ content.

Phytoplankton community composition and primary production vary in space and time (Finkel 2014). Generally, biomass and production are highest in regions where light and nutrients in the upper mixed layer of the ocean are sufficient to support high rates of photosynthesis, for example, in coastal and upwelling systems. In contrast, biomass and primary production becomes diminished and less variable in regions with deep surface mixed layers where average light experienced by phytoplankton is low, as occurs over much of the high-latitude oceans in winter and in low-nutrient regions, such as the subtropical central oceanic gyres. Inorganic nitrogen and iron and, to a lesser extent, phosphate are the most common elements limiting marine phytoplankton production. Other factors that influence the primary production include inorganic carbon concentration and pH, light dose, period, quality, turbulent mixing, and species interactions, as well as loss due to grazing by zooplankton and infection by parasites and viruses. The taxonomic and size structure of phytoplankton communities is shaped by environmental conditions and biotic interactions and, in turn, influences the structure of the food web and fraction of primary production that is ultimately exported out of the ocean surface to the sediments.

Basic Methodology

Traditionally phytoplankton have been collected via nets and water samples and identified using light microscopy (Mills 1989). Molecular analyses are increasingly being used to characterize phytoplankton community diversity (de Vargas

et al. 2015). Chlorophyll-*a* is often used to estimate phytoplankton biomass in the field, and satellite remote-sensed chlorophyll is used to generate global estimates of both biomass and net primary production (Falkowski et al. 1998).

- Carbon Cycle, Biological
- Cyanobacteria
- Cyanobacteria, Diversity and Evolution of
- Nitrogen Fixation
- Photosynthesis

Key Research Findings

Warming ocean temperatures over the coming century will lead to wide-ranging changes in the physical, chemical, and biological state of the ocean. The amount of phytoplankton biomass, their rate of production, and the species present will be modified as much of the surface ocean becomes warmer and lower in nutrients. There is evidence that increasing warming and water-column stratification will reduce phytoplankton primary production (Behrenfeld et al. 2006) and that increasing CO₂ concentrations could fundamentally alter rates of nitrogen fixation by key cyanobacteria such as *Trichodesmium* (Hutchins et al. 2007) and calcification by coccolithophores (Riebesell et al. 1993). Taken all together, these effects are expected to lead to widespread changes in phytoplankton community structure and the global biogeochemical cycles of carbon and nitrogen.

Future Directions

Wider application of molecular tools, culture work, and statistical analyses will further improve our understanding of phytoplankton and how these species respond to different chemical and physical stimuli. A better knowledge of how environmental conditions influence functional types will enable improved models of production, export of carbon to the deep ocean, and changes in trophic transfer efficiency through the food web.

Cross-References

- Algae
- Biogeochemical Cycles

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► Isoelectric Point

Piezophile

Daniel Prieur

Université de Bretagne Occidentale (University of Western Brittany), Brest, France

Institut Universitaire Européen de la Mer (IUEM), Technopôle Brest-Iroise, Plouzané, France

Keywords

Deep biosphere · Deep-sea · Extremophile · Hydrostatic pressure

Synonyms

Barophile

Definition

A piezophile (adjective – piezophilic) is an organism that lives under elevated hydrostatic pressure. While piezotolerant organisms only tolerate high pressures, piezophiles grow better under high pressures, and strict or obligate piezophiles require pressures above atmospheric pressure for growth. Piezophiles are known among vertebrates and invertebrates but prokaryotic piezophiles (Bacteria and ► [Archaea](#)) are the most extensively studied. They live in various habitats that are exposed to elevated hydrostatic pressure (deep aquifers, deep oil reservoirs, etc.), but the best known are from the deep ocean floor.

Overview

Hydrostatic pressure is a function of the weight of liquid above a given surface. Hydrostatic pressure is expressed in different units: $1 \text{ kg cm}^{-2} = 1 \text{ atm} = 1 \text{ bar} = 0.103 \text{ MegaPascal (MPa)}$. Hydrostatic pressure increases 0.103 MPa every 10 m of water. At the seafloor in the Marianna Trench (10,790 m), hydrostatic pressure is about 110 MPa. Study of piezophilic organisms requires the use of bioreactors that simulate high pressure conditions. After many years of research on this topic, microbiologist A. Yayanos (Scripps Institution of Oceanography, San Diego, USA) concluded that piezophily is a common property for bacteria isolated from cold deep oceans at depths from 1957 to 10,476 m. He observed that in cold oceans, there is a piezophily threshold at about 1800–2000 m, and that piezophily increases with the depth of capture. A. Yayanos was the first to isolate, from a dead amphipod collected at the Marianna Trench, the first strict piezophile, strain MT 41, that grows optimally at 2 °C and 69 MPa, with a generation time of 25 h. This organism was unable to grow at pressures below 39 MPa, and died when exposed at

atmospheric pressures. Only known for ► [psychrophiles](#) for many years, piezophilic organisms have recently been discovered for hyperthermophilic Archaea living at deep-sea hydrothermal vents. D. Prieur's laboratory (University of Brest, France) isolated the archaeon *Pyrococcus yayanosii* strain CH1 from samples collected at 4100 m from the mid-Atlantic Ridge. This strictly anaerobic organism grows optimally at 95 °C and 52 MPa, with a generation time of 51 min, and requires more than 15 MPa for growth. For bacteria, the cellular membrane and cell wall are involved in mechanisms of adaptation to elevated hydrostatic pressure. When grown at increasing pressures, piezophiles showed an increase in long chain polyunsaturated fatty acids located in the cell membrane. Also, it was found that specific porins located in the outer membrane of Gram-negative organisms were expressed with increasing pressures. Further studies on piezophiles will require the development of innovative techniques, such as diamond anvil cells, that allow microorganisms living under pressure to be imaged and Raman spectroscopy among other techniques to analyze their metabolism.

Cross-References

- [Black Smoker](#)
- [Deep Subsurface Microbiology](#)
- [Deep-Sea Microbiology](#)
- [Extremophiles](#)
- [Hot Vent Microbiology](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Hyperthermophile](#)
- [Psychrophile](#)

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Pigment Molecules

► Photosynthetic Pigments

Pilbara

► Pilbara Craton

Pilbara Craton

Martin J. Van Kranendonk
School of Biological, Earth and Environmental
Sciences, University of New South Wales,
Sydney, NSW, Australia

Keywords

Archean · Greenstone belt · Granite ·
Australia · Astrobiology sites · Stromatolites

Synonyms

Pilbara

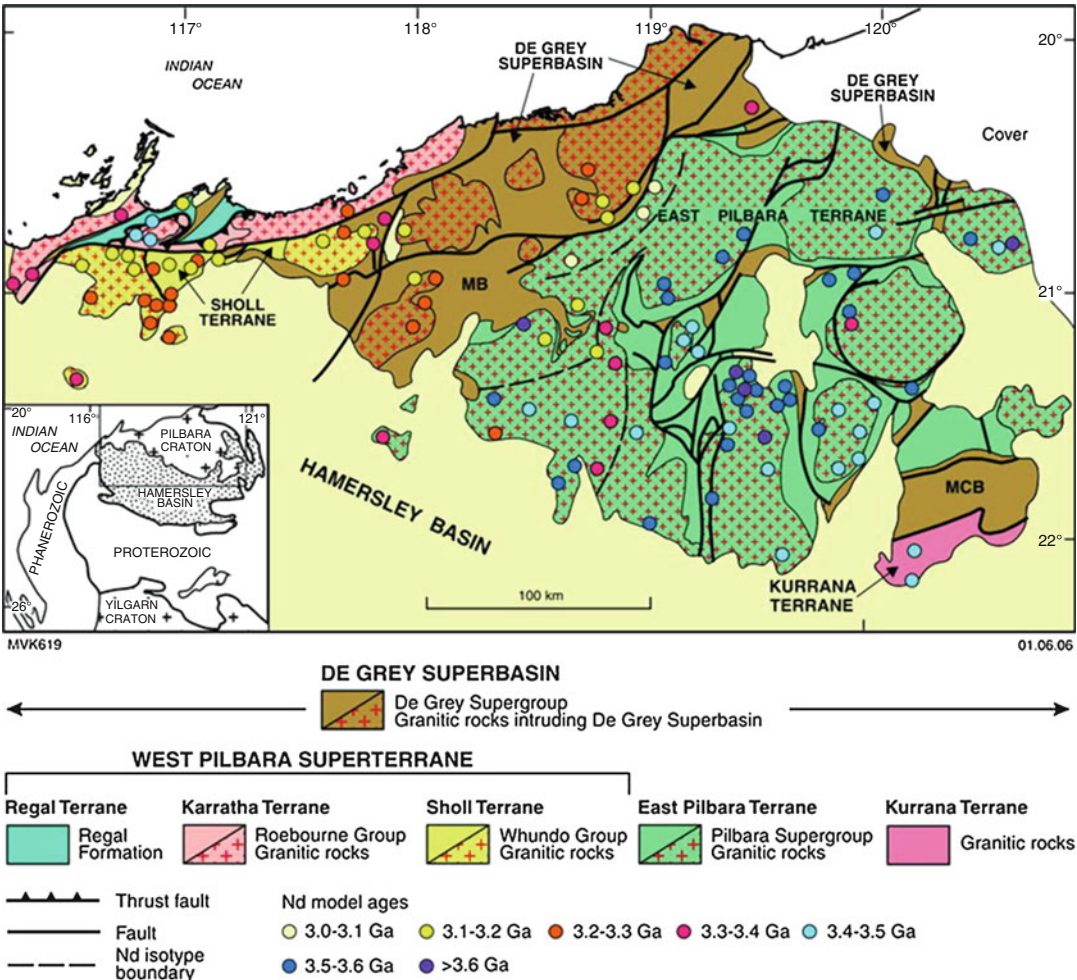
Definition

The Archean Pilbara Craton in northwestern Australia is a nearly circular piece of generally low-grade granite-greenstone crust, whose boundaries are defined by aeromagnetic and gravity anomalies and by flanking Proterozoic orogenic belts. The northern part of the craton is well exposed over an area of 530×230 km and is divided into several discrete terranes with distinct geological histories from 3.52 to 3.11 Ga that were stitched together by granites and overlain by late sedimentary basins during accretion and subsequent crustal relaxation from 3.07 to 2.83 Ga. The Pilbara Craton is famous for containing some of the Earth's oldest well-preserved rocks and fossil ► [stromatolites](#) and is a location for several astrobiology analogue sites and ► [Archean drilling projects](#) (see single entries listed below for a detailed description of those Pilbara's localities of astrobiology interest).

Overview

The Archean Pilbara Craton consists of five terranes, five late-tectonic, dominantly clastic sedimentary basins, a variety of granite suites, and a suite of large layered mafic-ultramafic igneous complexes (Fig. 1: Van Kranendonk et al. 2007). Terranes include the 3.53–3.17 Ga East Pilbara Terrane, representing the ancient nucleus of the craton; the ≥ 3.18 Ga Kurrana and ≥ 3.27 Ga Karratha terranes, which have older Nd-model ages and may represent rifted fragments of the ancient nucleus; c. 3.20 Ga Regal Terrane of ► [komatiites](#) and basaltic rocks; and juvenile volcanic rocks of the c. 3.12 Ga Sholl Terrane, interpreted as a rifted oceanic arc complex (Smithies et al. 2005).

The East Pilbara Terrane is underlain by the 3.53–3.17 Ga Pilbara Supergroup, which consists of four thick, autochthonous volcano-sedimentary



Pilbara Craton, Fig. 1 Simplified geological map of the northern Pilbara Craton, showing the East Pilbara Terrane, West Pilbara Superterrane, Kurrana Terrane, and the distribution of the c. 3.02–2.93 Ga De Grey Supergroup in the

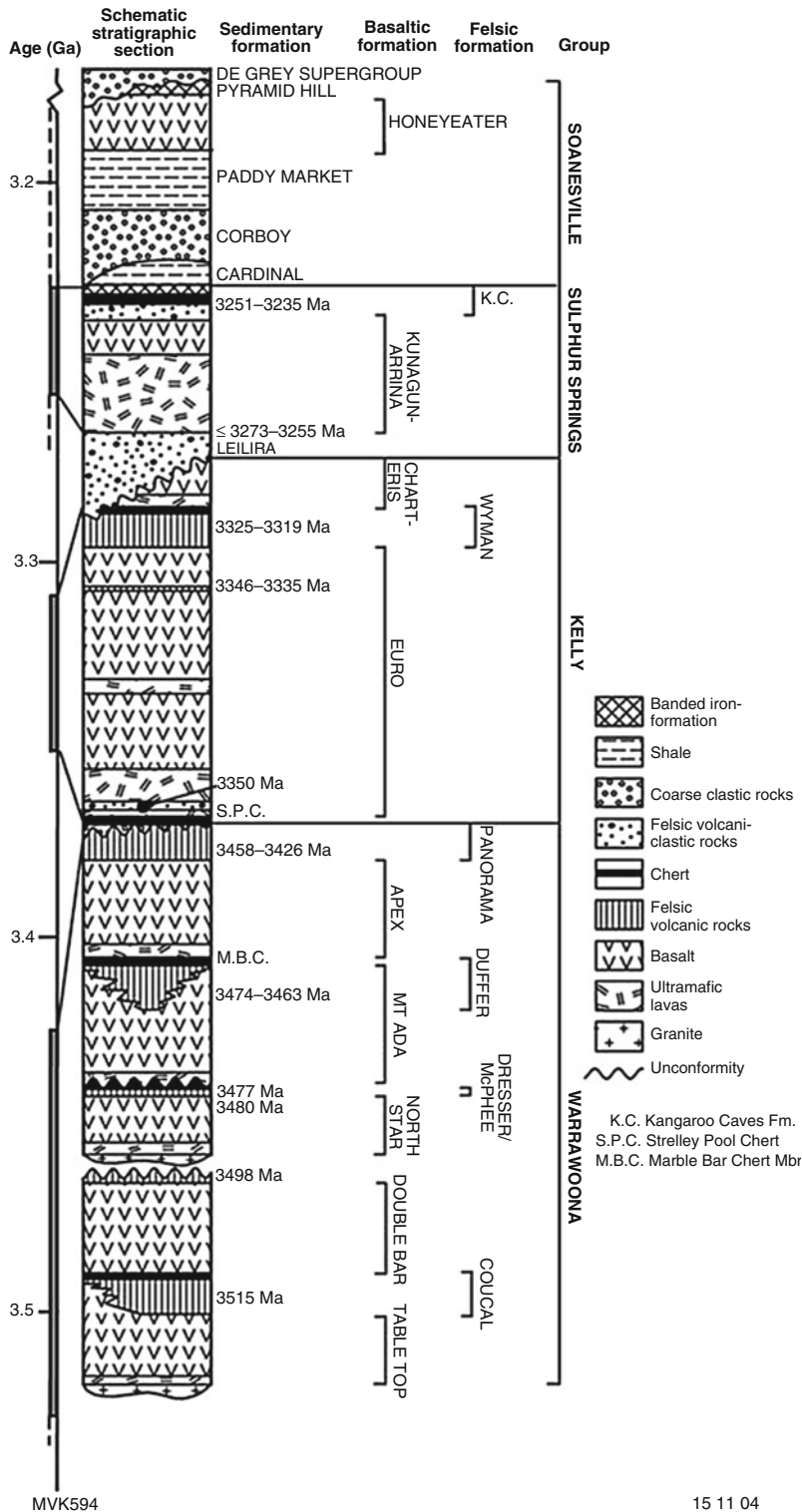
Mallina Belt (MB), Mosquito Creek Belt (MCB), and areas in between. Colored or gray dots denote whole-rock Nd model ages

groups deposited on granitic crust up to 3.82 Ga old (Fig. 2). The lower three groups were erupted episodically to 3.24 Ga from melts derived from both fertile mantle and progressively depleted subcontinental mantle, leading to a thick mantle root. The stratigraphically highest Soanesville Group was deposited during rifting of East Pilbara Terrane margins at c. 3.18 Ga, followed by ocean closure at 3.12 Ga and terrane accretion at 3.07 Ga. Diverse evidence for life is preserved at a variety of levels throughout the supergroup and elsewhere through the craton (Van Kranendonk et al. 2007).

The dominantly coarse clastic De Grey Supergroup was deposited across the whole of the craton during post-orogenic collapse (3.01–2.99 Ga) and subsequent regional orogeny (2.97–2.91 Ga). Major depositional basins include the c. 3.02 Ga Gorge Creek Basin across the whole of the craton, and the 2.97–2.94 Ga Mallina and Mosquito Creek basins (Fig. 1). Lithospheric extension occurred at c. 3.02 Ga and 2.97–2.95 Ga, followed by compressional deformation at 2.94–2.905 Ga during accretion of Kurrana Terrane (Van Kranendonk et al. 2007).

Pilbara Craton,

Fig. 2 Simplified stratigraphic column of the Pilbara Supergroup in the East Pilbara Terrane, showing available age dates. Unconformity at the top of the Coonterunah Subgroup is with the base of the Kelly Group. Unconformably overlying, topmost coarse clastic unit represents the De Grey Supergroup in the Lalla Rookh Basin



Cross-References

- [Apex Basalt, Australia](#)
- [Apex Chert](#)
- [Apex Chert, Microfossils](#)
- [Archean Drilling Projects](#)
- [Archean Tectonics](#)
- [Archaean Traces of Life](#)
- [Banded Iron Formation](#)
- [Barberton Greenstone Belt](#)
- [Earth, Formation, and Early Evolution](#)
- [Komatiite](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)
- [Stromatolites](#)

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process of conjugation involves a donor cell, which contains a particular type of ► [plasmid](#), a conjugative plasmid, and a receptor cell. Several plasmid genes are involved in the synthesis of sex pili. Only donor cells produce pili. Pili allow specific pairing between the donor cell and the recipient cell. The pili make specific contact with a receptor of the recipient cell and then retract, pulling the two cells together. When the contact between the donor and the recipient cells becomes stable, the plasmidic DNA is then transferred from one cell to the other. Through this mechanism, advantageous genetic traits can be disseminated among a population of bacteria. Not all bacteria have the ability to create sex pili; however, sex pili can interchange genetic information between bacteria of different species.

Cross-References

- [Conjugation](#)
- [Lateral Gene Transfer](#)
- [Plasmid](#)

Pili

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Pili are short filamentous structures composed of protein that extend from the surface of the cell. Pili are similar to fimbriae, but in general are longer and only one or a few pili are present on the cell surface. A pilus is typically 6–7 nm in diameter and is primarily composed of oligomeric pilin proteins. Although possibly involved in cell attachment, as are fimbriae, pili are clearly involved in the process of ► [conjugation](#). The

Pillars

Vincent Minier¹, Pascal Tremblin¹ and
Nicola Schneider²
¹CEA, Saclay, France
²I. Physik. Institut, University of Cologne,
Cologne, Germany

Keywords

HII region · Ionization · Interstellar medium ·
Star formation · Comet-tail · Cometary
globules

Synonyms

► [Elephant trunks](#)

Definition

Pillars are elongated structures made of molecular gas and interstellar dust.

Observed at the interface between HII regions, created by massive stars, and the associated molecular cloud, pillars are shaped by the stellar feedback of massive stars. This is mostly due to strong UV radiation but stellar winds can also play a role. Pillars are composed of a head facing the UV radiation, a tail elongated by ionization pressure, and a base where the initial clumpy structure within the parent molecular cloud was hit and transformed. They are still attached to the molecular cloud, while free-floating objects are commonly called globules.

History

The use of the word “pillars” in astronomy to describe an astronomical feature probably started in 1995. No clear occurrence in scientific paper abstracts (via ADS search) is retrieved before 1996, except for “pillars of cosmology,” with the meaning of foundation, or “sun pillar” in a rainbow. *Pillars of Creation* were first mentioned as the title of an image release aiming at publicizing observations of the Hubble space telescope in November 1995. The image exhibits three columns of interstellar matter and the text introduced them as “Undersea corral,” “Enchanted castles,” “Space serpents,” and then “incubators of new stars.” The title of the press release, including images and texts, clearly referred to the scientific paper: *Embryonic stars emerge from interstellar “Eggs.”* Seven months later, the scientific publication by Hester et al. (1996) resumed the observations with the title: *Hubble Space Telescope WFPC2 Imaging of M16: Photoevaporation and Emerging Young Stellar Objects*. No mention of the pillars is present in the whole paper. Hester et al. preferred “elephant trunks” and focused the study on the evaporating gas globules (EGGs) at the tip of the trunks. Since, “pillars” or “elephant trunks” were put forward in various publications, from scientific papers to press releases on results from infrared space telescopes like Herschel,

Spitzer, or WISE. The suggestive comparison of these elongated ionized gas objects and massive megaliths was studied by Kessler (2006). It was proposed that the Hubble images were produced with a romantic landscape iconography inspired from American painters in late nineteenth century like Thomas Moran and his *Chasm of Colorado*. The *Pillars of Creation* image symbolizes the ambivalent attitude and difficult choice to adopt between disseminating a valuable scientific result and making a pretty picture, the balance between scientific research and art powerful suggestiveness.

Overview

In star-forming regions within molecular clouds, stellar feedback in the form of ionizing radiation and stellar winds forms elongated, protruding gas structures at the interface between the ionized gas (HII region) and molecular clouds. Early examples of such structures can be found in Minkowski (1949) and Frieman (1954). Since, they were named as “comet-tail,” “elephant trunk,” “speck,” “teardrop,” and somehow connected to cometary globules. These globules are bubbles of cold gas that are inside the HII region and disconnected from the molecular cloud. Elephant trunks are cometary globules with tails that are attached to the molecular cloud. With the Hubble Space Telescope image of the Eagle Nebula released in 1995, but published in 1996 (M16, Hester et al. 1996), the term “pillar” was introduced to describe the features of a precise structure: a column-like shape and a physical connection to the gas reservoir of the molecular cloud. Note that the term pillar was not used in the scientific paper but imposed by the title of an image release. Typical characteristics of pillars include: a long (typical aspect ratio of at least a few) head-tail structure pointing toward the illuminating source; a bright rim at the edge of the head; a concentration of mass at the head, which might form stars; and a complex velocity structure that can be due to rotation with a period of 1–7 Myr, helical motion, and an intrinsic velocity gradient (e.g., Gahm et al. 2006).

Pillars are typically 1–4 pc long and 0.1–0.7 pc wide (Schneider et al. 2016; Sofue 2020). Star formation might be observed in the dense head of the pillars (e.g., Sugitani et al. 1989) and can lead to spectacular jets from proto-stars escaping of the head (e.g., HH901/902 in the Carina nebula, Smith et al. 2010). Despite these signatures, it is still unclear whether the star formation is indeed triggered by stellar feedback in these structures.

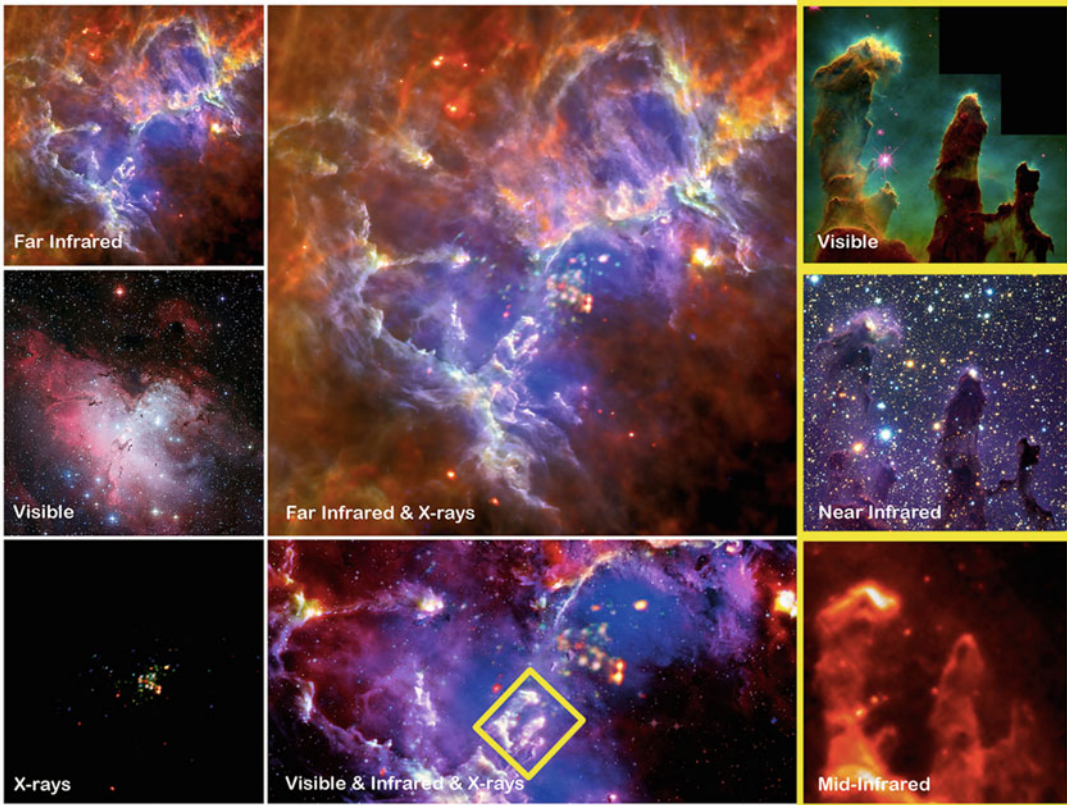
Basic Methodology

Infrared observations with the Herschel space observatory and the Spitzer space telescope revealed many more pillars in HII regions where OB stars have already formed, indicating that the UV radiation from massive stars plays a key role in their formation and possibly to stars inside. HII regions can have very complex shapes depending on the distribution of the ionizing sources and the initial structures in the surrounding gas. They range from spherical bubbles (e.g., RCW120, Zavagno et al. 2010), bipolar nebulae (e.g., RCW 36, Minier et al. 2013) to complex and large regions like Cygnus X OB2 and OB9 (Schneider et al. 2016). Dense layers of gas and dust are observed at the interface between the HII regions and their parent molecular clouds (e.g., Thompson et al. 2011; Zavagno et al. 2010). All around the inner shell of HII regions, elongated columns/pillars of gas are observed pointing toward the ionizing sources and usually connected to the molecular cloud (e.g., M16, Fig. 1). Various scenarios have investigated the physical connection between the formation of these clumpy structures and the appearance of pillars and globules. The collect and collapse scenario (see Elmegreen and Lada 1977) proposed that the shell could become sufficiently dense enough thanks to cooling of the swept-up gas, to reach the gravitational instability and therefore form dense condensations. Bertoldi (1989) proposed that cometary globules could be the result of the radiative implosion of an isolated gravitationally stable condensation. Mackey and Lim (2010) explained pillar formation by the shadowing effect of clumps in the density field. Parsec scale

simulations showed that most of clumps and pillars could be formed from the interaction between the turbulence of the molecular cloud and the ionization (e.g., Gritschneider et al. 2010). Tremblin et al. (2013) proposed that the most important parameter for the formation of pillars and clumps at the interface is the degree of curvature of the dense shell perturbed by preexisting structures. A high curvature triggers the collapse of the shell on itself to form pillars whereas low curvature only triggers the formation of dense clumps that are accelerated with and remain in the shell. The level of turbulence compared to the pressure of the HII region and the initial morphology of the molecular cloud would be key ingredients for the formation of clumps, pillars, and cometary globules.

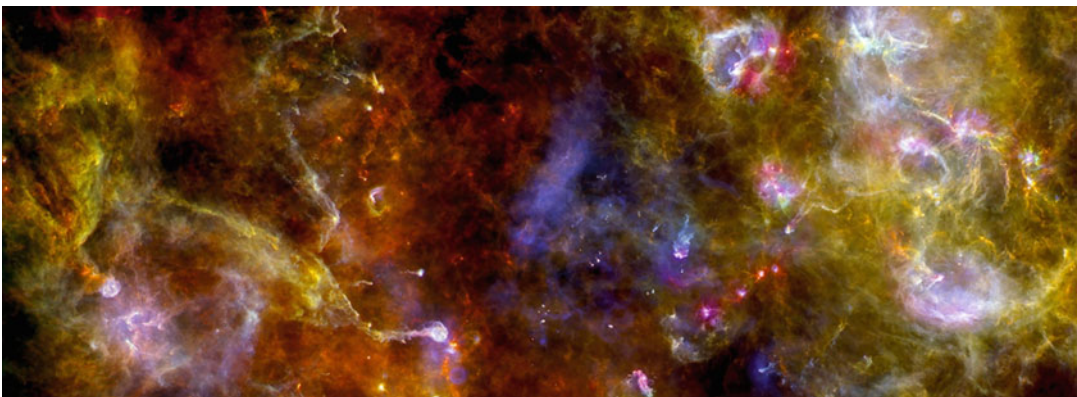
Key Research Findings

With the infrared and submillimeter wave data provided by Herschel and Spitzer, complementing atomic and molecular line emission observations, understanding pillar formation was possible thanks to comparison between observations and numerical simulations. A prototypical example of pillars are the features observed in M16 (Fig. 1). Other pillars can be observed in the Rosette Nebula, Cygnus X, Carina, M8, NGC6357, NGC2264, NGC7822, and W5, for instance (Fig. 2, e.g., Schneider et al. 2012a, b; Deharveng et al. 2012). There are, however, regions of massive star formation that do not show prominent pillars (RCW120, for example). The Eagle Nebula (M16) is located in the constellation of Serpens at 1.8 kpc from the Sun. A young stellar cluster NGC 6611 is ionizing the molecular gas of this star-forming region (Fig. 1). The principal ionizing sources are O4 and O5 stars whose combined ionizing flux is of order $2 \times 10^{50} \text{ s}^{-1}$. The region is chemically rich and spectral line studies of the region are numerous (e.g., White et al. 1999; Schuller et al. 2006; and many others). Flagey et al. (2011) studied the dust spectral energy distribution (SED) using Spitzer data. They showed that the SED could not be accounted for by interstellar dust heating by UV radiation but



Pillars, Fig. 1 Images showing the Eagle nebula (M16) and its pillars in various wavelengths, from far-infrared to X-rays. The iconic image of the Hubble space telescope is at the top right of this montage, with their image in near and

mid-infrared below. The center images propose a global view of the ionizing massive stars detected in X-rays and the interstellar matter reshaped by ionization observed with Herschel. (Credit: ESA, ESO, NASA)



Pillars, Fig. 2 Other examples of pillars observed by Herschel at the interface between molecular clouds and HII regions in Cygnus X (Schneider et al. 2016). (Credit: ESA/Herschel)

an additional source of heating was needed to match the mid IR flux. They proposed two possible origins: stellar winds or a supernova remnant.

Herschel provided new observations on the region, and Hill et al. (2012) studied in detail the impact of the ionizing source on the initial

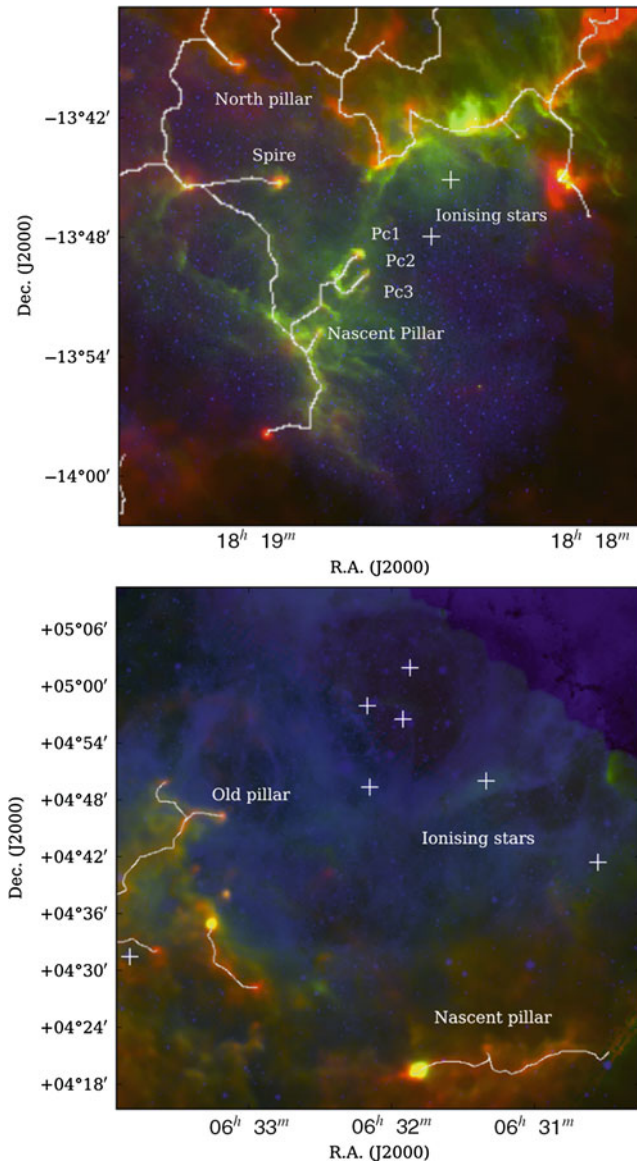
temperature of prestellar cores located at the edge or deep into the molecular gas and did not find evidence for an extra source of heating. Recent SOFIA (Stratospheric Observatory for Infrared Astronomy) observations of the 158 micron line of ionized carbon in various galactic massive star forming regions (Schneider et al. 2020) revealed expanding bubbles seen in this line and emphasized the importance of stellar winds for the dynamics of the gas.

Tremblin et al. (2013) revisited the Herschel data and confronted them to numerical

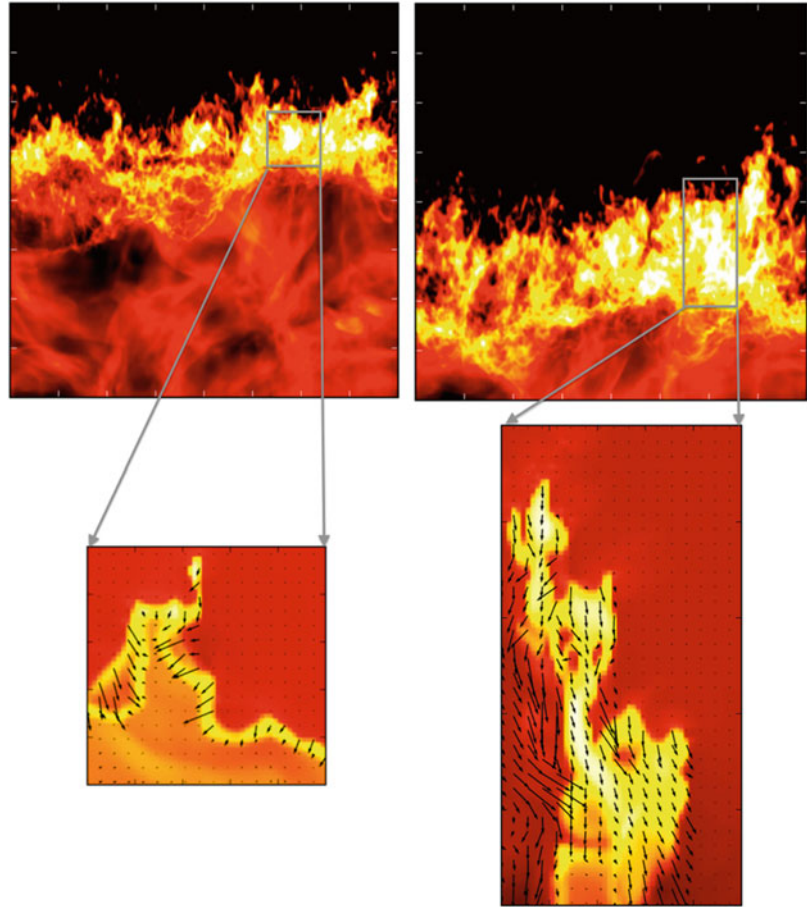
simulations of pillar formation. Using a crest-detection algorithm on column density maps, pillars appear as coherent structures pointing toward the ionizing sources and connected at the base to the rest of the molecular cloud by a triple point in the interstellar filament skeleton (Fig. 3). A nascent pillar was detected at the south of the Pillars of Creation and another one in the Rosette Nebula whose velocity structure is consistent with numerical simulations (Fig. 3). The velocity field has a characteristic pattern predicted by numerical simulations, showing that the compressed shell of

Pillars, Fig. 3 (Top)

Three-color image of the interface between the Eagle Nebula and the HII region around NGC 6611 (red: Herschel column density map, green: PACS 70 μm , blue: H α). The white crosses indicate the O stars. The white lines indicate the filamentary structure skeleton of the molecular cloud. (Bottom) Three-color image of the interface between the Rosette molecular cloud and the HII region around NGC 2244 (red: Herschel column density map, green: PACS 70 μm , blue: H α). The white crosses indicate the O stars



Pillars, Fig. 4 Pillar formation during the ionization of a turbulent molecular cloud. The top panels are two global column density snapshots of the simulation during the expansion of the ionized gas, the ionization is coming from the top of the box. The bottom panels are local density cuts with the velocity field represented by the black arrows. The left panel is a cut before the curved compressed layer (dense layer in yellow) collapses in on itself. The velocity field (black arrows) shows that the two sides of the curved layer are going to collide at the center. The right panel is a cut after the collapse, when the pillar is formed. After the collapse the pillar is connected to the rest of the compressed layer and moves down as shown by the velocity field. (Credit: P. Tremblin)



gas is curved and collapsing in on itself to form the elongated structure (Fig. 4). Another interesting feature that was discovered in pillars and globules is the fact that they show signatures of rotation (Gahm et al. 2006; Schneider et al. 2012b). The origin is not yet clear; it can be due to a residual momentum from the turbulent molecular cloud and/or the result of a magnetic field that is twisted around the pillar.

Summarizing the observations and numerical works propose a consistent picture of the formation of pillars and globules: (1) Pillars are formed when the shell is sufficiently curved to collapse in on itself. (2) If not sufficiently curved, formation of clumpy condensations is triggered inside the shell. (3) Pillars can detach from the parent molecular cloud when the turbulent ram pressure of the gas is bigger than the pressure of the ionized gas

and appear then as free-floating globules. This scenario is supported and extended with the proposition of an evolutionary sequence (Schneider et al. 2016) in which pillars evolve into globules, which in turn then evolve into other features such as evaporating gaseous globules (EGGs), transient condensations or proplyds (protoplanetary discs), or proplyd-like objects. Gravity-based scenarios such as the Rayleigh Taylor instability or more recently the remains of an accretion flow are ruled out by the velocity field structure in the case of the Pillars of Creation. All previous models do not predict a collapsing shell that is observed in the case of the nascent pillar in the Rosette Nebula. The structures both in M16 and Rosette are consistent with the interaction between ionization and turbulence, although other scenarios might still happen in other regions.

Applications

A direct consequence of this pillar formation scenario is that a preexisting dense clump will curve the shell around it, trigger the collapse and the formation of a pillar while a low-density perturbation will not sufficiently curve the shell to trigger the pillar formation. Instead, a dense clump is subsequently formed in the shell by the accumulation of matter triggered by the perturbation. This effect has been simulated in Tremblin et al. (2013) and also in Minier et al. (2013) in the special case of RCW36. Therefore, star formation happening at the tip of pillars is likely to happen even without ionization, while star formation in dense clumps in the shell is likely to be triggered by the feedback.

Future Directions

With the statistics of YSOs located at the edge of ionized bubbles (e.g., Thompson et al. 2011), it becomes clear that star formation triggered by the feedback of massive stars is indeed frequent and an important ingredient for the understanding of galactic star formation. Pillars, globules and clumpy condensations, and more generally HII region morphology are tools to disentangle physical phenomena responsible for star formation in a molecular cloud under the influence of high-mass star radiative feedback.

Cross-References

- [Infrared Space Observatory](#)
- [Interstellar Filaments](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Photoionization](#)
- [Star Formation, Feedback](#)

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Pillow Lava

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Definition

Pillow lava is a form of effusive (i.e., erupted at the surface) ► [igneous rock](#) which results when low-viscosity magma such as basalt erupts under water. Pillows are irregular tube-like structures, circular to elliptical in cross-section, typically 30 cm to about 1 m in diameter. They form when the crust of a lava flow, or of another pillow, fractures to allow the extrusion of a spurt of lava. A thin elastic crust forms at the surface so that lava continues to flow into the interior of the tube or pillow. Pillow lavas are common in all types of modern submarine volcanic settings – ► [midocean ridges](#), oceanic islands, and island arcs – and they form a common layer of the ► [oceanic crust](#) (Layer 2A) and are the most common volcanic feature in well-preserved Archean ► [greenstone belts](#). Pillow lava has received much attention by astrobiologists for the occurrence of tubular microscopic structures in samples of Archean age that could be related to biological activity (Furnes et al. [2004](#)).

Cross-References

- [Archean Eon](#)
- [Igneous Rock](#)
- [Mid-Ocean Ridge](#)
- [Oceanic Crust](#)

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Pioneer F for Pioneer 11

- [Pioneer Spacecraft](#)

Pioneer G for Pioneer 10

- [Pioneer Spacecraft](#)

Pioneer Spacecraft

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

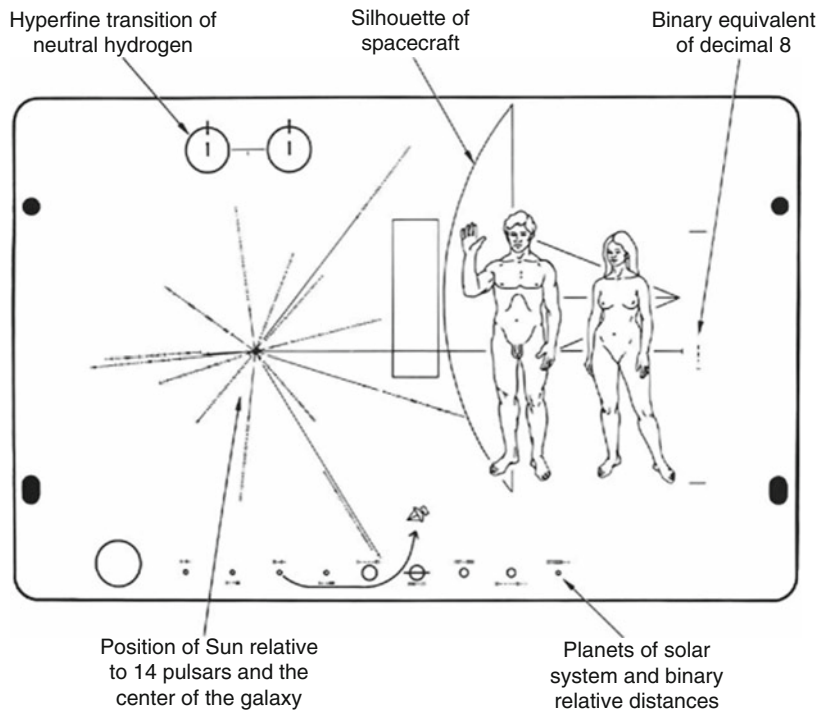
[Pioneer F for Pioneer 11](#); [Pioneer G for Pioneer 10](#)

Definition

These two NASA Pioneer probes were part of the Pioneer program to explore the Solar System. Pioneer 10 and 11 were aimed to visit the ► [Jupiter](#) and ► [Saturn](#), the two Giant planets of the outer Solar System. Pioneer 10 was launched from Cape Canaveral on March 2, 1972. It flew by Jupiter on December 3, 1973 and then continued its trip having gained sufficient momentum to

Pioneer Spacecraft,

Fig. 1 The drawing of the pioneer plate with explanations. (Photo NASA)



escape the Solar System. The last contact with the probe was on January 23, 2003, while it was heading toward the Aldebaran constellation that it will reach in about 2 million years. Pioneer 11 was launched as scheduled almost 13 months after its sister spacecraft on April 5, 1973. The spacecraft arrived at Jupiter and observed the planet's red spot on December 2, 1974 before heading toward Saturn. The spacecraft reached Saturn on September 1, 1979. The last contact with Pioneer 11 occurred on November 1, 1995.

The two identical spacecrafts were equipped with radioisotopic thermoelectric generators and have a dry mass of about 257 kg. Pioneer 10 carried a payload of 11 scientific instruments; Pioneer 11 carried one instrument more. The sister probes were designed to study the target ► **planets** and their satellites as well as the ► **space environment**, the solar wind, the cosmic rays, and the planetary and cosmic ► **magnetic fields**. Pioneer probes are recognized for their achievements (first photos from Jupiter, Saturn, Saturn's moons, ...). Both spacecrafts carry a gold-anodized plate (Fig. 1) designed by Carl Sagan, Linda Salzman-Sagan, and Frank Drake with a message to extraterrestrial

civilizations that they may encounter about the origin of the spacecrafts. They are also known for the detection of the so-called Pioneer anomaly. A Doppler drift in the radio signal demonstrated a slight unexpected change in the acceleration of the probes. The finding remains poorly explained to the present day and is of great interest to theoretical physics and cosmology. Nevertheless, some hypotheses have been published (Foot and Volkas 2001).

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<http://www.nasa.gov/centers/ames/missions/archive/pioneer.html#.UyLbNO-AGko>

α Piscis Austrinus b

► **Fomalhaut b**

PIXE

Jun-ichi Takahashi
Yokohama National University, Faculty of
Engineering, Yokohama, Japan

Synonyms

[Proton-induced X-ray emission](#)

Definition

Proton-induced X-ray emission (PIXE) is a technique used in the determination of the elemental makeup of a material or sample. Bombardment with MeV protons produced by an ion accelerator causes inner shell ionization of atoms, and outer shell electrons drop down to replace inner shell vacancies with certain allowed transitions. X-rays of a characteristic energy of the element are emitted and provide information about the composition of the sample. PIXE is a powerful yet nondestructive elemental analysis technique now used routinely. Recent extensions of PIXE using tightly focused beams (down to 1 μm) give the additional capability of microscopic analysis. This technique, called microPIXE, can be used to determine the distribution of trace elements with high spatial resolution in a wide range of samples.

Planet

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

The IAU (International Astronomical Union) General Assembly officially defined the term planet in resolution 5A (Resolution_GA26-5-

6) in 2006. According to this definition a planet is an object that orbits the Sun, has cleared the neighborhood around its orbit from pre-planetary debris, and has sufficient mass for its self-gravity to maintain a nearly round shape.

Cross-References

- ▶ [Debris Disk](#)
- ▶ [Dynamo, Planetary](#)
- ▶ [Jupiter](#)
- ▶ [Mars](#)
- ▶ [Mercury](#)
- ▶ [Neptune](#)
- ▶ [Planet Formation](#)
- ▶ [Planetary Migration](#)
- ▶ [Planetary Nebula](#)
- ▶ [Plate Tectonics](#)
- ▶ [Probing Lensing Anomalies Network](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Saturn](#)
- ▶ [Solar System, Inner](#)
- ▶ [Sun \(and Young Sun\)](#)
- ▶ [Uranus](#)
- ▶ [Venus](#)

Planet Characterization: Emitted and Reflected Light

Franck Selsis
CNRS, Laboratoire d'astrophysique de Bordeaux,
Pessac, France

Keywords

Transit · Eclipse · Phase-curve · Photometry ·
Scattering · Thermal emission

Definition

A planet reflects light from its host star and emits its own thermal radiation. Even when the planet and its host star cannot be spatially resolved, precise

photometry can be used to extract the planetary component of the unresolved source and constrain properties of the planet and its atmosphere.

Overview

Electromagnetic radiations received from a planet are – as a first approximation – composed of scattered stellar light (“reflection”) and the emission of the planet. Solar system planets being much colder than the Sun these two components are spectrally well separated: the scattered light being in the UV, visible and near-IR range while the emission becomes significant at longer wavelengths, but the scattered and emitted components can significantly overlap in the case of hot exoplanets.

When the image of the planet and its host star cannot be resolved, the light from the planet can be extracted from the spatially unresolved light from the system by different techniques. In transiting systems, the planet periodically disappears behind the star (during the secondary eclipse also called occultation or anti-transit), allowing to measure the stellar contribution and thus, by difference, the brightness of the planet dayside. This can be done in once single spectral band (Deming et al. 2005) or several (Charbonneau et al. 2008). Once the stellar flux is known, assuming it remains constant and that the observation is done with a stable instrument, the change of additional planetary contribution can be followed during its full orbit (Knutson et al. 2009). The variation of this planetary signal as a function of orbital phase is called phase-curve. If observed at wavelengths dominated by scattered light, the phase-curve is maximum at low phases (when the observer is looking at the dayside), decreases to zero toward high phases (when the nightside faces the observer) and constrains the planet albedo. If the observation band monitors mainly the planetary emission, the phase-curve informs on the day-night thermal contrast and more generally on the longitudinal distribution of temperature and therefore on the transport of heat. When several phase-curves are observed in different spectral bands, covering both the reflection and emission domain,

strong constraints can be put on the radiative budget of the planet and the presence and properties of an atmosphere (von Paris et al. 2016).

In practice, stellar variability and limited instrument stability have restricted such observations to hot short-period planets that offer sufficient planet/star contrast. Most measured eclipses and phase-curves are produced by hot Jupiters although it has been observed in the case of a very hot and large terrestrial planet: 55 CANCRI e (Demory et al. 2012).

In multiplanetary systems, individual phase-curves may be entangled making analysis more difficult (Kane et al. 2021).

The modulation of the unresolved star+planet light by the phase of the planet can also be monitored for non-transiting systems but in this case only the variations of the planetary flux can be measured (Selsis et al. 2011).

While broadband eclipse/phase-curves represent the majority of currently available observations, spectroscopy can be performed with the same principles, providing dayside spectra and/or spectral phase-curves carrying more information for characterization (Kreidberg et al. 2014).

High-resolution spectroscopy ($R > 20,000$, able to spectrally resolve single molecular lines, can also be used to extract molecular signatures belonging to the planet from the spatially unresolved star+planet spectrum. To isolate the planetary component, the method uses the Doppler shift associated with the planetary orbital motion and the fact that some molecules are not present in the hot stellar atmosphere. By detecting the water high-resolution signature of the exoplanet 51 Peg b, Birkby et al. (2017) were for instance able to determine the orbital inclination and true mass of the first exoplanet discovered (in 1995). High-resolution spectroscopy requires large ground-based telescopes.

Cross-References

- [55 Cancri](#)
- [Occultation](#)
- [51 Pegasi B](#)

- [Planet Characterization: High-Resolution Spectroscopy](#)
- [Transit](#)

Acronyms

HDS; HRS

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Definition

High-resolution spectroscopy is an observational technique used to detect atomic lines and molecular bands in the atmospheres of exoplanets. It makes use of high-resolution spectrographs mounted on medium to large ground-based telescopes, e.g., VLT-CRIRES, ESO-3.6 m-HARPS, VLT-ESPRESSO, CAHA-CARMENES, TNG-HARPS-N & GIANO, and CFHT-SPiROU. A key advantage of this technique is that it enables atmospheric characterization from the ground by disentangling exoplanet signatures from telluric contamination by Earth's atmosphere. The high spectral resolution (typically $>50,000$) separates spectral features originating in the stellar, planetary, and Earth atmospheres thanks to the different Doppler shifts involved. Moreover, it is possible to combine the signal from many individual spectral lines into a cross-correlation function with increased signal-to-noise ratio. This is particularly powerful for detecting molecular bands made of tens or hundreds of individual ro-vibrational transitions. Detection of chemical species with high-resolution spectroscopy constrains atmospheric composition, chemical abundances, and the pressure-temperature profile. In addition, the study of spectrally resolved line profiles provides constraints on planetary rotation rate, atmospheric circulation (winds), and chemical gradients across the planetary disk. The technique can be applied to transiting exoplanets, in transmission during transit, or in emission and reflected light during secondary eclipse. It can be applied to both transiting and non-transiting planets by following the Doppler-shifting planetary signal in emission or reflected light across different orbital phases.

Various atoms and molecules have been detected in many different exoplanets so far using high-resolution spectroscopy. A few examples are provided below, starting from close-in, massive planets toward cooler, Neptune-like objects. Ultra-hot Jupiters are a recently discovered category of planets whose atmospheric

Planet Characterization: High-Resolution Spectroscopy

Christophe Lovis
University of Geneva, Geneva, Switzerland

Synonyms

[High-dispersion spectroscopy](#)

temperatures are as high as Those of M dwarf stars. As a consequence, molecules are mostly dissociated into atomic species which Are detectable through cross-correlation techniques thanks to their numerous spectral lines, such as Fe (Hoeijmakers et al. 2018; Ehrenreich et al. 2020). Hot Jupiters are somewhat cooler objects that often show prominent bands of CO and H₂O in the near infrared (Snellen et al. 2010; Brogi et al. 2012; Birkby et al. 2013; Alonso-Floriano et al. 2019; Giacobbe et al. 2021; Pelletier et al. 2021). The alkali metals Na and K also have prominent spectral lines in the visible, which have been detected and modeled in several hot Jupiters (Wytenbach et al. 2015; Loudon and Wheatley 2015; Seidel et al. 2020). Finally, the He I transition at 1.08 μ m has recently emerged as a powerful tracer of atmospheric escape in several exoplanets, including Neptune-mass objects (Allart et al. 2018; Nortmann et al. 2018; Pallé et al. 2020).

In the near future, high-resolution spectroscopy will be used to characterize transiting rocky exoplanets, e.g., with the 39-m European Extremely Large Telescope (Serindag and Snellen 2019). Moreover, high-resolution spectroscopy will be combined with high-contrast imaging to characterize terrestrial exoplanets around the nearest stars, such as Proxima b (Snellen et al. 2015; Lovis et al. 2017). This promising new approach has already been demonstrated on the young giant planet β Pictoris b by Snellen et al. (2014). Ultimately, the detection of potential biosignatures such as O₂ and CH₄ in terrestrial exoplanets will be within the reach of the ELT in a few tens of hours of observing time.

Cross-References

- Atmospheric Circulation
- Atmospheric Retrieval for Exoplanets
- Biomarkers, Spectral
- Climates, Exoplanets
- Doppler Shift
- ESPRESSO
- Exoplanet, Detection, and Characterization
- Habitable Planet, Characterization
- HARPS
- HD 189733b

- HD 209458b
- Hot Jupiters
- Planet Characterization: Emitted and Reflected Light
- Planet Characterization: Transmitted
- Proxima-b
- Radial-Velocity Planets
- Rossiter-McLaughlin Effect
- Spectroscopy
- Transiting Planets

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Planet Characterization: Transmitted

Romain Allart

Department of Physics, and Institute for Research on Exoplanets, University of Montréal, Montréal, Quebec, Canada

Keywords

Transmission spectroscopy · Dynamic and composition of exoplanet atmosphere

Synonyms

Transmission spectroscopy

Definition

The transit of an exoplanet, an event where the planet passes between its host star and an observer, provides a direct measurement of the planetary radius. During the transit, a fraction of the stellar light can be filtered by the atmosphere of the exoplanet. The latest absorbs the stellar flux at specific wavelengths depending on its atomic and molecular composition. The planet is, thus, seen more opaque at specific wavelengths. Therefore, the measured planetary radius changes as a function of the wavelength and results in the transmission spectrum of the atmosphere.

Overview

The atmospheres of exoplanets provide a unique opportunity to better understand the physical, chemical, and evolutionary processes occurring on exoplanets. Information on the atmosphere can be obtained through its transmitted, reflected, or emitted lights, which are sensitive to different layers of the atmosphere. While the reflected and emitted lights probe deeper in the atmosphere (closer to the opaque radius), the transmitted light probes the upper layers from the stratosphere to the exosphere. The transmission spectrum, which expresses the planetary radius variation as a function of the wavelength, reveals the atomic and molecular composition of these layers (Sing et al. 2016), the presence of clouds and/or hazes (Kreidberg et al. 2014), the dynamic of winds (Snellen et al. 2010) but also more complex phenomena such as precipitation (Ehrenreich et al. 2020).

Atmospheric characterization has mainly been done for hot gas giant planets as their atmospheres extend on several scale heights, which corresponds to the change of altitude when the pressure decreases by a factor e , leading to stronger spectral features. These detections have been obtained

through different atmospheric tracers such as H_2O , Na, H, or He. However, the atmospheric characterization of smaller planets remains a difficult task even if the presence of helium has been detected on warm Neptunes (Allart et al. 2018) and the detection of water has been obtained on one temperate mini-Neptune (Tsiaras et al. 2019; Benneke et al. 2019).

Sing et al. (2016) revealed the large diversity of compositions, induced by different physical and chemical processes, for hot Jupiters. They measured the abundance of Na, K, and H_2O but also constrained the presence of diverse clouds and hazes by using a broad spectral range at low spectral resolution. This study reveals how complex exoplanet atmospheres can be, and ask for more observations, and for more in-depth theoretical studies on atmospheric chemistry and the formation of clouds and hazes (Marley et al. 2013).

While the transmission spectrum at visible and infrared wavelengths probes mainly the lower layers accessible through transmitted light, ultraviolet wavelengths are sensible to the outermost layer of an exoplanet atmosphere, the exosphere. It is the region where particles are no more gravitationally bound to the planet and escape into space. Such observations can be done by tracing the hydrogen atoms through the Lyman- α line. The most spectacular result was obtained for GJ436b (Ehrenreich et al. 2015), where a gigantic cloud of hydrogen surrounds the planet, forming a cometary-like tail. Such phenomena can provide crucial information on the formation and evolution of exoplanets. The mass-loss rate of hydrogen for Neptune-size exoplanets could explain the dearth of hot Neptunes (Bourrier et al. 2018).

Linking the lowest layers to the exosphere requires to study the thermosphere. Atomic species such as Na, K, or Fe probe up to the thermosphere and have been extensively studied at high spectral resolution (~ 100000) from the ground. The use of high spectral resolution unlocks the full potential of those lines by resolving them individually. Several studies of these species revealed strong wind dynamics in the thermosphere of hot Jupiters (Wytenbach et al. 2015; Seidel et al. 2019) but also the peculiar chemistry

of the ultra-hot Jupiters (Hoeijmakers et al. 2018). Similarly, the helium triplet at near-infrared wavelengths was revealed as a promising atmospheric tracer to link the thermosphere to the exosphere (Seager and Sasselov 2000; Oklopčić and Hirata 2018). Its recent discovery (Spake et al. 2018; Allart et al. 2018; Nortmann et al. 2018) makes it difficult to have a broader picture but interestingly the transmission spectrum of WASP-107b (Allart et al. 2019) shows two components that can be related to the thermosphere and the exosphere, respectively.

It is also important to note that such lines can be affected by the Rossiter McLaughlin effect. This effect impacts lines present in the stellar spectrum by deforming them due to the partial occultation of the stellar surface by the planet. The most impressive result is for the well-known hot-Jupiter HD209458b (Casasayas-Barris et al. 2021).

The use of different instruments provides complementary information on the study of transmitted light by combining different wavelength ranges but also by using different spectral resolutions. While the low resolution provides a more direct measurement of abundances and constrains clouds and hazes (Sing et al. 2016; Kreidberg et al. 2014), the high resolution provides information on the structure and dynamics of the atmosphere by resolving the lines (Snellen et al. 2010; Ehrenreich et al. 2020). To have a complete view of an exoplanet atmosphere, it is thus necessary to combine multiple atmospheric tracers across the largest spectral range using both low and high spectral resolution.

Upcoming facilities (JWST and the ELTs) will provide first insights into the atmospheric composition of temperate rocky planets such as the Trappist-1 planets (Turbet et al. 2018). Oxygen is foreseen as one of the most promising biosignatures and has the advantage to have strong absorption bands at both visible and near-infrared wavelengths. However, its detections alone will not be proof of life as false positive and false negative scenarios exist (Meadows et al. 2018 and references therein). Nonetheless, by understanding the environmental context of those worlds, we will be able to give more

confidence in the detection of life. Finally, other molecules (e.g., CO₂, CH₄, PH₃) are foreseen as great biosignatures but against the complexity of life, it is necessary to have detections of multiples molecules with the right abundances to claim a robust detection of life on an extraterrestrial world.

Cross-References

- Atmosphere, Structure
- Atmospheric Circulation
- Biomarkers (Atmosphere)
- Climates, Exoplanets
- Clouds
- Hot Jupiters
- Hot Neptunes
- Magnetic Fields and Planetary Systems Formation
- Mini-Neptunes
- Planet Characterization: Emitted and Reflected Light
- Planet Characterization: High-Resolution Spectroscopy
- Planet Formation
- Planetary Evolution
- Rossiter-McLaughlin Effect
- Scale Height
- Stratosphere
- Thermosphere

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Planet Detection: Eclipse Timing Variation

Nader Haghighipour

Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Exoplanets · Transit

Definition

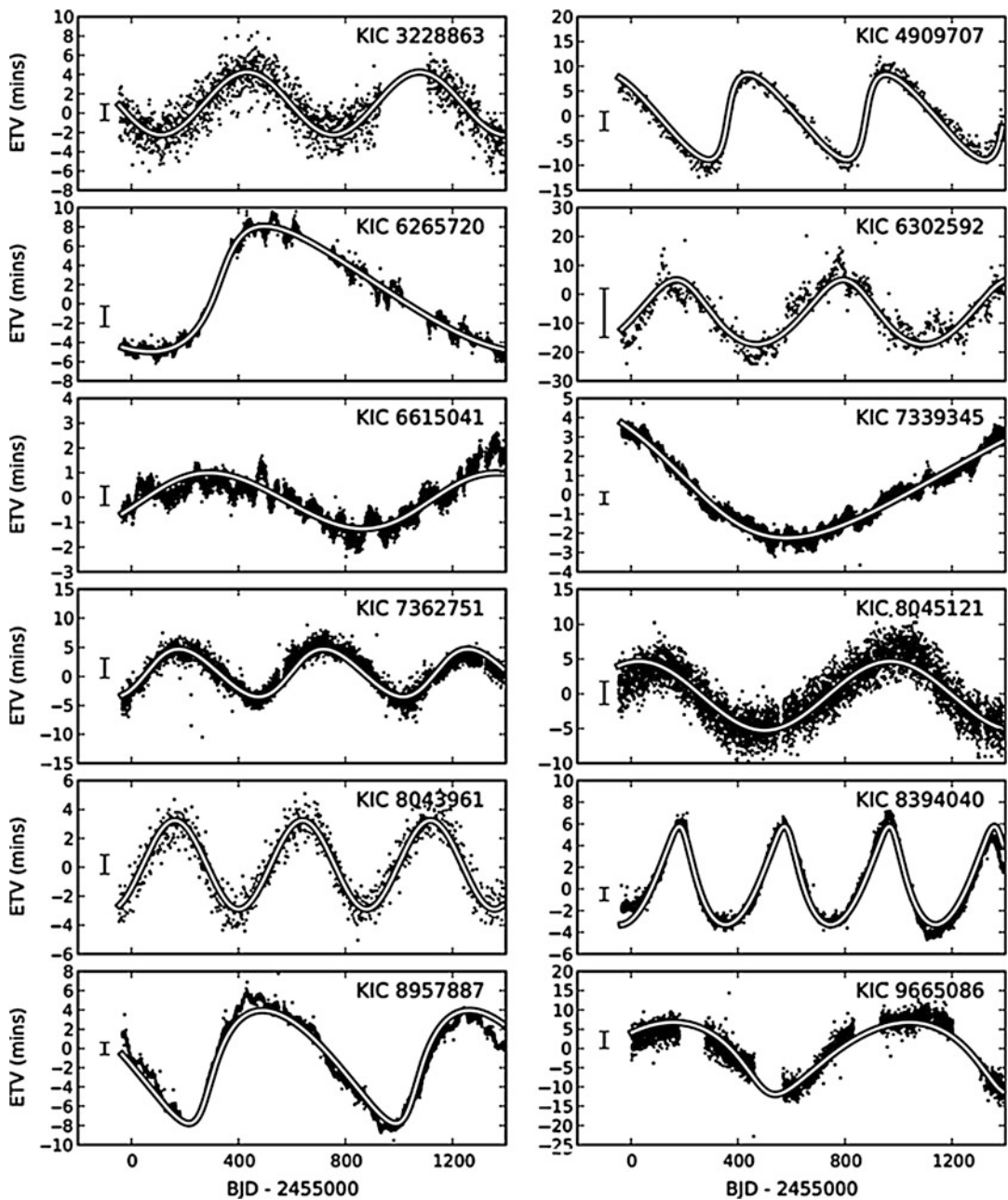
Planet detection from eclipse timing variations is a method for determining the existence and properties of a planet in an eclipsing binary star system from the gravitational perturbations the planet induces in the orbit of the binary.

Overview

The mutual orbit of an isolated, unperturbed binary star system is purely Keplerian. That is, the two

stars of the binary revolve around their center of mass in Keplerian orbits. In such systems, the orbital evolution of the system can be predicted precisely. If the two stars eclipse each other (in which case the system is known as an eclipsing

binary), the eclipses will happen at the same time and will have the same durations. However, if the orbit of the binary is perturbed, changes will appear in the period of the binary eclipses. This is known as eclipse timing variation or ETV.



Planet Detection: Eclipse Timing Variation, Fig. 1 Gallery of ETV signals due to the LITE found in close binaries KIC 3228863, 4909707, 6265720, 6302592, 6615041, 7339345, 7362751, 8045121, 8043961,

8394040, 8957887, and 9665086. Horizontal axis in days. Typical errors for ETV measurements are shown to the left of the data (Conroy et al. 2014)

Eclipse timing variations may be induced by several processes (Conroy et al. 2014):

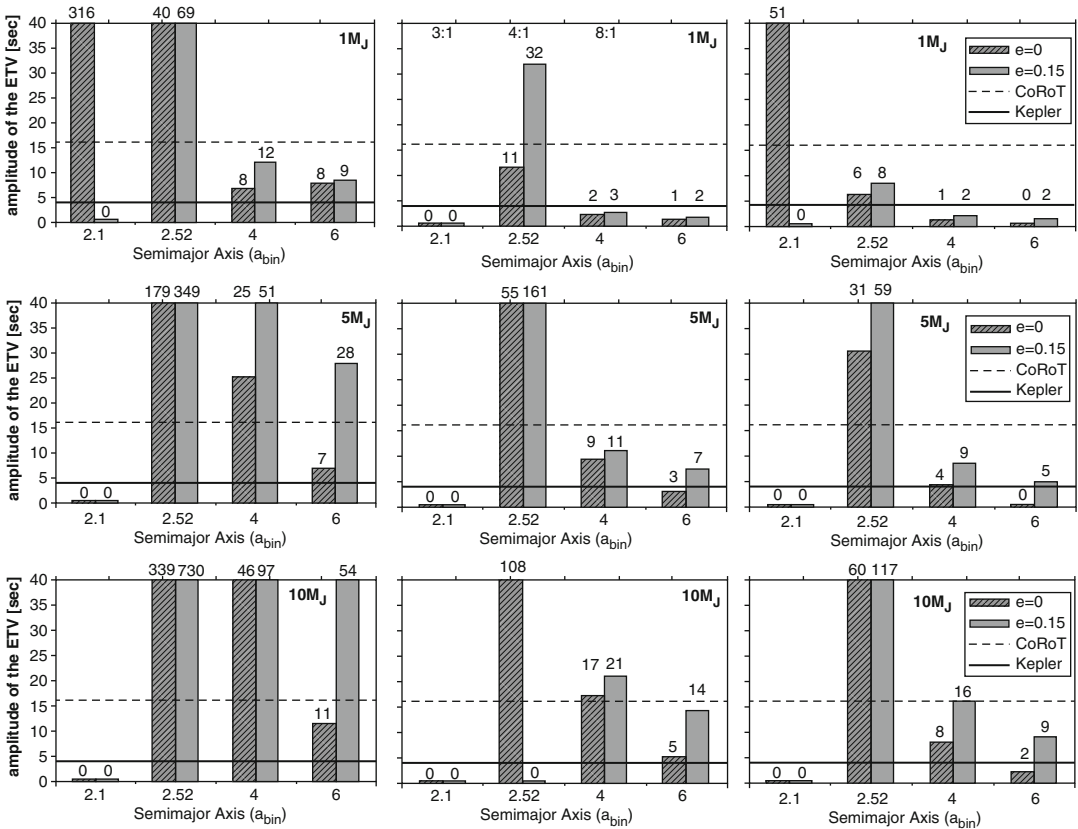
1. Light travel time effect (LITE): a third body perturbing the center of mass of the binary system creates a light-time delay along the line of sight which can cause eclipses to appear earlier or later than expected.
2. Nonhierarchical third body: the presence of a third body actually changes the period of the binary over time.
3. Mass transfer: mass transfer between the components in the binary changes the period.
4. Gravitational quadrupole coupling (Applegate effect): spin-orbit transfer of angular momentum in a close binary due to one of the stars being active produces period changes up to

10–5 times the binary period (Applegate 1992).

5. Apidal motion: the rotation of the line of apsides causes a change in the time between primary and secondary eclipses even though the period remains unchanged (requires an eccentric orbit; see Apidal Angle).
6. Spurious signals: due to spots and other effects that distort the eclipsing binary light curve.

Figure 1 shows a gallery of ETVs caused by the LITE.

Using eclipse timing variations to find exoplanets is a well-known method (Schwarz et al. 2011). The idea of photometric detection of extra-solar planets around eclipsing binaries was first presented by Schneider and Chevreton (1990).



Planet Detection: Eclipse Timing Variation, Fig. 2 Graphs of the maximum amplitude of ETVs for three binary models with zero orbital eccentricity. The locations of the bars on the horizontal axis correspond to mean motion resonances (MMR) of 3:1 MMR at 2.1 a_{bin} , 4:1 MMR at 2.52 a_{bin} , 8:1 MMR at 4 a_{bin} , and a

nonresonant case at 6 a_{bin} , where a_{bin} is the semimajor axis of the binary orbit. Graphs are shown for two values of the planet's orbital eccentricity (0 and 0.15). As a point of comparison, the maximum values of detectable timing amplitudes (sensitivity limits) for CoRoT and Kepler (Sybalski et al. 2011) are also shown (Schwarz et al. 2011)

This idea was later developed by many authors (Schneider and Doyle 1995; Doyle et al. 1998; Doyle and Deeg 2004; Deeg et al. 2008; Muterspaugh et al. 2010) and is based on the fact that a circumprimary/circumbinary planet can perturb the orbit of the two stars and create variations in the timing and duration of their eclipses. The measurement of these variations, when compared with theoretical models, can reveal information about the mass and orbital elements of the perturbing planet.

Similar to transit timing variations (TTVs) in close eclipsing binaries, variations in a binary's eclipse timing may be due to a circumbinary planet. The difference between the observed time of mid-eclipse and its theoretically expected (i.e., calculated) value, known as O-C, when determined for different eclipse numbers (or cycles) can be used to extract information about the mass and orbital properties of the perturber (i.e., the circumbinary planet). As expected, when the orbital periods of the planet and binary are commensurate (in the ratio of small integers), the perturbing effect of the planet on the motion of the binary is enhanced. This causes the measured value of the time of mid-eclipse to show large variations from its expected value. As a result, the amplitude of the O-C diagram is amplified when the planet and binary are in a mean motion resonance, making the detection of such planets more practical (Schwarz et al. 2011). Figure 2 shows the maximum values of O-C for different eclipsing binaries with circumbinary planets in different mean-motion resonances.

Cross-References

- [Exoplanet, Detection, and Characterization](#)
- [Light Travel Time Effect](#)
- [Planet Detection: Transit Timing Variation](#)
- [Transiting Planets](#)

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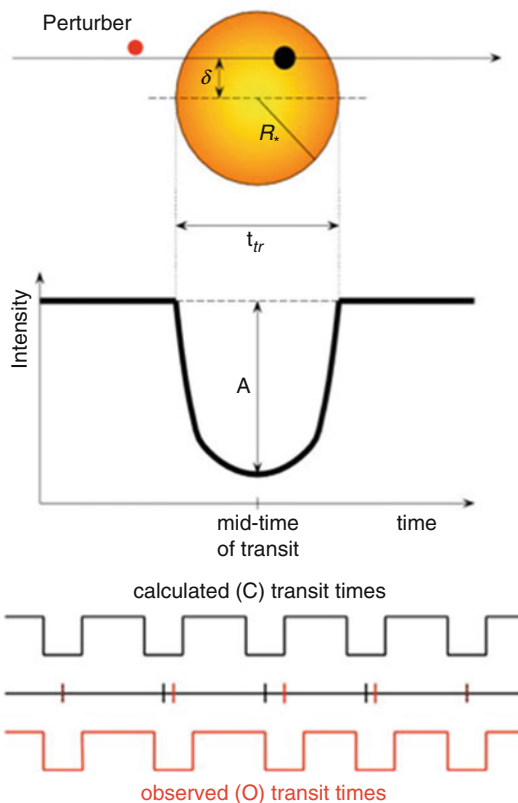
Planet Detection: Transit Timing Variation

Nader Haghighipour
Institute for Astronomy, University of Hawaii,
Honolulu, HI, USA

Definition

Planet detection from transit timing variations is a method for determining the existence and

properties of a planet from the gravitational perturbations it induces on the orbit of another transiting planet. In an unperturbed planetary system consisting of a star and a planet, the two bodies revolve around their center of mass in a ► [Keplerian orbit](#). If in this system the planet transits the star, it will cross the disk of the star at same time during each transit. As a result, the time of the middle of the transit will be identical every time the planet completes one orbit. If because of some external perturbation (e.g., a second planet), the motion of the transiting planet deviates from purely Keplerian, the time of the mid-transit will be different from one orbit to another. This is known as transit timing variation (TTV). Figure 1 shows this schematically.



Planet Detection: Transit Timing Variation,
Fig. 1 Schematic view of transit timing variation

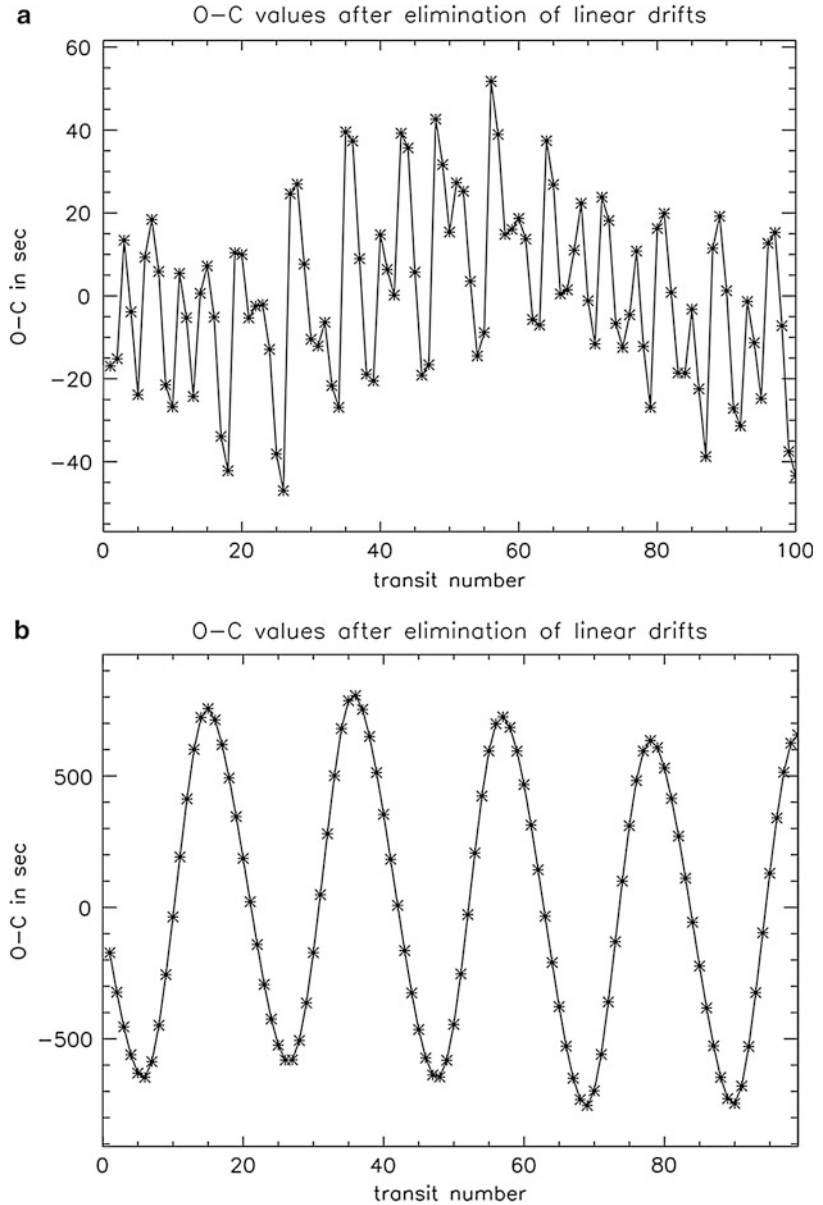
Overview

The difference between the observed time of mid-transit and its theoretically expected (i.e., calculated) value, known as O–C, when determined for different transit numbers (or cycles) can be used to extract information about the mass and orbital properties of the perturber. This is known as the transit timing variation method of planetary detection. As expected, when the orbital periods of the two planets are commensurate (in the ratio of small integers), the perturbing effect of one planet on the orbital motion of the other is enhanced. This causes the measured value of the time of mid-transit of the transiting planet to show large variations from its expected value. As a result, the amplitude of the O–C diagram is amplified when the two planets are in a ► [mean-motion resonance](#) (Agol et al. 2005; Steffen and Agol 2005; Agol and Steffen 2007). Figure 2 shows this for a three-body system with a 0.367 solar-mass star, a Jupiter-mass transiting planet in a 10-day orbit, and an Earth-mass perturber. The top panel shows the TTVs when the perturber is in a 16.11-day orbit. The bottom panel corresponds to near an interior 1:2 resonance of the two planets (Haghighipour and Kirste 2011). As expected, the amplitude of TTV is enhanced by an order of magnitude. The enhancement of the O–C amplitude when the two planets are in a resonance (i.e., with commensurate orbits) increases the possibility of the detection of these variations. The two outer planets of the Kepler 9 system (Kepler-9b and c) are the first to have been confirmed using the TTV method. These two planets are in a near 2:1 mean-motion resonance (Holman et al. 2010) (Fig. 3).

Because different combinations of the mass and orbital elements of the transiting planet and perturber can produce similar values of O–C, the TTV method suffers from strong degeneracies when used as a mechanism for detecting planets. Several efforts have been made to analyze the O–C diagram and determine the relevant planetary candidates quickly (Nesvorný and Morbidelli 2008; Nesvorný 2009; Nesvorný and Beaugé 2010; Borkovits et al. 2011). Once a region of

Planet Detection: Transit Timing Variation,

Fig. 2 A system with a 0.367 solar-mass star, a Jupiter-mass transiting planet in a 10-day orbit, and an Earth-mass perturber. The *top* panel shows the TTVs when the perturber is in a 16.11-day orbit. The *bottom* panel corresponds to near an interior 1:2 resonance (Haghighipour and Kiste 2011). The amplification of the O–C amplification is by an order of magnitude



the parameter space is identified which can produce the O–C values, other detection techniques need to be employed in order to break this degeneracy. In cases when the free eccentricities of the planets are sufficiently small, TTVs can be used to determine the mass and eccentricity of each planet (Lithwick et al. 2012).

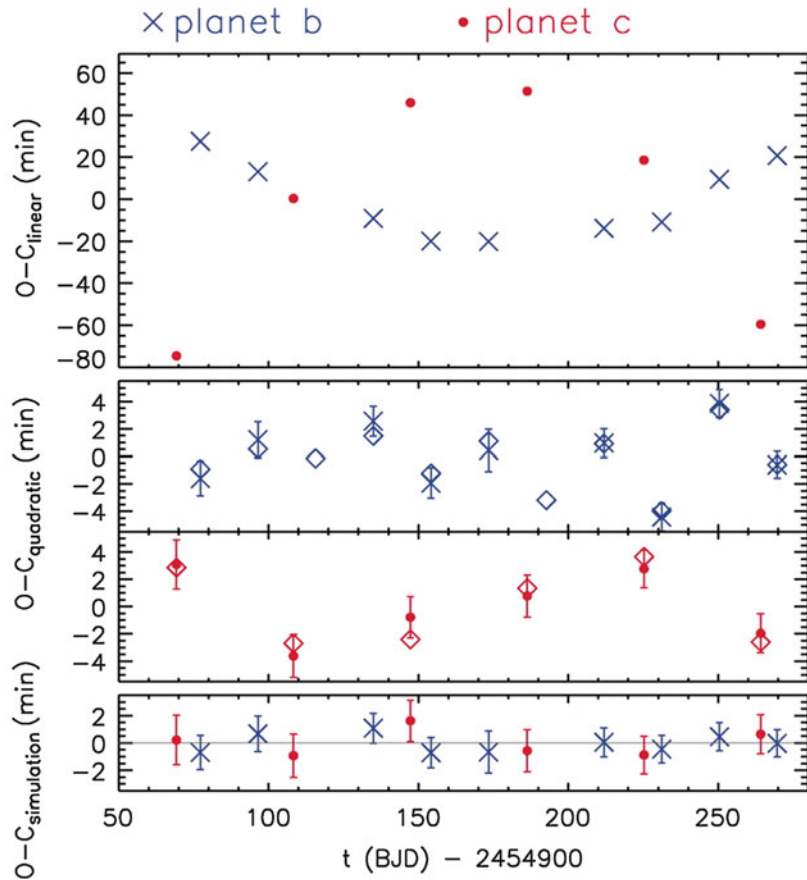
The transit timing variation method has been used to assess the detectability of a variety of systems including extrasolar satellites (Kipping

2009a, b; Schneider et al. 2014), Trojan and co-orbital planets (Ford and Gaudi 2006; Haghighipour et al. 2013), as well as habitable terrestrial planets and super-Earths around a low-mass star (Haghighipour and Kiste 2011).

Recently, the TTV method has been used to determine the masses of the planets of the TRAPPIST-1 system (Gillon et al. 2017). This system hosts seven planets and three of them are in the traditional habitable zone. Knowing the

Planet Detection: Transit Timing Variation,

Fig. 3 Variations in transit times of planets Kepler 9b (blue crosses) and Kepler 9c (red dots) (Holman et al. 2010). The three panels show three different ways of estimating the calculated transit times “C”. Top panel: the calculated transit times “C” were estimated with linear ephemerides (where $C = A + P \cdot t$, where A and P are constants, t is the epoch of transit). Middle panel: the calculated transit times “C” were estimated using quadratic ephemerides. Bottom panel: the calculated transit times “C” were estimated using the outcome of a numerical simulation of the orbital evolution of the two planets with fitted planetary masses and orbits



masses of the planets is important to assess their potential for habitability. The first estimate was performed by Grimm et al. in the year 2018, and it was recently revisited by Agol et al. in 2021 with additional data from the Spitzer satellite (see also the review entry on TRAPPIST-1).

Cross-References

- ▶ [Exoplanet, Detection, and Characterization](#)
- ▶ [Transiting Planets](#)
- ▶ [TRAPPIST-1 System](#)

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Planet Formation

Alessandro Morbidelli

Observatoire de la Cote d’Azur, Nice, France

Keywords

Planetesimals · Protoplanetary disk · Accretion disks

Synonyms

[Accretion](#); [Planetary](#)

Definition

Planet formation is the process by which planetary bodies are formed from a disk of gas and dust around a protostar. Planets can form in two ways. In the regions far from the central star, where the disk can cool efficiently, giant gaseous planets might form as a result of the gravitational instability of the disk; alternatively, these planets may form from the protoplanetary cores discussed below. In the inner regions, planets are expected to form in a more complex, multistage process: first, the dust settles onto the disk’s midplane and coagulates to form asteroid- or comet-like bodies called ► [planetesimals](#). Then, the planetesimals accrete with each other during low-velocity collisions to form *planetary embryos* or *protoplanetary cores*. The former are rocky bodies with masses of the order of the lunar to Martian mass, which form in the hottest region of the disk, where water is not in solid form. The protoplanetary cores, which form beyond the ► [snow line](#), are a mixture of rock and ice and are expected to have multiple Earth masses. These protoplanetary cores then accrete a massive hydrogen and helium atmosphere before the disappearance of the gaseous component of the disk and become ► [giant planets](#). ► [Planetary embryos](#) collide with each other at moderate velocities giving rise to terrestrial-like planets.

Overview

In the ► [protoplanetary disk](#), the most refractory materials condense first, gradually followed – while the local temperature drops – by more and more volatile elements. The dust grains thus formed float in the gas. Collisions stick the grains together, forming fractal aggregates, possibly helped by electrostatic and magnetic forces. Other collisions then rearrange the aggregates and compact them. When the grains reach a size of about a centimeter, they begin to rapidly

sediment onto the median plane of the disk, in a time of the order of 10^3 years. This timescale, however, could be longer if the nebula is strongly turbulent.

The growth from centimeter-size grains to kilometer-size planetesimals is still unexplained. Particles of centimeter size are too small for gravity to be effective in particle-particle collisions but are too big to stick through electrostatic forces. Moreover, grains are subject to ► [gas drag](#), which makes them drift toward the central star (Weidenschilling 1977). The drift speed is size dependent; thus, particles of different sizes must collide with non-negligible relative velocities (of the order of several cm/s). At these velocities, particles should break, rather than coagulate. Because the drift speed toward the central star is maximal for meter-size boulders, this issue is known as the ► [“meter-size catastrophe,”](#) though it is likely that this bottleneck for accretion starts already at much smaller sizes (cm or dm).

One possible solution of this problem is that planetesimals form thanks to the collective gravity of massive swarms of small particles, concentrated at some locations (vortices or intervortex regions, depending on particle sizes) by the turbulence of the disk (Johansen et al. 2007; Cuzzi et al. 2008). This model can explain the formation of large planetesimals (100 km or larger) and the internal structure of these bodies as revealed by the petrology of undifferentiated meteorites.

Once the protoplanetary disk contains a substantial population of planetesimals, the second stage of planet formation starts. The dynamics of accretion is first dominated by the effect of the gravitational attraction between pairs of planetesimals, which increases the collisional cross sections. A ► [runaway growth](#) phase starts, during which the big bodies grow faster than the small ones, hence increasing their relative difference in mass (Greenberg et al. 1978). This process can be summarized by the equation

$$d/dt(M_1/M_2) > 0,$$

where M_1 and M_2 are, respectively, the characteristic masses of the “big” and of the “small” bodies, and can be explained as follows.

Generally speaking, accretion is favored by a high collision rate, which occurs when the relative velocities are large, but also by large collisional cross sections and gentle impacts, which occur when the relative velocities are low. Therefore, the relative velocities between the different planetesimal populations govern the growth regime.

At the beginning of the runaway growth phase, the largest planetesimals represent only a small fraction of the total mass. Hence, the dynamics is governed by the small bodies, in the sense that the relative velocities among the bodies are of the order of the escape velocity of the small bodies, $V_{\text{esc}(2)}$.

This velocity is independent of the mass M_1 of the big bodies and is smaller than the escape velocity of the large bodies, $V_{\text{esc}(1)}$.

For a given body, the collisional cross section is enhanced with respect to the geometric cross section by the so-called gravitational focusing factor:

$$F_g = 1 + V_{\text{esc}}^2/V_{\text{rel}}^2$$

where V_{esc} is the body’s escape velocity and V_{rel} is the relative velocity of the other particles in its environment. Because $V_{\text{rel}} \sim V_{\text{esc}(2)}$, the gravitational focusing factor of the small bodies ($V_{\text{esc}} = V_{\text{esc}(2)}$) is of order unity, while that of the large bodies ($V_{\text{esc}} = V_{\text{esc}(1)} \gg V_{\text{esc}(2)}$) is much larger. In this situation, one can show that the relative growth rate (Ida and Makino 1993) is an increasing function of the body’s mass, which is the condition for the runaway growth.

The runaway growth stops when the mass of the large bodies becomes important (Ida and Makino 1993) and the latter start to govern the dynamics. The condition for this to occur is

$$n_1 M_1^2 > n_2 M_2^2,$$

where n_1 (respectively n_2) is the number of big bodies (respectively small bodies).

In this case, the growth rate of the embryos gets slower and slower as the bodies grow and the relative differences in mass among the embryos are also slowly reduced. In principle, one could

expect that the small bodies catch up, narrowing their mass difference with the embryos. But in reality, the now large relative velocities prevent the small bodies from accreting with each other. The small bodies can only participate in the growth of the embryos. This phase is called ► *oligarchic growth*.

The runaway growth phase happens all through the disk, with timescales that depend on the local dynamical time (Keplerian time) and on the local density of available solid material. This density will also determine the maximum size of the embryos and/or planets when the runaway growth ends (Lissauer 1987). Assuming a reasonable surface density of solid materials, the runaway growth process forms planetary embryos of lunar to martian mass at 1 AU in 10^5 – 10^6 years, separated by a few 10^{-2} AU. Beyond the so-called snow line at about 4 AU for a solar luminosity star, where condensation of water ice occurred thanks to the low temperature, enhancing the surface density of solid material, runaway growth could produce objects as large as several Earth masses, called protoplanetary cores, in a few million years (Thommes et al. 2003). Then, the last stage can lead to the formation of the planets.

Giant Planet Formation

When the protoplanetary cores reach a mass of 5–10 Earth masses, they start to accrete a significant amount of gas from the protoplanetary disk. The gas accretion continues at a roughly constant rate over a few million years, until a total mass of 20–30 Earth masses is reached; then, the gas gravitationally collapses onto the planet: the mass of the planet grows exponentially and reaches hundreds of Earth masses in $\sim 10,000$ years (Pollack et al. 1996). A giant planet is formed.

This model explains well the structure of Jupiter and Saturn, gaseous planets with solid cores of 5–15 Earth masses. It also explains the nature of Uranus and Neptune, ~ 15 Earth-mass planets with only a few Earth masses of gas: these cores would have formed more slowly, given the larger distances to the Sun, so that the gas was removed from the protoplanetary disk before the conditions for the gas gravitational collapse could be met.

There are, however, many conceptual problems with this model. First, although analytic theories predict the formation of 10 Earth-mass cores beyond the snow line, numerical simulations show that the cores have problems to grow above ~ 1 Earth mass (Levison et al. 2010) for various dynamical reasons. Second, planetary cores should undergo a fast orbital migration toward the central star, as a result of their gravitational interactions with the disk of gas (known as “Type I migration”; Ward 1997). Consequently, they should be lost before having a chance to accrete a massive atmosphere and become giant planets. Third, according to theoretical estimates, the conditions for the onset of the gravitational collapse of the gas might not be met before several millions of years (Podolak 2003), a time longer than the typical lifetime of protoplanetary disks (Haisch et al. 2001). Finally, if the gas gravitational collapse takes place, the planet should grow to 5–10 Jupiter masses in a very short time, which makes it difficult to explain the much smaller terminal masses of Jupiter and Saturn.

To circumvent some of these problems, particularly those related to the formation of the cores and their survival in the disk, it has been proposed that giant planets might form directly from concentrations of gas, like a star, without the need of the prior formation of massive solid cores (Boss 2000). In fact, it has been shown that a cold, massive protoplanetary disk can break into a number of self-gravitating gas clumps, which then contract forming giant gaseous planets (Durisen et al. 2007). The key issue is the temperature: as the concentration of gas increases, the temperature rises, which tends to prevent the further accumulation of gas. Thus, the formation of self-gravitating clumps and their subsequent contraction requires an efficient cooling of the gas. For this reason, new hydrodynamical simulations that model more accurately the thermodynamics in the protoplanetary disk find that formation of long-lived self-gravitating clumps of gas is likely only at large distances from the central star (more than 50–100 AU; Boley 2009). It is still unclear, though, whether the end products of these clumps can be giant planets or must be ► *brown-dwarf-mass* objects (Stamatellos and Whitworth 2008).

For all these reasons, the gravitational instability model is now less favored than the core accretion model for the formation of the giant planets of the solar system as well as most extrasolar planets, while it might be an explanation for the origin of massive distant extrasolar “planets” such as those of the HR 8,799 system.

The core accretion scenario, on the other hand, has been recently strengthened by the proposal of a new mechanism for the growth of the solid cores that overcomes the 1 Earth-mass barrier discussed in Levison et al. (2010). According to this new mechanism, dubbed “pebble accretion,” the largest planetesimals which formed from self-gravitating clumps of small pebbles continue to accrete pebbles from the protoplanetary disk (Lambrechts and Johansen 2012). In fact, due to gas drag, most of pebbles passing through the Hill sphere of a growing planet would spiral down to the planetary surface and deliver their mass. Pebble accretion is extremely efficient and fast and potentially can lead to the formation of a 10 Earth-mass core well within the gas disk lifetime.

Terrestrial Planet Formation

The terrestrial planets form from the collisions of the planetary embryos that accreted during the runaway and oligarchic growth phases, in the inner part of the disk. In our solar system, given the presence of Jupiter at ~ 5 AU, the typical result of this highly chaotic collisional phase – simulated with several numerical N-body integrations – is the elimination of all the embryos originally situated in the asteroid belt (2–4 AU) and the formation of a small number of terrestrial planets on stable orbits in the 0.5–2 AU region in a time-scale of ~ 50 –100 My (Chambers and Wetherill 1998; O’Brien et al. 2006; Raymond et al. 2007). This scenario explains the small number of terrestrial planets existing in our system, their orbital eccentricities and inclinations, their accretion timescales determined from the analysis of the radioactive chronometers (Kleine et al. 2009), and their enrichment in volatile elements (including water; Morbidelli et al. 2000) relative to what is expected for planetesimals formed well inside of the snow line.

The main problem of this scenario is that the mass of the synthetic planet formed in the simulations at the location of Mars is typically ~ 5 times too massive (Raymond et al. 2009). Hansen (2009) proposed an original solution to this problem, showing that if the disk of planetesimals and embryos, out of which the terrestrial planets formed, had an outer edge at 1 AU, the large mass ratio between the Earth and Mars is systematically reproduced in the simulations. Mars in this case is an embryo which is rapidly ejected out of the annulus of material by a close encounter with the proto-Earth. Consequently, the accretion of Mars is aborted and the planet can preserve its small initial mass.

The existence of the outer edge of the disk at 1 AU was just an ad hoc assumption in Hansen’s work, but its origin was later explained in Walsh et al. (2011), by invoking the migration of Jupiter during the gas-disk phase. More specifically, hydrodynamical simulations have shown that Jupiter migrates inward while it is “alone” in the disk, but when Saturn reaches its current mass, the presence of this second planet is capable of reversing the migration direction of Jupiter, forcing the latter to move outward. The inward-then-outward migration of Jupiter severely depletes the portion of the disk crossed by the planet. Thus if Jupiter reversed migration (or “tacked”) around 1.5 AU, the disk of embryos and planetesimals would have been truncated at ~ 1 AU, just as required in Hansen’s model. This scenario is now called “Grand Tack scenario.”

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Giant Planets](#)
- [Gravitational Collapse, Planetary](#)
- [Late-Stage Accretion](#)
- [Meter-Size Catastrophe](#)
- [Oligarchic Growth](#)
- [Planetary Migration](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Protoplanetary Disk Instability](#)

- [Runaway Growth](#)
- [Snow Line](#)
- [Terrestrial Planet](#)

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Planet V Hypothesis

Sean N. Raymond

Laboratoire d’Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

The Planet V hypothesis proposes that a fifth terrestrial planet (named “planet V”) formed exterior to Mars’ orbit and became dynamically unstable several hundred million years after its formation. This instability could have led to the impact of a large number of asteroids on the Earth-Moon system. The Planet V hypothesis is the main alternate mechanism to the ► [Nice model](#) for the origin of the ► [Late Heavy Bombardment](#).

Cross-References

- [Late Heavy Bombardment](#)
- [Nice Model](#)

References and Further Reading

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biological candidates and hardware material for astrobiological experiments in Earth orbit) and for assessing the habitability of other planets (e.g., of Mars). They were extensively used for preparation and long duration astrobiological carriers like NASAs LDEF (Long duration exposure facility), ESAs EURECA (European Retrievable Carrier), and ESA/Russian BIOPAN on Foton capsules up to the recently flown ESA exposure facilities EXPOSE-E, -R, and -R2 on the ISS.

Planetary

- [Planet Formation](#)

Planetary and Space Simulation Facilities

Corinna Panitz

German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Keywords

Microgravity · Simulation facility · Space environment · Temperature · UV · Vacuum · VUV · X-ray

Definition

The Planetary and Space Simulation Facilities are laboratory devices aimed at mimicking individual or combined extreme environmental conditions as of space (vacuum, temperature, and radiation), or other celestial bodies (atmospheric composition, pressure, temperature fluctuations, and radiation), or moons (gas mixture, pressure, low temperature) for exposure of life forms, e.g., microorganisms, plant seeds, lichens, and organic chemical compounds. They are valuable instruments in the preparation of space experiments and mission parallel ground references (selection of suitable

Overview

In the Planetary and space simulation facilities six recipients and three computer controlled cryostats, three solar simulators, four specialized UV-radiation sources, and a calibrated double monochromator spectroradiometer with calibration source allow a broad range of tests of biological and chemical as well as physical material individually or integrated into space hardware. The close vicinity to molecular biology, genetic, and cell laboratories as well as anaerobic biology laboratories and ISO 8 clean rooms provide the full infrastructure for preflight preparation and postflight analysis of astrobiological and cell biological space missions. The results of these experiments support the design optimization and verification of spacecraft devices, the selection of the most promising biological and chemical material for flight experiments, and the selection of search for life experiments for planetary missions. The following extraterrestrial conditions have been simulated for astrobiology purposes:

- *Simulation of outer space conditions:* Space simulation facilities have been first developed for testing and qualifying space hardware. Test parameters were ultrahigh vacuum, low temperature, extraterrestrial solar ► [UV radiation](#), and X-rays for the simulation of the ionizing component in space. With the increasing interest in astrobiology, these facilities were adapted to expose organics and biological organisms to simulated space (Horneck 1999; Rabbow et al. 2005, 2016). Space simulation

facilities have the common construction principle of stainless-steel cylinders of different sizes equipped with numerous flanges and ports for instrumentation and observation. The main vacuum chamber is connected to different high-performance pumping systems to generate a lowest possible vacuum for the simulation of representative space conditions. A solar simulator, consisting of an array of powerful lamps, reproduces the extraterrestrial solar electromagnetic radiation (from ultraviolet to infrared radiation) at high intensities. Optical filter systems allow the selection of desired wavelength bands and controlled intensities of the radiation. Furthermore, cryogenic systems provide controlled temperatures. Space simulation facilities were intensely used in preparation of the astrobiology exposure experiments in space, such as those using the space ► [exposure facilities](#) on Spacelab 1 and D2, ► [ERA](#) on ► [EURECA](#), Exostack on LDEF, ► [BIOPAN](#) on Foton, and ► [EXPOSE](#) on the ISS (Cockell et al. 2005; Fekete et al. 2005; de la Torre et al. 2007;

Rabbow et al. 2009). They were used as test systems in the preparation of the flight experiments, as well as for the simultaneous ground control experiments (Fig. 1). Similar to the flight parameters of temperature and UV fluences Mission Ground Reference experiments were performed parallel to the respective mission in flight identical sample sets.

- *Simulation of spaceflight (microgravity) conditions:* Various ground-based methodologies have been employed to simulate microgravity for studying its effects on microorganisms, cells, and small biological objects. One of the most common devices used to provide a functional weightlessness is the clinostat. Sedimentation is compensated by fast rotating a small sample centered on a horizontally positioned axis perpendicular to the direction of the gravity vector. Another device is a rotating wall vessel (RWV) bioreactor. While maintaining cells in suspension as they continuously fall through the medium under $1 \times g$ conditions, the RWV bioreactor can also induce a perfusion of nutrients to and waste



Planetary and Space Simulation Facilities, Fig. 1 Overview of the astrobiological planetary and space simulation facilities. Computer controlled and monitored vacuum recipients, cryostats, and solar simulators are combined

from the cell environment. Other approaches for exploring the effect of altered gravity conditions on living systems while still on Earth are free fall, neutral buoyancy, and diamagnetic levitation (Clément and Slenska 2006; Horneck et al. 2010).

- *Simulation of planetary surface conditions:* The evolution of facilities for simulating Mars conditions has progressed over time from very simple anoxic systems to highly sophisticated simulation chambers (reviewed by Hansen 2007). They generally consist of a stainless-steel chamber with control of gas composition, pressure, temperature, and humidity as well as provision of a UV radiation source with optical filters simulating the UV radiation climate of Mars (Schuerger et al. 2003, 2006; Tauscher et al. 2006; Jensen et al. 2008; Osman et al. 2008; de Vera et al. 2010).

Cross-References

- BIOPAN
- Cosmic Rays in the Heliosphere
- Desiccation
- Environment
- ERA
- EURECA
- Expose
- Exposure Facilities
- Extreme Ultraviolet Light
- Foton Capsule, Spacecraft
- Gravitational Biology
- Habitat
- International Space Station
- Ionizing Radiation, Biological Effects
- Mars
- Microgravity
- Radiation Biology
- Solar UV Radiation, Biological Effects
- Space Biology
- Space Environment
- Space Vacuum Effects
- UV Climate
- UV Radiation
- UV Radiation Dose
- UV Radiation, Biological Effects

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Planetary Chronostratigraphy

► [Chronostratigraphy](#)

Planetary Core

► [Core, Planetary](#)

Planetary Debris Disks

► [Debris Disk](#)

Planetary Ecosynthesis

Christopher P. McKay
NASA Ames Research Center, Moffett Field, CA,
USA

Keywords

Biospheres · Global ecology · Life · Mars ·
Terraforming

Synonyms

[Ecopoesis](#); [Terraforming](#)

Definition

Planetary Ecosynthesis: The purposeful alteration of another planetary environment so as to improve the chances of survival of an indigenous biology or, in the absence of any native life-forms, to allow for habitation of most, if not all, terrestrial life-forms.

History

Terraforming was first used as a word in a science fiction short story in 1942 by Jack Williamson. The first scientific discussion was a suggestion by Carl Sagan, as part of a paper in *Science*, to remove the thick carbon dioxide atmosphere of ► [Venus](#) by seeding the planet with algae. The seminal suggestion to use supergreenhouse gases to warm ► [Mars](#) was made by Lovelock and Allaby (1984) in their science fiction book *The Greening of Mars*. The first technical paper dealing entirely with terraforming was in *Nature* in 1991 by Chris McKay, Brian Toon, and James Kasting, entitled *Making Mars Habitable*. The first discussion of the environmental ethics issues appeared in 1990 in the book *Moral Expertise* in chapters written by Robert Haynes and by Chris McKay. In 1997, the NASA Astrobiology Institute included as one of its six founding questions “What is the potential for survival and biological evolution beyond the planet of origin?” The two international journals *Astrobiology* and the *International Journal of Astrobiology* both include terraforming studies in the scope of papers they publish.

Overview

Terraforming has been discussed for the Moon, Venus, Mars, and Titan (the moon of Saturn). Only for Mars does planetary ecosynthesis appear feasible in the near term. Mars appears to have had habitable conditions in the past, and the fundamental challenge of restoring habitable conditions to Mars is to warm the planet from its current $-60\text{ }^{\circ}\text{C}$ to somewhat over $10\text{ }^{\circ}\text{C}$. Humans have demonstrated the technology to warm the Earth by

a few degrees using greenhouse gases. On Mars, the warming needed would be tens of degrees – many times larger than on Earth. The materials needed to construct a biosphere are water, carbon dioxide, and nitrogen. These are likely to be present on Mars in adequate supply, although there is uncertainty in the total nitrogen available. The fundamental physical aspects of Mars that would be virtually impossible to alter, such as axial tilt, rotation rate, and eccentricity, are similar to the corresponding values for Earth, except for surface gravity, which is 0.38 of the Earth value. If the sunlight incident on Mars was captured with 100% efficiency, it would take only ~ 10 years to warm that planet. Greenhouse gas efficiencies of 10% are plausible, and thus, the timescale for warming Mars is ~ 100 years. In contrast, it would take over 100,000 years to produce enough oxygen on Mars to support humans, and this is based on the optimistic assumption that the efficiency for oxygen production of Mars' biosphere would be the same as Earth's current biosphere. Thus, warming Mars and recreating a thick carbon dioxide atmosphere is within current technology and human timeframes, but creating an oxygen-rich atmosphere is not. Humans would require a source of oxygen, but many microorganisms, some plants, and even a few animals could survive despite the low oxygen content. The practical method to warm Mars involves low levels of supergreenhouse gases composed only of the elements F, S, C, and H. Supergreenhouse gases containing Cl and Br are not used because of the effect these gases have on ozone. If there is enough carbon dioxide ice present in the polar regions of Mars, then a warming of 20°C caused by artificially produced greenhouse gases would cause the complete evaporation of that ice through a positive feedback mechanism. The first ecosystems on Mars would probably resemble alpine ecosystems. A key biological threshold would be the first growth of trees – treeline.

Cross-References

- Mars
- Venus

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Planetary Embryo

Yann Alibert¹ and Ravit Helled²

¹Space Research and Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland

²Geophysical, Atmospheric and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

Keywords

Planet formation · Solar nebula

Definition

In ► **Planet Formation** theory, planetary embryos are solid bodies that dominate gravitationally in their ► **Feeding Zone**. Planetary embryos form from ► **planetesimals**, with the formation process leading to a bifurcated mass distribution as a result of ► **oligarchic growth**; they typically have masses of fractions of an Earth mass.

Cross-References

- [Feeding Zone](#)
- [Oligarchic Growth](#)
- [Planet Formation](#)
- [Planetesimals](#)

Planetary Evolution

Jean-Pierre Bibring
Institut d'Astrophysique Spatiale, Université
Paris Sud, Orsay, France

Keywords

Planets · Solar system evolution

Definition

All solar system bodies (planets, satellites) show an extraordinary diversity in their physical aspect and properties. This entry describes the different physicochemical processes involved in the evolution of a planet, which may be responsible for changes in its internal structure, surface, atmosphere, or magnetosphere, and eventually account for such a diversity.

Overview

From Motion to Evolution

Planets (*vagabonds*, in Greek) have first been recognized and characterized by their apparent movements in space, traveling among the fixed frame of stars. Their motion was proposed as heliocentric by Copernicus and then formalized by Newton; this ended a long, complex, and tough quest, over centuries, with more and more accurate measurements contradicting the dogma of a centrally located Earth. A critical outcome has been that the Earth and the planets belong to the same family. As a consequence, the fact that the Earth has a History and thus evolves implies that all planets do, possibly in a manner similar to the

Earth: worlds' plurality has long been a concept of reference.

However, the prime role of the Sun in controlling the planetary motion and their illumination has erroneously been extrapolated to most, if not all planetary properties: that they would be primarily influenced by the solar gravitational and electromagnetic fields. The planets would thus differ from stars in their lack of energetic means to evolve by themselves: they would essentially simply respond to solar inputs.

Space exploration has dramatically modified this view, in enabling close and in situ analyses of the planets and satellites, which had long remained poorly resolved objects in ground telescopic observations. All these objects exhibit a degree of diversity totally unexpected, and far beyond what could be achieved if the Sun was solely responsible of their evolution.

The state of the four Jovian Galilean satellites, revealed by the NASA/Voyager flybys in 1979, is exemplary of this diversity: these bodies, of similar mass, location, and age, have followed totally distinct evolutionary pathways. Io has been discovered to be a world of extreme volcanic activity, the most intense of the entire solar system: its surface is entirely reprocessed on a timescale of some thousands of years. The surface of ► [Callisto](#) is still saturated with impact craters acquired just after it formed, during the heavy bombardment period; no global resetting seems to have erased this ancient record. ► [Europa](#) is entirely covered with a thick layer of fresh water ice, with a number of crevasses and no craters nor volcanoes. ► [Ganymede](#) is a mixture of rocks and ices, with faults and other features recording past tectonic activity.

The inner planets exhibit similar contrasts. ► [Mars](#) has a few but giant volcanoes, all having ceased to outflow; none are observed on ► [Mercury](#), but thousands on ► [Venus](#). The atmospheric pressure varies from 90 bars at Venus, down to 10 mbars at Mars, and almost zero at Mercury. The cloud coverage varies from none, for Mercury and the Moon, to full, for Venus; the Earth is somewhat in between Venus and Mars, for both its atmospheric pressure and cloud cover. Apart from the Earth, no object, within

the solar system, has been found sustaining liquid water at its surface.

This high degree of diversity strikingly contrasts with the large commonalities in their origin that all solar system objects share: the catastrophic origin of the planets has been definitely abandoned in favor of their being accreted in a single collapsing molecular cloud, formed at the same time (some 4.57 billions of years ago), at the same location in our Galaxy, from essentially the same material. How to account for their differences? What triggers and drives planetary evolution?

It is one of the prime goals of planetary exploration to characterize the specificities of each planet and to derive the clues of their distinct evolution. A central focus is on the Earth, with particular still unresolved questions such as what are the unique conditions that prevailed and still do, which harbored life and maintained its adaptive evolution, up to now? What are the subtle processes at work that sustain the biosphere, with a highly specific ocean and cloud cover? These questions are not of mere curiosity, as our environment changes with an increasingly shortening timescale, now only decades.

To address these questions, as for any dynamical system, one needs to decipher both the *initial conditions* that shaped the planetary evolution, and the *energies* at work all along their history.

Initial Conditions

The initial conditions of planetary formation consist actually in a sequence of processes, over millions to tens and hundreds millions of years.

During its collapse, the protosolar cloud has been subjected to a very specific chemical evolution, ending with a highly complex molecular mixture dominated by H_2 , with abundant H_2O and a wide variety of C-rich species. In particular, large carbon chains were built, giving rise to refractory organics – possibly with chirality trapped in. The cloud was first heated by the energy released while the central core was collapsing, until it reached thermodynamic equilibrium. The p-p thermonuclear chain then started; the Sun, as a star, was born. The emitted radiation blocked further collapse. The cloud started

cooling, and minerals condensed through a sequence primarily dictated by the elemental and molecular composition of the gas. At distances far enough for H_2O ice to become stable, it constituted the most abundant solid phase: the growing bodies accreted predominantly water ice, as a matrix in which most other grains and species, including the organics, were trapped.

The composition of the material subjected to collisions did thus strongly vary with heliocentric distance. Within the inner solar system, minerals were the only solid grains. Slow enough collisions (typically less than hundreds of meters per second) led to accretion of ► [planetesimals](#), some of which accreted further to become planetary embryos; they were essentially anhydrous. At larger distances, water ice started to be stable, first as a minor constituent (>2 astronomical units, AU), then as a major one for >4 AU, typically. Large ice-rich bodies of ~ 10 terrestrial masses grew fast enough to trap and bind gravitationally the surrounding nebula, ending as “giant” gaseous planets. The rapid formation of ► [Jupiter](#), and to a lesser extent of ► [Saturn](#), had a major impact on the further evolution of the entire nebula by the gravitational perturbations they induced, both in the inner and outer parts of the system.

Although this is not fully confirmed yet, Jupiter and Saturn did actually migrate, in a very specific pattern that severely modeled the further evolution of most solar system objects. In this scenario referred to as the “Nice model”, Jupiter migrated inward first, emptying most of the disk from their planetesimals, down about 1.5 astronomical units (AU). Saturn then arrived, at a distance corresponding to a $2/3$ resonance with Jupiter. The mass ratio of these two large bodies prevent them to pursue their inward migration, and made them migrating outward, blocked in this resonance, leaving most of the inner disk confined within 1 AU: its further evolution led to the accretion of the inner planets with their proper mass distribution, characterized by Mars being much smaller than Earth. This accretion was accompanied with inner grains ejected outward, and outer materials injected to the growing inner protoplanets, which led to both repopulating the

asteroidal belt, and feeding the inner planets with water and other volatile compounds. When stabilized close to their present orbit, Jupiter and Saturn gravitational perturbations to objects forming closer and beyond, resulted in stopping their growth, as “small bodies”, which preserve, up to now, the records of these early times. Some of the later, predominantly formed of ices and volatile species, were eventually re-ejected into the inner solar system by later (planetary or stellar) perturbations: their partial sublimation when passing close to the Sun (a few astronomical units apart at most) produces “comae” of gases surroundings their nucleus, thus they are being called ► *comets*.

Thus, the growth of Jupiter and other ► *giant planets* has preserved bodies small enough to have avoided further differentiation, maintaining their pristine composition, in particular in volatile (e.g., H_2O) and organic species. During the early phases of the dynamical evolution of the solar system, collisions played a critical role, in particular when the inner planets, depleted in volatile compounds, were impacted by small bodies formed at larger distances that were thus loaded with low temperature constituents such as ices: this fed the inner planets with large amounts of organics and of water. The terrestrial oceans thus seem to have an extraterrestrial origin. Their seeding with refractory organics might have favored the emergence of biochemistry.

The same process – collisions – which led to planetary accretion for small relative velocities also triggered destruction for large impact velocities (in the kilometer per second range). This explains that the planets and satellites which have, at least partially, preserved the surface structures acquired during the first hundreds of millions of years after they formed are heavily cratered. Actually, some 4 billion years ago, all planets were similarly cratered and looked as most of the Moon and Mercury surface still does. What has differed for planets like the Earth, which no longer exhibits cratered terrains, is their further activity, which erased the records of this ancient bombardment.

The Earth has preserved a key record of its primordial bombardment: its Moon. It is now generally accepted that the formation of the

Moon results from a giant impact of a large embryo, with mass of about 1/10 of that of the Earth, on the proto-Earth. This impact deeply modified the further evolution of the Earth. It melted most, if not all of it, and ejected in a disk a large fraction of the impacting embryo, as well as Earth’s mantle material. Re-accretion within the disk formed the Moon, whose presence still induces important gravitational (tidal) effects. In particular, it prevented the Earth’s obliquity from oscillating around its mean value of 23° by more than 1.5° , which is totally unique in the solar system. Earth has maintained rather steady climatic conditions over its entire history, and this may constitute a key ingredient to the survival of habitable conditions on the Earth, at least for complex organisms. Most of the volatile constituents of the disk fell rapidly back to the Earth. Water in particular was mixed to the outer part of the magma, whose hydration may have eased its convection and contributed to initiating ► *plate tectonics*.

Other planets might have also been subjected to giant impacts. For example, it has been suggested that the present Mars dichotomy, with its northern hemisphere some 15 km below the altitude of the southern terrains, might have been formed in this way; the two small moons of Mars, Phobos and Deimos, could have re-accreted within the circumplanetary disk. However, their very small mass is insufficient to block the chaotic oscillation of Mars’s obliquity, which has driven part of Mars’s climatic evolution.

Did the heavy bombardment steadily decrease over the first half billion years, or was it made of more than one episode? No definite answer is available yet, although several lines of evidences seem to favor the second scenario, exhibiting at least two phases of bombardment. The first one, coupled to the planetary accretion, lasted some tens of millions of years; for the Earth, it included, and possibly ended with the giant impact from which the Moon formed. This bombardment dropped with the decline in the number of potential impactors. Some hundreds of millions of years later, the impact rate suddenly increased, giving rise to a ► *“late heavy bombardment”* (LHB) phase. Its possible trigger is the following: During

their rapid inward, then outward migration, according to the Nice model, Saturn and Jupiter remained in their 2/3 resonance. However, their gravitational interaction with the outer solar system objects, Uranus and Neptune primarily, broke this resonance some hundreds of millions years later, leading to a massive inward ejection of grains and bodies (the LHB), giving rise to a violent bombardment of the inner planets, during tens of millions of years, some 4 billion years ago. A large fraction of the craters, still visible on the Moon, Mercury, and Mars, results from this LHB.

It happens that the migration of Jupiter and Saturn stopped at heliocentric distances larger than 1 AU. This is in striking contrast with the situation found in many other stellar systems, in which giant exoplanets are located much closer to their star, as a result of a much longer migration. The evolution of the Earth and other inner planets would likely have been deeply disturbed if Jupiter had spiraled over them rather than staying at significant distances.

The diversity of our present solar system does not merely originate from the early dynamical history. The composition – elemental, isotopic, molecular, and mineralogical – acquired during the accretion also played a key role. It is remarkable that bodies having preserved records of this primordial composition still exist, enabling its deciphering. This is mainly a result of the specific dynamical history of the protosolar nebula, with the rapid growth of the giant planets inhibiting further growth of comets and asteroids, which remain “small bodies”: with limited energetic content precluding their thermal modification, they still preserve the composition and properties acquired at the time they formed. They constitute objects of utmost importance to trace back the initial conditions of the solar system, from a compositional standpoint. Their characterization can be performed in two ways: by in situ space exploration and, in the laboratory, by analyses of samples either collected and returned from them, or impact ejected from these parent bodies, as meteorites and micrometeorites.

With the highly sophisticated tools nowadays available, most analyses can be performed down to the scale of individual grains. These methods

point out the effects of the isotopic and molecular composition, acquired during the final stages of protoplanetary accretion, on the evolution of the growing bodies. As examples, the “short-lived” radioactive species such as ^{26}Al , trapped together with ^{27}Al in minerals during the condensation sequence, have constituted the dominant energy input at a protoplanetary scale, eventually triggering early mineralogical differentiation of these bodies. Icy grains and hydrated phases, condensed at large heliocentric distances, brought most of the volatile molecules to the inner bodies, including in particular water and complex macromolecules of potential astrobiological relevance.

A fundamental contribution of the isotopic analyses is their enabling of a precise dating of the events that paved the early history of the solar system, within the first tens to hundreds of millions of years following its birth, some 4.57 billion years ago. Some of them are now determined with an accuracy of 1 Ma. One can both identify the processes that were operating within the early solar system and time tag them in a global and accurate cosmo-chronology.

Energy Sources

The sources of energy that sustain activity fundamentally differ between planets and stars. Stellar evolution is essentially driven by the strong interaction, through nuclear reactions triggered by the temperature and pressure produced by the gravitational collapse. At a given point in their life cycle only a few nuclear reactions are enabled, and the stars maintain almost steady global conditions, which allow classifying them in families according to their evolutionary stage. By contrast, all the physical interactions operate for planets, with distinct intensities and time constants, building distinct evolutionary paths and leading to a wide diversity.

The electromagnetic interaction acts predominantly through the solar irradiation. However, photons only penetrate into liquids and solids down to very shallow depths: the solar flux does not contribute to the internal activity. Other electromagnetic effects can operate deep in the planet's interiors, such as phase changes. Whenever gaseous species condense, liquid freezes or

solidifies, energy is released. As examples, the formation of helium rain deep in the atmosphere of giant planets might constitute an important energy input for their evolution. Similarly, the progressive solidification of the outer liquid core within planets releases energy that slows down their transformation.

The gravitational interaction acts through self-collapsing for individual gaseous bodies and through remote interactions for all of them. Tidal effects play specific roles, such as synchronizing rotation and revolution for corotating bodies (planets and satellites). In a few cases, tides may constitute the dominant driver of internal activity. This happens with Io, the closest Galilean satellite, whose strong gravitational lock by Jupiter varies along its elliptical orbit, and is perturbed by Ganymede and Callisto: the energy dissipated deep within Io's mantle produces the highest degree of volcanism within the entire solar system, with plumes some hundreds of kilometers in altitude. Io's surface is entirely remodeled by volcanic outflows on a timescale of a few thousand years.

The weak nuclear interaction is a key provider of energy, through the radioactive decay of isotopes with time constants similar to the age of the planets (10^9 – 10^{10} years typically). Actually, only very few such nuclei exist, and those playing the dominant role are ^{238}U , ^{235}U , ^{232}Th , and ^{40}K . Their relative abundance is low, leading to power release in the order of 10^{-8} W/m³. However, they are present in the bulk of the planetary interior, which makes their input dominate the internal evolution of a variety of planets, in particular of the inner planets, including the Earth.

A specific feature associated with the radioactive energy is its time dependence: as the release is coupled to the transformation of parent nuclei, it necessarily decreases with time. A planet cannot remain in a steady state, as stars do; its activity declines with time. Since the energetic load varies as the volume in which the radioactive species are distributed, while the energy loss operates by surface radiation, the thermal balance depends on the radius. The larger the body, the higher the volume/surface ratio and thus the energy gain/loss ratio, therefore the temperature onset before declining: the later the geological death will occur. This

explains why it happened for the Moon some 3 billion years ago, for Mars some tens of millions of years at most, while the Earth is still active. On the other hand, objects small enough (tens of kilometers in size at most) to efficiently radiate their internal energy have escaped major heating and preserved their primitiveness.

Internal Activity

The internal activity depends both on the available energy and on its transportation throughout the object. For example, the initial gravitational energy load produced during accretion is still partially present in most planets, at least in their core: for the Earth, up to half of the total available energy today might still originate from this early input.

A key feature must be outlined. When the temperature gradient enables convection to operate, sustained motions of matter take place, possibly up to the surface: the object is active.

Mineralogical differentiation under gravity precipitates the denser materials downward, leaving the lightest ones toward the surface. A high density (~ 8) solid core forms, constituted of metal-rich compounds, dominated by Fe/Ni alloys; it is possibly surrounded by a liquid envelope of similar elemental (metallic) composition. If turbulent convection in this outer liquid core occurs, a dynamo is generated: the planet develops a global magnetic field.

Above the core, a mantle of fused rocks exists, covered by a light crust. As the temperature decreases toward the surface, both the upper part of the mantle and the crust are cold enough to be solid, constituting a *lithosphere* (Greek for “sphere of stones”); the inner part of the mantle down to the core is sufficiently warmed to be fluid, thus it is called an [asthenosphere](#), swept by convection movements. Upwelling flows of magma slowly solidify as rigid plates as they approach the surface, and then drift horizontally at a velocity of some centimeters per year. They thicken by cooling, until their mass forces them to sink back to the mantle, at *subduction* zones. This latter movement is severely constrained and proceeds by pulses capable of generating earthquakes and tsunamis.

These convective cells drive the global planetary internal activity, known as *plate tectonics*. In the case of the Earth, most of these plates are covered with oceans. The remaining ~30% are covered with continents, which are thus carried in the drift of the plates. As the continents are made of material less dense than the underlying floor, they remain at the surface and stay blocked over the subduction zones, where they eventually collide with a continent moving counterward: the shock results in mountains and faults.

This geological evolution typically operates over timescales of tens to hundreds of millions of years. With the slow decrease of internal energetic resources, and the correlated thickening of the outer rigid layer, the planet approaches its geological death: it occurs when its surface becomes no longer affected by the internal activity. Only exogenous and atmospheric processes may further drive their evolution.

Atmospheric Evolution

The planetary atmospheres evolve both in composition and density, with timescales ranging from long-term variations to seasonal changes. As an example, the present-day terrestrial atmosphere, with a pressure of one bar dominated by N₂ (78.9%) and O₂ (20.1%), differs from the early one in at least two respects: most of the CO₂, whose pressure amounted to tens of bars (as is still the case for Venus), have been dissolved and trapped into carbonates, thanks to the sustained presence of stable oceans, leaving N₂ the most abundant species; on the contrary, most of the present O₂ appeared long after the planet formed. It results from the photosynthetic activity of living organisms, as an outcome of their building C-rich molecules from CO₂. Both these changes operated over hundreds of millions of years. By contrast, a huge enrichment of the amount of CO₂ is observed nowadays, with timescales of decades, most likely as a result of human activity – most energy is produced through the combustion of C-rich molecules (oil, coal, wood).

Importantly, the atmospheric content in major, minor, and trace elements does depend on the planet's internal activity, in at least two ways: through outgassing mostly coupled to volcanic

activity and through plate tectonics. For example, a fraction of the CO₂ originates from the dissociation of carbonates within continents reaching subduction zones. As such, the radioactive energy plays a key atmospheric – and thus climatic – role in sustaining the recycling of key species, as discussed below for greenhouse gases.

However, by far the dominant energy source that drives atmospheric processes originates from the solar irradiation. The radiation transfer is highly dependent on the composition of the atmospheric constituents: gases, clouds, ices, aerosols, and grains. A complex photochemistry takes place, thermodynamically constrained, resulting both in a layering of the atmosphere and in its movement, with circulation loops at different scales.

These interactions translate into a specific thermal profile of the atmosphere, well described in the case of the Earth. The temperature profile exhibits three *inversion* layers (inversion of the sign of temperature vertical gradient). From the surface upward, the temperature slowly decreases within the *troposphere*, mostly heated by contact with the surface. At some 20 km in altitude, the thermal gradient becomes positive: in the overlying *stratosphere*, the temperature increases, through the absorption of ultraviolet (UV) solar photons. O₂ is dissociated and the freed O atoms, reacting primarily with O₂ and N₂, form ozone (O₃) and a variety of N-rich molecules, blocking all the UV solar photons. The stratosphere thus shields the troposphere against the lethal effects of these high-energy photons. The upper limit of the stratosphere (~40 km) is defined by the pressure above which the cross section for the O₂ photodissociation becomes marginal (the pressure is too low): in the absence of photon absorption, the temperature thus decreases with altitude in the *mesosphere*, as it does in the troposphere. At still higher altitudes (~80 km), solar X-rays are absorbed and ionize the atoms: the top atmospheric layer above the mesosphere is accordingly named the *ionosphere*.

Consequently, the incoming solar flux is progressively depleted in its high-energy photons (X, UV), in the ionosphere and then the stratosphere, before entering the troposphere, where the visible

wavelengths (0.4–0.8 μm) dominate. The photons that are not reflected (mostly by the clouds and the surface ice) are absorbed on the ground. They are then reemitted with a distinct energy distribution, imposed by the surface temperature, which is some 20 times lower than that of the solar photosphere: their spectrum covers primarily the infrared (IR) range, according to Planck's law. Minor constituents of the terrestrial atmosphere, such as H_2O and CO_2 , have no transition in the visible, but strong vibration modes in the IR: they are transparent to the incoming solar flux, but highly absorbing for the radiation emitted by the surface at longer wavelength. They constitute very efficient *greenhouse* gases responsible for an increase in the Earth's surface temperature of $\sim 33^\circ$. More generally, the surface temperature of a planet, in particular with respect to water stability, does not merely depend on the solar influx, but also on its atmospheric composition, in particular with respect to its content in greenhouse gases.

The orbital evolution of the planets has strong effects on their level of insulation. Over the year, the total amount of solar energy received varies with the distance to the Sun, with larger variations for more eccentric orbits. In addition, the insulation depends on the obliquity, defined as the angle between the planetary axis of rotation and the orbit plane – known as the ecliptic. The Earth is closer to the Sun in early January; it receives some 6% more energy in northern winters than in northern summers which, given the distribution of continents and oceans, contributes to damping the global annual temperature variations. This configuration changes over time, as the axis of rotation spins with a period of some 25,000 years (precession of the equinoxes). Actually, all orbital parameters vary with time, which induces variations of most climatic parameters, primarily of the temperature distribution with average amplitude changes of some degrees. This is the major driver of the recurrent glaciations, as first demonstrated by Milutin Milanković.

An important factor that dictates the temperature of the lower atmosphere is the cloud coverage, which strongly differs from one planet to the next. The cloud $\blacktriangleright$ [albedo](#) is high enough to reflect a large fraction of the incident solar flux:

terrestrial cumulus clouds block up to 50% of the incoming energy. Has their coverage changed with time, which would have led to significant variations of the global averaged temperature? Actually, a definite answer cannot be given yet, since cloud formation results from a rather complex suite of processes, involving still unknown nucleation sites on which water or other molecules condense, if enabled by thermodynamics. This microphysics remains an era of deep studies, with potential major outcomes for the present climatic change operating on Earth: clouds, which have a greenhouse effect given their composition, are also cooling agents by reflecting a fraction of the incident solar input, thus decreasing the energy available at lower altitudes. The potential for part of the water, which increasingly evaporates from the oceans as the temperature rises, to condense as clouds might thus constitute an efficient retroactive means to control the global temperature.

Altogether, the evolution of planets result from a highly complex coupling of processes involving all forces, with often key roles played by minor or trace species, such as long-lived radioactive isotopes for the internal activity, greenhouse gases for surface temperatures, and nucleation sites for cloud formation. The early dynamical evolution has paved the entire solar system history with unique properties.

The more we observe and decipher this complexity, the more we realize that the diversity we discover does not result from observational biases, but rather constitutes a key feature of planetary evolution.

Cross-References

- $\blacktriangleright$ [Chronological History of Life on Earth](#)
- $\blacktriangleright$ [Cratering Chronology](#)
- $\blacktriangleright$ [Differentiation, Planetary](#)
- $\blacktriangleright$ [Giant Planets](#)
- $\blacktriangleright$ [Late Heavy Bombardment](#)
- $\blacktriangleright$ [Lithosphere, Planetary](#)
- $\blacktriangleright$ [Planetesimals](#)
- $\blacktriangleright$ [Plate Tectonics](#)
- $\blacktriangleright$ [Protosolar Nebula, Minimum Mass](#)

Planetary Formation

► Accretion

Planetary Mapping

Giulia Alemanno
Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Keywords

Planetary surfaces · Mapping · Geologic maps

Definition

Planetary mapping is the process of creation of geologic and geospatial maps of surface features of planetary and small bodies surfaces based on the current state of discoveries and knowledge. Planetary maps are created based on the use and analysis of several orbital data sets, so they evolve continuously with time thanks to new discoveries and to the use of new orbital data.

Overview

Planetary mapping involves geologic, imaging, and geospatial mapping of planetary surfaces structures, materials, and landforms. These maps provide a contextual framework for the study and interpretation of the history of planetary surfaces and their evolution through time. Planetary maps are usually composed by at least three layers: a base image (that can be for example a photomosaic or a topographic mosaic of the bodies surfaces); a grid; and a nomenclature (Hargitai 2006). Geologic maps of planetary bodies surfaces are a powerful tool for the scientific community for several reasons. Those maps contribute to the investigation of processes that characterize planetary surfaces and their shallow subsurfaces, thus

allowing to reconstruct geologic timescales and to provide an interpretation of the sequence of events that characterized the evolution of a planetary surface. Surface geologic maps are also used for target investigations such as those based on the characterization of landing sites for lander/rover missions. At the same time, planetary maps can be created using tools that target the general audience thus involving their interest to the scientific discoveries regarding the other worlds that surround us.

The US Geological Survey (USGS) started to publish planetary geologic maps in 1962 (Hackman 1962). So far, several maps of planetary bodies have been published (e.g., Hansen 2000; Grant et al. 2009; Irwin III and Grant 2013; Alemanno et al. 2018). Planetary bodies have been mapped at a variety of scales, using the available topographic and photographic orbital data. An international overview catalogue containing over 2200 planetary maps produced worldwide between 1600 and 2018 has been published from Hargitai and Pitura (2018). However, the production of maps of planetary surfaces is a continuous effort: new data are continuously acquired from the planetary bodies of our Solar System at increasing resolution providing the basis for new discoveries and updated geologic maps.

Cross-References

- Mars
- Mercury
- Moon, The
- Planetary Surface Ages

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Planetary Migration

Avi M. Mandell
Goddard Space Flight Center, Greenbelt, MD,
USA

Keywords

Type I migration · Type II migration · Type III migration

Synonyms

[Tidal migration](#)

Definition

Planetary migration is the decrease or increase in the orbital radius of a planet embedded in a ► [protoplanetary disk](#) due to interactions with the surrounding gas and/or solid material. Migration occurs when a planetary body loses or gains orbital angular momentum due to either friction (either through aerodynamic drag with the surrounding gas or dynamical friction with surrounding smaller planetesimals) or the imbalance of momentum transfer between the planetary body and the nearby disk material. Planetary migration is thought to account for the position of giant extrasolar planets discovered orbiting at very

small orbital radii and may be an important dynamical process in the evolution of protoplanetary bodies of all sizes.

Overview

Prior to the discovery of the first extrasolar planets orbiting very close to their parent stars, planets were thought to form and evolve in the same general region of a planetary system over their whole lifetime (unless a planet's orbit was dramatically altered due to scattering from a close encounter with another planetary body). Small planetesimals would grow into larger bodies by accreting nearby material, and accretion would stop when a planet had depleted its local orbital region of material. In this relatively quiescent picture of ► [planet formation](#), a mature planet found at a specific orbital radius could be assumed to have formed in situ from a collection of smaller bodies with similar compositional properties.

However, the existence of giant planets at small orbital radii immediately confounded the idea that all planets form and remain in their initial orbital locations. Giant planets are composed primarily of a massive gaseous atmosphere and for the atmosphere to gravitationally contract the planet must form in a relatively cold region of the disk (beyond ~ 3 AU; Bodenheimer et al. 2000). The first extrasolar planet, a Jupiter-mass planet orbiting at 0.04 AU, therefore, suggested that some mechanism must have transferred the planet from the outer regions of the system to its current location.

The theory of planetary migration had been postulated prior to the discovery of close-in extrasolar planets; in fact, dynamical theorists might have predicted the existence of these planets if they had correctly interpreted their results on the evolution of giant planets embedded in viscously evolving protoplanetary disks. Papaloizou and Lin (1984), and Lin and Papaloizou (1986), first showed that a planet with a mass significantly large with respect to a surrounding gaseous nebula could open a gap in the disk, leading to angular momentum transfer between the inner and outer regions of the disk and the planet. They correctly

showed that this would lead to orbital migration of the planet if the difference in mass between the two regions of the disk was significant; the authors, therefore, concluded that the amount of nebular gas interior and exterior to Jupiter's formation region in our own Solar System must have been equal to $0.1 M_{\text{Sun}}$ in order to avoid the rapid migration of Jupiter either inward or outward. This mechanism for planetary migration, eventually codified as "type II" gas-driven migration by Ward (1997), was immediately posited as the process responsible for transporting extrasolar giant planets to very small orbital radii (Lin et al. 1996).

In the next paragraph, we will discuss the various theoretical mechanisms for orbital migration in a circumstellar disk of planetary and protoplanetary bodies, ranging from giant planets down to micron-size dust particles, and the current evidence for the role that each process plays in the evolution of a planetary system. Please note that there exists another type of orbital migration due to tidal interactions between a star and planet (see ► [Tides, Archean](#)).

Migration Mechanism

Gas-Driven Migration

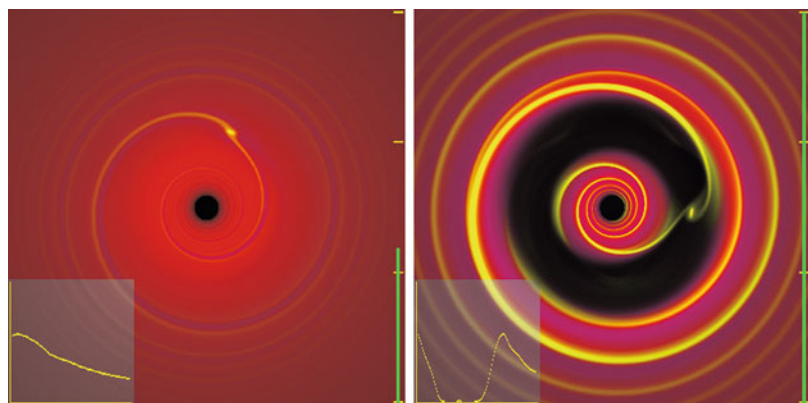
Gas-driven migration refers to a loss of orbital angular momentum from a planet due to gravitational interactions with the gaseous disk. This mechanism is the most common process referred to when discussing planetary migration, due to the early adoption of gas-driven migration as the most

likely scenario to explain the existence of close-in extrasolar planets. As the name suggests, type II gas-driven migration was not actually the original form of gas-driven migration proposed. "Type I" gas-driven migration, first theorized by Goldreich and Tremaine (1980) and discussed in more detail by Ward (1986), operates on planets whose mass is low enough (thought to be close to the mass of Saturn for a disk around a solar-type star) to avoid perturbing the disk enough to open a gap. Type II gas-driven migration describes a similar mechanism for higher-mass planets which perturb the disk enough to block the infall of gas toward the star and create a gap, leading to the locking of the planet with the viscous evolution of the disk (i.e., the spiralling in of the disk material onto the central star) (Fig. 1).

Type I Gas-Driven Migration

Type I gas-driven migration relies on the torques exerted on a planet from density waves that are excited in the gaseous material close to the planet's Lindblad resonances (the orbital locations relative to a planet where the orbital period of a satellite around the planet equals the orbital period of the planet around the star, leading to a resonant orbital motion). These density waves remove energy from the planet, which can lead to a decrease in the orbital velocity and an inward migration. The originally calculated timescale for an Earth-mass body to fall into the central star from 5 AU due to type I gas-driven migration was $\sim 10^4$ years, making this process the most rapid migration mechanism acting in

Planetary Migration, Fig. 1 Results from simulations of gas-driven migration, showing the disk density for a planet that is unable to open a gap and therefore experiences "type I" migration (*left*) compared with a high-mass planet that clears a gap and experiences "type II" migration (*right*). (Source: Armitage and Rice 2005)



protoplanetary disks and a huge problem for the survival of planets, since the lifetime of a gaseous protoplanetary disk is $\sim 5 \times 10^6$ years. The rate of type I migration increases with increasing planet mass until the planet reaches the gap-opening threshold.

Research is ongoing to determine how type I gas-driven migration is slowed (it must be slowed since we observe planets the size of Earth and larger in both our own Solar System and other planetary systems, so they must survive). Initial models for calculating the migration efficiency assumed a very simplistic version of a protoplanetary disk: no turbulence, no temperature variations, constant viscosity throughout the disk, etc. Many different theories are being explored that rely on more realistic details of the disk conditions and structure to decrease the migration rate, and it is currently unclear which slowing mechanisms are dominant in different disk conditions. The most promising theories focus on non-isothermal conditions near the planet and the resulting effects on energy transfer (Jang-Condell and Sasselov 2005; Paardekooper and Mellema 2008), and inclusion of turbulence (e.g., Laughlin et al. 2004) and investigations of “dead zones” in the disk where the disk viscosity drops to near zero, leading to a dramatic decrease in the energy transfer rate between the planet and the disk (Oishi et al. 2007). In recent years, large progress has been made in the determination of the planetary migration rate, for different thermodynamical properties regimes in the protoplanetary disk (Paardekooper et al. 2011).

Type II Gas-Driven Migration

As stated above, the mechanism known as type II gas-driven migration becomes important when a planet becomes large enough to be comparable with the scale height of the disk, causing all the material in an annulus around the star to either be accreted onto the planet or transferred out of the orbital region by mass transfer to the outer disk. Once the annulus is cleared, no material is transferred across the boundary, but the planet is still gravitationally pulled toward a faster orbital velocity by material from the inner disk, while

losing angular momentum to material in the outer disk. If the outer disk is more massive, this transfer of angular momentum is imbalanced and the planet loses energy and spirals inward. Since the planet is locked to the viscous evolution of the disk, it migrates at a rate unrelated to the mass of the planet; two-dimensional and three-dimensional simulations suggest timescales of $\sim 10^5$ years for the migration time from 5 AU (D’Angelo et al. 2003).

This timescale is still shorter than the dissipation of the disk, and therefore a stopping mechanism must be invoked to stop planets from falling into the central star. Initial stopping mechanisms invoked interactions with the central star to explain the origin of close-in giant planets – either a removal of disk material by some process such as magnetospheric clearing or photoevaporation, or tidal interactions with a rapidly rotating star (Lin et al. 1996). However, these mechanisms are only applicable at very small distances from the parent star. For planets from 0.1 AU out to 3 AU, there must be either a different stopping mechanism or a different migration mechanism at work. The explanation of last resort has always been the “last of the Mohicans” argument, which suggests that the only planets we see are the last ones to migrate in and become stranded when the disk finally dissipates (Trilling et al. 1998). However, the currently favored explanation is that when two or more planets form in relative proximity in time and orbital radius, they can quickly migrate into a resonant relationship (such as the 3:2 ► [mean-motion resonance](#)), at which point their gaps can overlap and cause them to cease migrating or even reverse their migration direction (Morbidei and Crida 2007; Morbidelli et al. 2007). This explains the lack of a close-in extrasolar planet in the Solar System, while leaving considerable parameter space for a wide range of planetary configurations. In addition, planetary systems with more than one planet can become unstable after the gas disk dissipates, scattering one planet out of the system and leaving only a single remaining giant planet in an eccentric orbit – a scenario observed frequently in extrasolar planetary systems.

Migration Due to Aerodynamic Drag

Gas-driven migration is effective for both giant planets (type II) and Earth-mass planets down to km-sized bodies (type I), but the gaseous disk also leads to migration of very small planetesimals ($r < 1$ m) due to aerodynamic drag. First analyzed with respect to protoplanetary disks by Adachi et al. (1976), frictional drag due to a particle's motion through the gaseous disk can lead to eccentricity and inclination damping and inward radial migration on timescales as short as 100 years from 1 AU for cm-sized particles. For smaller particles, the grains become entrained with the gas and their differential velocity decreases; for larger particles, the aerodynamic drag force is too small to affect the angular momentum of the body significantly.

Drag forces can help to enhance the growth of bodies as a result of accretion, by damping collisional velocities between particles, but this would be of no consequence if particles were quickly lost into the central star on 100-year timescales. This problem is called the “cm-sized barrier,” connoting the difficulty of growing planetesimals beyond this limit, since traditional collisional accretion timescales for expected particle densities are much longer than 100 years. Possible solutions to this problem include rapid planetesimal growth due to gravitational instabilities, which have recently been shown to form km-sized bodies from pebbles over the course of 5–10 orbital timescales (Johansen et al. 2009), as well as phenomena that could cause pileups of inwardly drifting material in the disk, such as condensation fronts (Stevenson and Lunine 1988). Radial migration of small bodies due to aerodynamic drag may also have had a beneficial effect on planet formation and habitability by delivering volatile-rich bodies from the outer solar system into the dry inner disk, leading to increased water contents for the terrestrial planets (e.g., Ciesla and Cuzzi 2006).

Planetesimal-Driven Migration

Planetary migration can also be achieved without the need for a gaseous disk. Loss of angular

momentum from a planet can be achieved by transferring it to smaller nearby solid bodies during a scattering event. First suggested by Safronov (1972), the mechanism was first modeled numerically by Fernandez and Ip (1984) for giant planets in the Solar System, and the outward migration of Neptune due to the scattering of outer-disk planetesimals can be traced by mapping the scattered and resonant ► [Kuiper Belt](#) objects (e.g., Malhotra 1993). More recently, inward migration of the giant planets in the Solar System due to planetesimal scattering was invoked to explain the Late Heavy Bombardment as a critical aspect of the ► [“Nice model”](#) (Gomes et al. 2005). According to the Nice model, Jupiter and Saturn would slowly have migrated inward due to the migration instability, eventually crossing into a mean-motion resonance which pumped up their eccentricities dramatically, leading to a chaotic reshuffling of the outer Solar System.

The planetesimal-driven migration instability has also been suggested as an important migration mechanism in extrasolar planetary systems (Murray et al. 1998). However, in order to move a Jupiter-mass planet from the outer system all the way to within 0.1 AU of the star, a disk with approximately 1 Jupiter mass of planetesimals would be required interior to the planet's original orbit. This would require a massive disk ($\sim 0.1 M_{\text{Sun}}$), and while this is not impossible, it would be unlikely to be responsible for the bulk of migration in extrasolar planetary systems.

Cross-References

- [Exoplanets, Discovery](#)
- [Gas Drag](#)
- [Hot Jupiters](#)
- [Mean Motion Resonance](#)
- [Nice Model](#)
- [Planet Formation](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Tides, Planetary](#)
- [Water, Delivery to Earth](#)

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Planetary Nebula

Nikos Prantzos

Institut d'Astrophysique de Paris,
Paris, France

Definition

A planetary nebula is the glowing shell of gas, typically one light-year across, ejected during the late AGB phase of intermediate and low mass stars. The name derives from the appearance in a small telescope, similar to that of a planet. It surrounds the hot, luminous core of the star, which emits ultraviolet radiation and ionizes the gas. The planetary nebula phase lasts for only a few 10^4 years, after that the star (the future ► [white dwarf](#)) is no longer hot enough to ionize the gas. This material eventually dissolves in the interstellar medium, enriching it with the nucleosynthesis products of the parent star (He-4, C-12, N-14, and ► [s-process](#) elements). The number of planetary nebulae in the Galaxy is estimated at 3,000.

Cross-References

- ▶ [Asymptotic Giant Branch Star](#)
- ▶ [S-Process](#)
- ▶ [White Dwarf](#)

Planetary Protection

Catharine A. Conley
NASA Headquarters, NASA Ames Research
Center, Washington, DC, USA

Keywords

Backward contamination · Contamination control · Forward contamination · Life detection · Sample return

Synonyms

[Planetary quarantine](#)

Definition

Planetary Protection is the process of preventing contamination of planetary environments by living organisms from other planets, in accordance with Article IX of the 1967 Outer Space Treaty and policies maintained by the Committee on Space Research (▶ [COSPAR](#)). Nations sending missions to other planets must ensure that Earth life does not contaminate them (forward contamination), and that any samples brought to Earth do not release harmful organisms into our environment (backward contamination). Protecting the Earth is the highest priority for planetary protection. Protecting other planets from Earth life preserves our investments in scientific exploration and the search for life elsewhere.

Overview

Planetary protection requirements are based on the type of planetary mission and target location

(s), according to Categories defined in COSPAR policy. The lead agency for a mission is responsible for ensuring compliance by all participants with planetary protection requirements, and reporting to COSPAR on mission activities.

▶ [Mars](#), ▶ [Europa](#), and ▶ [Enceladus](#) are Solar System objects considered to have the highest probability for hosting Indigenous life, and for contamination by transported Earth life. The probability of contaminating these objects with Earth life must be less than 1×10^{-4} per mission. Missions to Mars are allowed to meet this requirement by limiting the number of ▶ [“spores”](#) contaminating the spacecraft at launch, based on calculations performed by ▶ [NASA’s Viking](#) project in the 1970s. Missions that search for life, either in situ or in samples returned to Earth, must ensure that samples being analyzed are not contaminated by ▶ [biomarkers](#) from Earth life. A high-confidence life detection event would impose more strict cleanliness requirements on subsequent missions, so minimizing “false positive” results is required by planetary protection. To protect the environment of the Earth, any samples that are returned to Earth from objects that might host Indigenous life (e.g., ▶ [Mars Sample Return](#)) must be contained similarly to the most infectious human pathogens, until they have been demonstrated to be non-hazardous. A “false negative” result could increase risk to the Earth, if unidentified extraterrestrial organisms are subsequently released.

Missions encountering only targets that cannot host Earth life are not required to limit ▶ [bioburden](#), but mission operations and disposition of hardware must be documented. Missions encountering objects of interest for understanding prebiotic chemistry and the origins of life (e.g., Venus, the Moon) must retain samples of all organic materials carried on the spacecraft in quantities that might be detectable by future missions.

Planetary protection requirements for human missions are still being developed but must meet the same goals of preventing forward and backward contamination. However, it will not be possible to prevent astronauts from being exposed to planetary materials, nor is it possible to ensure that no Earth life is released into a planetary

environment. Thus, constraints on human missions focus on understanding what Earth organisms are present on the mission and how they change over time to affect astronaut health, as well as minimizing and documenting cross-contamination between terrestrial and other planetary materials.

Cross-References

- [Bioburden](#)
- [Bioburden Reduction](#)
- [Biomarkers](#)
- [COSPAR](#)
- [Mars Sample Return Mission](#)
- [Outer Space Treaty](#)
- [Panspermia](#)
- [Sample Receiving Facility](#)
- [Spore](#)
- [Sterilization](#)

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Planetary Protection Category

Catharine A. Conley
NASA Ames Research Center, Moffett Field,
CA, USA

Definition

Individual missions are assigned a ► [planetary protection](#) category based on the type of mission (flyby, orbiting spacecraft, landing probes) and the target object that the spacecraft will investigate. The categorization system is used to set requirements based on the level of concern

regarding the possibility of contaminating a target object by Earth life, as well as the possibility that returned samples might contain extraterrestrial life, as specified in ► [COSPAR](#) planetary protection policy. The possible assignments include missions that target locations of no concern for contamination by Earth life and no relevance to investigations of prebiotic chemistry (Category I), missions to locations where Earth life could not survive but there is interest in studying possible prebiotic organic chemistry (Category II), and missions that target locations where Earth life could survive and reproduce (Category III for flybys and orbiting spacecraft, Category IV for landing probes). All missions that return samples to Earth are assigned to Category V but only missions returning samples from locations that might host indigenous life (e.g., ► [Mars](#), ► [Europa](#), ► [Enceladus](#)) are designated Restricted Earth Return and have additional restrictions beyond those imposed on the outbound portion of the mission.

Planetary Quarantine

- [Planetary Protection](#)

Planetary Rings

Françoise Roques
Laboratoire d'Etudes Spatiales et
d'Instrumentation en Astrophysique (LESIA),
Meudon, France

Keywords

Accretion · Collisions · Giant planets ·
Particles · Resonance · Tide · Waves

Synonyms

[Circumplanetary disk](#)

Definition

Planetary rings are systems of dust, particles, and small satellites orbiting around the ► [giant planets](#) of the solar system, in the nearby vicinity of a planet, where large satellites cannot form because of tidal effects.

Overview

Before observations were possible, the ancients imagined that stars were similar to the Sun and were surrounded by exoplanets, but no one imagined the possibility of planets surrounded by rings. In fact, all the giant planets are surrounded by a ring system located close to the planet. Giant planets own also large and regular satellites with prograde and circular orbits and, farther away, irregular satellites with orbits possibly retrograde and/or inclined.

The first telescope allowed Galileo Galilei to observe in 1610 that ► [Saturn](#) has a strange shape, which changed in course of time. It was only 46 years later that Huyguens (1656) proposed that “Saturn is surrounded by a thin flat ring, nowhere touching and inclined to the ecliptic.” This correct interpretation of poor-quality observations was based on the philosophical model of Descartes that a vortex is a natural shape in the Universe. It was only in 1857 that theoretical considerations led JC Maxwell to conclude that the ring is composed of small orbiting particles and not a solid ring, as initially thought.

In 1977, the ► [occultation](#) of a bright star by ► [Uranus](#) was observed by Elliot and his colleagues to study the planet’s atmosphere. The star disappeared very briefly nine times before and after the occultation by the planet, revealing Uranus’ ring system. This was the discovery that Saturn was not the only planet to be surrounded by rings and that narrow planetary rings can be stable. Subsequently, Goldreich and Tremaine (1982) showed that gravitational interactions between ring particles and nearby satellites can account for narrow and eccentric rings. This shepherding mechanism is one of the numerous and complex phenomena due to ring-satellite interactions.

The next ring was discovered around ► [Jupiter](#) by a space mission, Voyager 1, in 1979. This third ring system is very different from the first two; it is broad and ethereal, a million times less opaque than the dense Saturn rings. The dust particles, governed by nongravitational forces, have short lifetimes and must be permanently resupplied by moons. Dusty rings exist in the four planetary systems and are associated with satellites.

The last giant planet hid its ring system until 1984. Again, it was a stellar occultation that revealed a ring structure around ► [Neptune](#) (Hubbard et al. 1986). This discovery included another surprise, as the ring was detected on one side of the planet but not on the other side, showing an incomplete ring. An intensive campaign of stellar occultation observations revealed that one-tenth of the ring length is denser than the rest. This was confirmed when Voyager 2 imaged, in 1989, three dense arcs embedded in dusty ethereal rings. From this time, the three arcs have evolved to four arcs, two of which have partially vanished, showing the short lifetime of these structures. Resonances with moons on eccentric and/or inclined orbits explain the stability of incomplete rings. However, recent observations found that the arcs are not at the position predicted by the theory, leaving a puzzling situation.

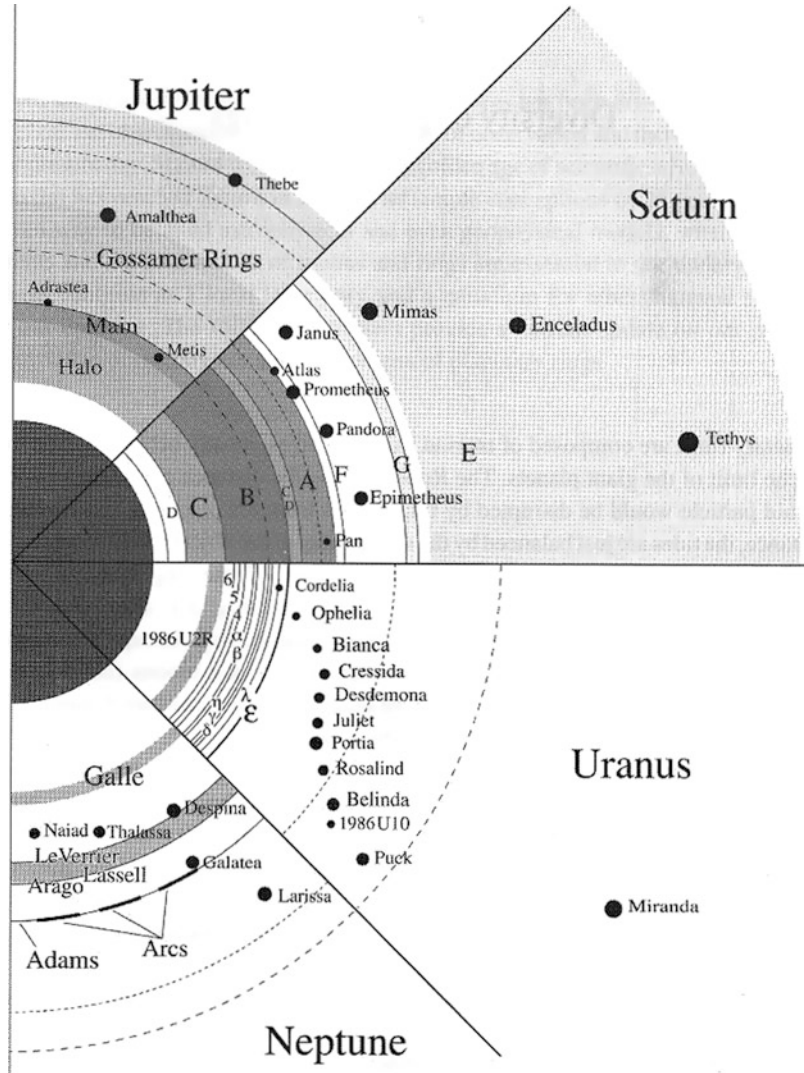
The four ring systems and embedded satellites are described in Fig. 1. Particle characteristics are summarized in Table 1. The Saturn system is composed of five rings, with most edges confined by observed satellite resonances. In the ethereal Jupiter system, a 1,000-km wide region between the Adrastea and Metis orbits could be the location of invisible (smaller than 0.5 km) bodies, “parents” of dusty rings. Shepherding by satellites of the narrow Uranus rings and the Neptune arcs is not yet completely explained.

Basic Methodology

Observations from ground and from space (survey and orbiter missions) of the last 50 years have led to a good knowledge of the ring systems. After Pioneer surveys of Jupiter and Saturn, Voyagers I and II in the 1980s explored the four systems and

Planetary Rings,

Fig. 1 A comparison of the four planetary ring systems, including the nearby satellites, scaled to a common planetary equatorial radius. Density of cross-hatching indicates the relative optical depth of the different ring components. Synchronous orbit is indicated by a *dashed line*, the Roche limit for a density of 1 g cm^{-3} by a *dotted line* (From Esposito 2006)



led us to the current conception of young and dynamic rings. The Cassini orbiter is now in orbit around Saturn after having flown by Jupiter. Evolution in ring structures can also be monitored from the ground, thanks to high-angular-resolution observations. Special events such as stellar occultations and ring-plane crossings provide unique information on the ring structures and particle sizes.

N-body simulations with tens of thousands of particles, taking into account mutual gravitational forces, can simulate formation of viscous instability, collective wakes, and accretion phenomena (Salo 2001). The rings and their evolution can

also be fruitfully simulated as fluid (hydrodynamics) or gas (kinetic theory).

Planetary rings are a laboratory where dynamic mechanisms including waves, wakes, braids, clumps, confinement, or migration are observed and studied at all scales (Fig. 2). These mechanisms are certainly involved in other astrophysical disks, such as occur in galaxies, accretion disks, protoplanetary disks, disks of second generation, etc.

The natural evolution of colliding particles orbiting around a planet is to aggregate into a satellite because of inelastic collisions. However, within the Roche limit (D_R) of

Planetary Rings, Table 1 Planetary rings characteristics (From Esposito 2006)

	Planetocentric distance (width) (km)	Optical depth	Dust fraction (%)	Power-law index (particle size distribution)	Notes
Jupiter					
Halo	92,000–122,500	10^{-6}	100	?	12,500 km thick
Main ring	122,000–12,980	3×10^{-6}	~50(?)	$q < 2.5$	Bounded by Adrastea
Amalthea Gossamer	129,000–182,000	10^{-7}	100(?)	?	2,000 km thick
Thebe Gossamer	129,000–226,000	3×10^{-8}	100(?)	?	4,400 km thick
Saturn					
D ring	66,000–74,000	10^{-3}	5–100	?	Internal structure
C ring	74,490–91,983		<3	3.1	Some isolated ringlets
B ring	91,983–117,516	<2.5	<3	2.75	Abundant structure
Cassini division	117,516–122,053	0.05–0.15	<3		Several plateaus
A ring	122,053–136,774		<3	2.75–2.90	Many density waves
F ring	140,200 ($W \cong 50$ km)	09.1–0.5	>98	2–3	Narrow, broad components
G ring	166,000–173,000	10^{-6}	>99	1.5–3.5	
E ring	180,000–450,000	10^{-5}	100		Peak near Enceladus
Uranus					
1986 U2R	37,000–39,500	$10^{-4} - 10^{-3}$	?	?	Still unnamed
Dust belts	41,000–50,000	10^{-5}	?	?	Fine internal structure
6	41,837	0.3	<1	$q > 3.5$	
5	42,234	0.5	<1	$q > 3.5$	
4	42,570	0.3	<1	$q > 3.5$	
α	44,718	0.3	<1	$q > 3.5$	
β	45,661	0.2	<1	$q > 3.5$	
η	47,175	0.3	<1	?	
γ	47,627	2	<1	?	
δ	48,300	0.4	<1	?	
λ	50,023	10^{-3}	>95	?	
ϵ	51,149	0.5–2.3	<1	$2.5 < q < 3.0$	Adjacent to Cordelia
Neptune					
Galle	41,000–43,000	$4-10 \times 10^{-5}$	?	?	
LeVerrier	53,000 ($W = 10$ km)	10^{-2}	4–70	?	Adjacent to Despina
Lasell	53,000–58,000	$1-3 \times 10^{-4}$	?	?	
Adams	62,930 ($W = 50$ km)	10^{-2}	2–50	?	Adjacent to Galatea
Adams arcs	62,930 ($W = 10$ km)	10^{-1}	4–70	?	

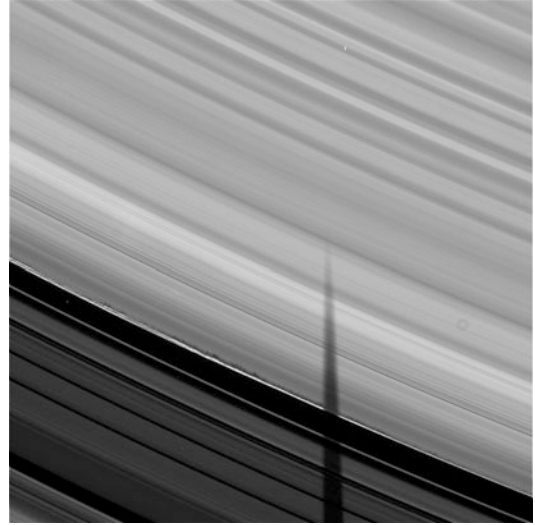
$$D_R = 2.456 * R \left(\frac{\rho_P}{\rho} \right)^{1/3}$$

where R is the planet radius, ρ is the particle density, and ρ_P is the planet density, differential gravity (tides) caused by the planet can overcome the gravitational attraction between the particles. As a result, satellites can orbit inside the Roche limit only if they are small enough to be held together by their tensile strength, rather than by their own gravitation.

As inelastic collisions dissipate energy but overall angular momentum is conserved, the initial particle orbits flatten within a short timescale into the equilibrium plane, that is, the equatorial plane of the planet.

The spreading timescale is longer than the flattening one. The relative motion between particles is dominated by Keplerian shear (i.e., particles closer to the planet move faster than more distant ones). Collisions between a more rapid inner particle and a slower outer particle make the inner particle slow down and lose angular momentum and the outer particle accelerate and win angular momentum.

Most images of rings, and in particular of dense rings, show very small structures, down to the limit of definition of the images. They are caused by different-size particles gravitationally interacting. Perturbations of a satellite create visible structures in the ring at locations of resonance. At these locations, successive gravitational perturbations are cumulative. Resonance effects are complex, because they concern three parameters for each orbit: mean motion, apsidal precession of an eccentric orbit, and node of an inclined orbit. The mean motion of the satellite orbit is $n_S = \frac{2\pi}{P} = \left(\frac{GM}{a^3} \right)^{1/2}$, where P is the revolution period, G is the gravitation constant, M is the planet mass, and a is the semimajor axis of the orbit. The epicyclic frequency, κ_S , is connected to the motion of the elliptical orbit apsidal line and the vertical frequency, μ_S , to the motion of the node of an inclined orbit. If the planet is oblate, $\mu_S > n_S > \kappa_S$, the apsidal line regresses and the node precesses. Resonance occurs when the forcing satellite frequency, $W_f = m.n_S + p\kappa_S + k\mu_S$,



Planetary Rings, Fig. 2 Shadows on the Saturn rings: bright upper part is the outer part of the B ring showing several wave patterns. The outer B ring is confined by the 2:1 resonance with Mimas. The lower dark region is the Cassini division. The bright structures along the B ring edge are 3 km in height above the ring and throw laced shadows on the ring. The longest shadows are 100 km long. The Sun is 1.9° above the ring plane. The long shadow is caused by Mimas, which is 70,000 km away from this image (© NASA/JPL/SSI)

where m , p , and k are integers, matches one of the three particle natural frequencies (Fig. 2).

The most spectacular effect of resonances is the shepherding of a narrow ringlet by two satellites as observed for the ϵ ring of Uranus or the F ring of Saturn. The resonances accumulate near the satellite orbit, and the cumulative torque of a satellite on a ringlet of width w , at a distance d is

$$T \approx \frac{G^2 m_S^2 \sigma a r}{n_S^2 d^4},$$

where m_S is the satellite mass and σ is the ring surface density. Note that dissipation is essential even if the torque intensity does not depend on the dissipation mechanism.

Dusty ring particles are sensitive to non-gravitational forces. Solar radiation pressure, plasma effects, and magnetic perturbations limit the lifetimes of particles. Consequently, these rings must be replenished continuously by micro-meteoroidal bombardment or collisions of

“parent” bodies. Dusty radial structures, called “spokes,” have been observed in the Saturn rings but remain partially unexplained.

Key Research Findings

Rings orbit in the sense of the planet’s rotation, as do most of the satellites. This makes one think that they are formed in the same protoplanetary disk. However, the short timescale of involved mechanisms favors a recent creation from a disrupted satellite. Moreover, the very short lifetimes of observed structures require active processes for maintaining them.

Modeling shows that dense ring material is subject to very rapid (week timescale) growing mechanisms, with smooth collisions and sticking of small particles, until house-sized objects are formed and disrupted. These structures are called DEBs (dynamic ephemeral bodies) or rubble piles.

The origin of the Saturn rings is still controversial. It is difficult to give a scenario explaining at the same time the spreading timescales, which are smaller than the age of the solar system, and the large mass of Saturn’s rings, as capture and/or disruption of a satellite sufficiently massive to make the rings is very unlikely after the end of the planet formation period.

The ethereal Jupiter rings are clearly the by-product of small satellites. If the Saturn ring is coeval with the planet, the question is why Jupiter has not a similarly large ring system.

The Uranus and the Neptune rings are more easily explained by a captured object. The disruption inside the Roche limit would have left a mixture of small satellites and particles reorganized in the observed configuration.

Future Directions

The next generation of high-contrast imaging instruments will provide the first unresolved image of an extrasolar planet. While the emitted infrared light from the planet in thermal

equilibrium should show almost no phase effect, the reflected visible light will vary with the orbital phase angle. A ring around an extrasolar planet, both obviously unresolved, can be detected by its specific photometric signature (Arnold and Schneider 2004).

Cross-References

- [Giant Planets](#)
- [Jupiter](#)
- [Neptune](#)
- [Occultation](#)
- [Roche Limit](#)
- [Saturn](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)

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Planetary Surface Ages

- [Chronostratigraphy](#)

Planetary Theories and Cosmology, Islamic Theories

Ahmed Ragab

Harvard Divinity School, Cambridge, MA, USA

Keywords

Islam · Islamic astronomy · Andalus · Iberia · Medieval · Tusi · Averroes · Maragha · Observatory · Zij · Kindi · Avicenna · Tusi couple · al-Haytham

Overview

Following Ptolemy's instructions in the *Almagest* that "he who comes after us throughout the epochs take measurements as we have done, and if they find an imperfection, they should correct," Islamic works of astronomy were motivated in part with this process of minor rectifications, along with two other lines of inquiry: creation of astronomical tables (*zij*) and timekeeping, on the one hand, and planetary theories on the other.

Ptolemy's *Almagest* remained the more influential text in medieval Islamic astronomy, along with Aristotle's *De Caelo*. The *Almagest* provided astronomers with important tools to solve their different practical problems, and its explanations of planetary movement were sufficiently viable to allow for its continual usage. *De Caelo* presented a robust philosophical system explaining planetary movement but without a viable practical model. The first class of Islamic authors included al-Kindi (d. 873; explained *Almagest*'s first book and wrote on Platonic cosmological theories), Thābit ibn Qurra (d. 901; addressed transfer of motion across orbs), and al-Battānī (d. 929; composed one of the earliest *zij*s). The contradictions between Ptolemy and Aristotle motivated a number of responses through history, such as those of Ibn Tufayl and his students in al-Andalus, and of the "Maragha School."

Ibn Sīnā (Avicenna; d. 1037) and his student al-Juzjānī (d. 1070) objected to Ptolemy's eccentrics, as they violated Earth's centrality. Avicenna

claimed to have reached a solution to this problem, but only after so much effort that he was not willing to share it. Juzjānī proposed an alternative to the Ptolemaic model that proved unsuccessful. In Andalusia, Ibn Tufayl (d. 1185), sharing the same objections, claimed to have found an alternative solution, but never wrote it. His more famous student, Ibn Rushd (Averroes; d. 1189) proposed that Aristotle's solutions were lost and should be rediscovered but left the task of rediscovery to his younger students. Another student of Ibn Tufayl, al-Bitruji (Alpetragius; d. 1204), proposed a solution that avoided eccentrics by employing only concentric orbits around the earth and suggesting the possibility of the orbs' poles circling other orbs. The contributions of these Andalusian scholars had little influence on other Islamic astronomers. However, these views carried more influence with renowned Jewish astronomers such as Yosef Nahmias and Levi Ben Greson.

The Maragha School, led by al-Ṭūsī (d. 1274), al-Shīrāzī (d. 1311) and al-'Urdī (d. 1266), took to rectifying Ptolemaic models without attempting to overrule them as did their Andalusian predecessors. One of the more famous accomplishments of this school is the Tusi couple, which was a geometrical device that transformed circular movement into linear one. The goal of al-Ṭūsī's work was to explain orbital movements in relation to the different physical principles. The Maragha scholars were rooted in a tradition of criticizing Ptolemy and uncovering the problems with his model that started with Ibn al-Haytham's (Alhazen; d. 1040) "Doubts on Ptolemy," where the latter showed how a number of Ptolemy's propositions violated laws of Aristotelian physics. However, probably similar to Ibn al-Haytham, who did not reject Ptolemy entirely, the Maragha astronomers seemed to remain invested in the Ptolemaic model, with all its practical possibilities, and did not reject it in favor of Aristotle's more elegant, yet less practical, model of planetary and orbital movement.

Cross-References

- [Al-Andalus, Cosmological Ideas](#)
- [Al-Ṭūsī, Nasir al-Dīn](#)

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PLANetary Transits and Oscillations of Stars

- [PLATO 2.0 Satellite](#)

Planetesimals

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In models of planetary formation, planetesimals are small bodies in orbit around a star that can be accreted by forming planets. The formation process and the mass function of these objects are subject to active research and are not well known. Planetesimals are usually assumed to be significantly larger than 1 m, e.g., 100 m to 100 km in radius.

Cross-References

- [Dynamical Friction](#)
- [Gas Drag](#)
- [Gravitational Collapse, Planetary](#)
- [Late-Stage Accretion](#)
- [Meteorites](#)
- [Planet Formation](#)
- [Planetary Migration](#)
- [Viscous Stirring](#)

Planet-Forming Disk

- [Protoplanetary Disk](#)

Planetoid

- [Asteroid](#)

Planets in Binary Star Systems

Nader Haghighipour
Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

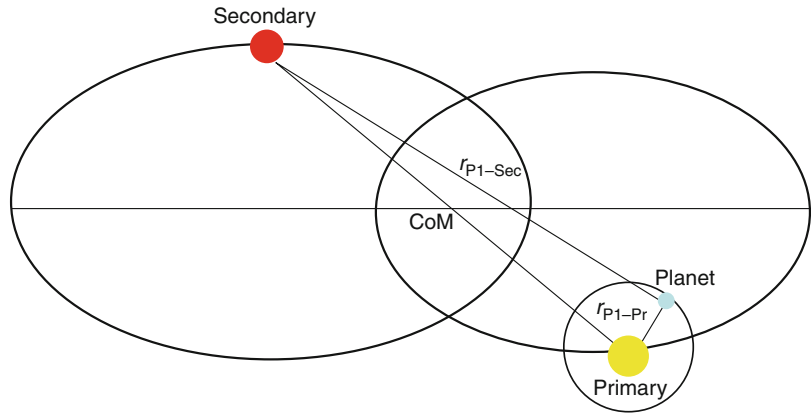
Definition

A survey of currently known planet-hosting stars indicates that approximately 3% of extrasolar planetary systems are within dual-star environments. Several of these systems contain stellar companions on orbits moderately close to one of the stars, or have planets in circumbinary orbits. The following website presents an up-to-date list of all of these systems: <http://www.univie.ac.at/adg/schwarz/binary.html>

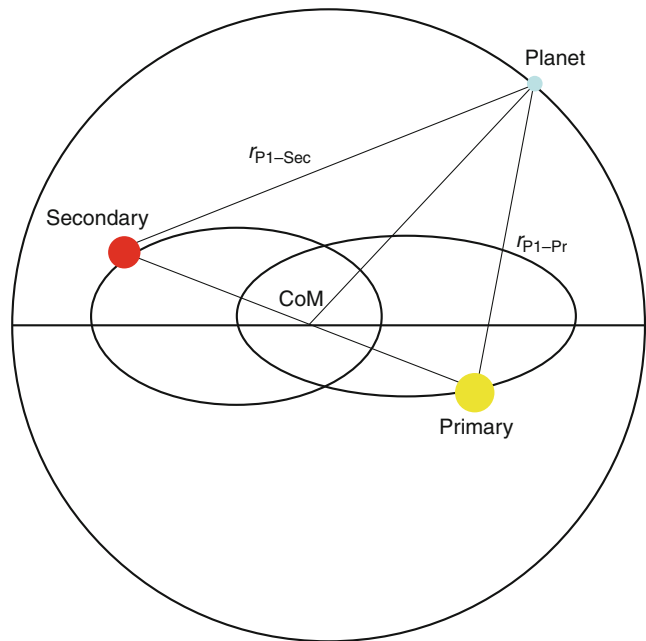
From a dynamical point of view, three types of orbits are recognized for the motion of a planet in

Planets in Binary Star Systems,

Fig. 1 Schematic presentation of an S-type system



Planets in Binary Star Systems, Fig. 2 General schematic presentation of a P-type system



a binary star system. These orbits have been historically labeled as:

1. The S-type (or Satellite-type) orbit where the planet revolves around one of the stars of the binary (see ► [circumprimary planet](#), Fig. 1)
2. The P-type (or Planetary-type) orbit where the planet revolves around the entire binary system (see ► [circumbinary planet](#), Fig. 2)
3. The L-type (or Libration-type) where the planet moves in the same orbit as the secondary star, but 60° ahead or behind it (analogous to the position of the ► [Trojan asteroids](#) relative to ► [Jupiter](#))

For more details, see the book entitled “Planets in Binary Star Systems” (Haghighipour 2010).

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- [Triton](#)
- [Venus](#)

Planck, Max

Fernando B. Figueiredo
CITEUC, University of Coimbra, Coimbra,
Portugal

Planitia

Roland J. Wagner
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

A planitia designates a low-lying plain on the ► [terrestrial planets](#) ► [Mercury](#), ► [Venus](#), Moon, and ► [Mars](#), on the Saturnian satellites ► [Enceladus](#) and ► [Titan](#), and on ► [Triton](#) (► [Neptune](#)). A planitia can extend from a few ten thousands to several millions of square kilometers across a planetary surface. Guinevere Planitia on Venus is the largest one known with a diameter of 7,520 km. Tectonism or impacts are the primary processes that can create vast low-lying plains. On planets or satellites with an atmosphere (Venus, Mars, Titan), planitiae can be subsequently modified by material deposited in the plain by wind or fluid flow.

Cross-References

- [Enceladus](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Neptune](#)
- [Planet](#)
- [Planum](#)
- [Satellite or Moon](#)
- [Terrestrial Planet](#)
- [Titan](#)

History

Max Karl Ernst Ludwig Planck (1858–1947) was a German physicist Nobel laureate in 1918 by his discovery of energy quanta. He postulates that the energy did not flow in a steady continuum but in discrete packets or quanta. He established a relationship between the energy (E) radiated from a heated body and the frequency of that radiation (ν): $E = h\nu$ (where h is known as Planck's constant and has the value $6.62606957 \times 10^{-34}$ Js).

The NASA/ESA partnership space mission, which was launched on May 14, 2009, was designed to measure the Cosmic Microwave Background (CMB) over a broad range of far-infrared wavelengths.

Cross-References

- [Line Emission](#)

Plankton

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto
Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

Plankton refers to the microscopic organisms, mainly ► [algae](#) and protozoa, which are present in oceans and freshwater bodies. These

microorganisms float and drift passively and support a significant part of the food chain for larger organisms in bodies of water.

- [Triton](#)
- [Venus](#)

Cross-References

- [Algae](#)
- [Eukarya](#)
- [Oxygenic Photosynthesis](#)
- [Photosynthesis](#)
- [Protists](#)

Planum

Roland J. Wagner
German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

A feature termed planum is a topographically high-standing plain or plateau. These features are found on the terrestrial planets ► [Mercury](#), ► [Venus](#), Moon, and ► [Mars](#), on Jupiter's satellite ► [Io](#), and on Neptune's satellite ► [Triton](#). The spatial extent (diameter) of a planum is a few hundred kilometers up to approximately 2,400 km (Lakshmi Planum, Venus). High-standing plains were created by (cryo-)volcanism and/or tectonism.

Cross-References

- [Cryovolcanism](#)
- [Io](#)
- [Jupiter](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Neptune](#)
- [Planitia](#)
- [Satellite or Moon](#)
- [Terrestrial Planet](#)

Plasma

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Definition

A plasma is a gaseous medium principally made of charged particles: ions and electrons. A plasma is globally neutral as it contains balanced charges of positive and negative types. Since a plasma is electrically conductive, it responds strongly to electromagnetic fields. For instance, a plasma is the medium where Alfvén waves can develop and propagate. Plasmas are found everywhere: in stars, in the upper atmospheres of planets, in the interstellar medium (HII regions), in stellar envelopes (planetary nebulae), at the center of clusters of galaxies, etc. It is generally admitted that more than 99% of the baryonic matter in the universe is in the form of plasma.

Cross-References

- [HII Region](#)

Plasma Chemistry, Laboratory

Nathalie Carrasco
LATMOS, Paris-Saclay University, Guyancourt, France

Definition

Plasma Chemistry refers to chemical processes occurring in partially ionized media. In planetary science, plasma setups, such as capacitively coupled plasma, corona discharge, or spark

discharge, are often used as proxies to simulate the complex chemical networks triggered in upper planetary atmospheres by Far- and Extreme-UV stellar radiations (Szopa et al. 2006; Tigrine et al. 2016; He et al. 2019). Such chemical systems couple the reactivity of neutral species, positive and negative ions, and electrons, involving, for instance, neutral-neutral reactions, ion-neutral reactions, and dissociative recombination reactions. The densities (and temperatures) of the neutrals, the ions, and the electrons are highly variable according to the plasma source considered, leading to varying possible degrees of ionization (Cable et al. 2012).

Cross-References

- [Corona Discharge](#)
- [Electron Dissociative Recombination](#)
- [Ion-Neutral Reaction](#)
- [Neutral-Neutral Reaction](#)
- [Photochemistry, Atmospheric](#)
- [Plasma](#)

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Plasma Membrane

- [Cell Membrane](#)
- [Membrane](#)

Plasma, High-Energy Density in Laboratory

Andrea Ciardi

LERMA, Sorbonne University and Observatoire de Paris, Paris, France

Definition

High-energy density laboratory plasmas (Drake 2009) are produced on high-power lasers and pulsed-power facilities by focusing large energies (kilo-joule to megajoule) into small cubic-cm-size volumes of matter. The extreme plasma conditions generated include temperatures of millions of degrees at pressures of the order of a megabar. Research applications range from the production of energy via thermonuclear fusion by inertial confinement (Betti and Hurricane 2016), to laboratory studies of astrophysical phenomena (Remington et al. 2006; Lebedev et al. 2019). The latter include, but are not limited to, strongly radiative magnetohydrodynamic shocks and flows, particle acceleration at shocks, and equation of state for planetary interiors.

Cross-References

- [Plasma](#)

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Plasmid

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

Episome; Extrachromosomal genetic element

Definition

A plasmid is a genetic element with autonomous replication within a suitable host. Plasmids are extrachromosomal elements frequent in ► [bacteria](#) and ► [archaea](#), and they are also found in certain yeasts. Plasmids are, together with viruses, the main mobile genetic elements involved in ► [lateral gene transfer](#) throughout evolution. They are circular or linear double-stranded ► [DNA](#) molecules of 10^3 to 10^6 nucleotides in length, maintained within the cell either in single copy or in multicopy format. In general, they are not essential for the organism but they may confer a selective advantage. For example, bacterial plasmids may carry genes that code for proteins able to degrade naturally occurring antibiotics – therefore producing antibiotic-resistant phenotypes – or to metabolize a wide range of organic compounds. Plasmids used in genetic engineering and biotechnology, called vectors, allow the biological amplification of exogenous genetic material, the insert, through ► [cloning](#) the recombinant plasmid – vector + insert – in a culturable host organism.

Cross-References

- [Amplification \(Genetics\)](#)
- [Bacteria](#)
- [Cloning](#)
- [Conjugation](#)
- [DNA](#)
- [Genome](#)

- [Lateral Gene Transfer](#)
- [Replication \(Genetics\)](#)
- [Yeast](#)

Plate Accretion

- [Accretion](#)

Plate Tectonics

Karel Schulmann and Hubert Whitechurch
Ecole et Observatoire de Science de la Terre,
Institute de Physique de Globe, Université de
Strasbourg, Strasbourg, France

Keywords

Earthquake · Hot spot · Lithospheric plate ·
Mantle convection · Mid-ocean ridge ·
Orogeny · Plate boundary · Plate tectonics ·
Subduction · Volcano

Definition

“Plate tectonics” (*from the Greek* $\tau\epsilon\chi\tau\omicron\kappa\omicron$ = builder) refers to the theory describing the motion of the plates, 100–200 km thick, which form Earth’s ► [lithosphere](#). These rigid plates, which consist of continental or oceanic crust underlain by lithospheric ► [mantle](#), are displaced above the higher-density and lower-strength ► [asthenosphere](#). They move with respect to each other along one of three possible plate boundaries: convergent (or subduction/collisional) boundaries; divergent (or spreading), and transform boundaries (where plates move parallel to each other). Earthquakes and magmas produced by mantle melting characterize most plate boundaries.

Convergent boundaries are expressed by topographic lows called trenches, which coincide with sites of subduction of oceanic plates. Also involved are orogenic processes leading to the formation of mountain chains, with subsequent

regional metamorphism and continental partial melting. Spreading centers coincide with topographic highs, called ► [mid-ocean ridges](#), where upwelling asthenosphere partially melts and produces new oceanic crust. Movement along transform boundaries accumulates shear stress that is discharged through earthquakes, a common phenomenon along these boundaries (the San Andreas fault, California, is the best-known example). Lithospheric plates are driven by thermal or compositional density variations in the underlying mantle which causes large-scale convection. These movements are transferred to overlying rigid plates through gravitation forces from high-standing ridges (ridge-push) or the downward drag of dense subducting slabs (slab pull).

This review starts with some history: the hypothesis of continental drift and the evolution of ideas that led to the plate tectonics theory. Methods used to investigate plate tectonics are briefly reviewed. The lithospheric plates are then defined, together with the nature of plate boundaries, plate kinematics, and the driving forces of plate movements. The theory is completed with a discussion of the concepts of hot spots and mantle convection and some comments about the growth of the crust and construction of the continents.

History

The Theory of the Continental Drift

The German geophysicist and meteorologist Alfred Wegener proposed the theory of continental drift in 1915 in his book *Die Entstehung der Kontinente und Ozeane* (The Origin of Continents and Oceans). One of the main arguments for continental drift was the similarity between the east coast of South America and the west coast of Africa. The British philosopher Francis Bacon (1620) and subsequently many others had already proposed the possible attachment of these two continents. Wegener was the first who used isostasy and paleobotanical and paleofacies data compiled by the South African geologist A. du Toit, in particular traces of Carboniferous glaciation in Australia, India, and Africa, combined with geodetic measurements to confirm a simple

observation – that the continents are moving. However, Wegener failed to explain the forces driving the continental drift. Since Wegener, geologists have compared rock strata at the edges of separate continents to verify whether they once formed a continuous sequence and were initially joined. One good example is the Variscan belt in Europe and the Appalachians in North America which formed a continuous mountain belt before being split by the Atlantic Ocean.

Confirmation of the Wegener theory came initially from the “mobilistic” approach of the Swiss geologist Emile Argand, who in 1924 wrote the book *La Tectonique de l'Asie* (The Tectonics of Asia) using Wegener's idea of tectonic indentation (the penetration of one continent into another) and mountain building to explain the collision of India with Eurasia by closure of the Tethyan ocean (Tethys). He also used the notion of indentation to explain the collision of Africa with Europe. Argand was thus the pioneer of tectonics of convergent boundaries.

The mechanism behind continental drift was proposed by British geologist Arthur Holmes who studied the concentration of radioactive elements in some minerals to estimate the age of the Earth, proposing first 1.6 Ga in 1911 and later 3.4 Ga (Holmes 1928). He concluded that the amount of radiogenic elements decreased with the depth and that in order to evacuate heat from the interior of the Earth, convection currents are needed. He proposed that continental drift was an inevitable consequence of thermal convection. Later, the Dutch geophysicist Vening-Meinesz confirmed the hypothesis of mantle convection by gravity field studies and attributed the mass deficiency underneath deep ocean trenches to downward drag of the subducting oceanic plate.

The Birth of the Modern Plate Tectonics

The most important findings that shaped the theory of plate tectonics came from oceanographic studies. In 1947, the American geophysicist and oceanographer Maurice Ewing and his coworkers confirmed the existence of a topographic rise in the central Atlantic Ocean. These workers found that the oceanic crust is basaltic in composition and significantly thinner than granitic continental

crust. The American geologist Harry Hess provided decisive input in the understanding of plate tectonics in the beginning of 1950 when he used a magnetometer to record magnetic variations across the ocean floor. These magnetic variations are associated with the magnetite contained in oceanic basalts, which records the orientation and intensity of the Earth's magnetic field at the time of basalt extrusion. Most importantly, magnetic studies revealed the existence of alternating stripes of normal and reverse polarity which are symmetrically distributed on either side of the mid-ocean ridge (Vine and Matthews 1963). The alternation of normally and reversely polarized bands, called magnetic striping, led to the theory of sea-floor spreading. In the 1960s, it was suggested that the mid-ocean ridges mark structurally weak zones where the ocean floor was split in two along the ridge crest. It was suggested that pulses of magma rise along the ridge and create new oceanic crust which then migrate laterally away from the ridge – the process called sea-floor spreading. The alternation of direct and inverse magnetic polarity is related to periodical changes in the polarity of the Earth's magnetic field, which is recorded in the basaltic rocks. The explanation of the magnetic striping led to the rapid acceptance of sea-floor spreading as a key element of plate tectonics theory.

A consequence of sea-floor spreading is that new crust is continuously formed. Carey (1958) used this concept to propose a model of Earth expansion, then Hess (1962) suggested that if the ocean floor is expanding along ridges, it must be removed at oceanic trenches, the deep valleys rimming the Pacific Ocean. In other words, as new crust forms at oceanic ridges by magma accretion, old crust is destroyed along trenches – in oceanic subduction zones. The modern theory of plate tectonics proposes that the continents are not moving through oceanic crust (as in the continental drift concept of Wegener) but that oceanic crust and in some cases attached continents move together on the same crustal unit called a “plate.” Soon after, plate tectonics evolved significantly with the recognition of transform faults by the Canadian geologist Tuzo Wilson (1965). In his model, the oceans are created, grow, and

disappear; and the continents are fragmented, separated, and reassembled in what are now called “Wilson cycles.”

Further understanding of plate kinematics came from the work of the American geophysicist William Jason Morgan (1968), who explained relative displacements of two adjacent plates. He showed that the movements are parallel to transform faults and centered on a pole of rotation (the Euler pole), and that variations of sea-floor expansion are a function of the distance from the pole of rotation. Xavier Le Pichon (1968) built on Morgan's concept and proposed a kinematic reconstruction of the formation of the Atlantic and Indian oceans within the frame of six rigid plates including continental masses. Geological aspects of the theory of plate tectonics were developed by Dewey and Bird (1970), who showed that the structure of active continental margins is dependent on the geometry and kinematics of subduction zones. This seminal paper showed geologists how the orogenic belts are linked to movements of the oceanic lithosphere, and explained the relationship between plate tectonics and both the complex three-dimensional movements at continental margins and the magmatic and metamorphic processes of mountain building.

Basic Methodology

Three methods had a decisive impact on the development and further understanding of plate boundaries: seismology, ► [paleomagnetism](#), and modern paleoclimatic and paleobiogeographic studies.

Seismology

Seismology developed rapidly in the twentieth century with the construction of seismographs that enabled geophysicists to understand the Earth's internal structure, the composition of continental and oceanic crust, and the boundary between the crust and mantle – the so-called Mohorovičić discontinuity or ► [“Moho”](#), named after its discoverer, the Croatian seismologist Andrija Mohorovičić. The second major discovery was that earthquakes tend to be located along

plate boundaries, from the oceanic trenches downwards, as well as along the spreading ridges and transform faults. The seismologists Hugo Benioff of the California Institute of Technology and Kiyoo Wadati of the Japan Meteorological Agency independently identified earthquake zones that were several hundred kilometers long, oriented parallel to the trenches, and dipping at 40° – 60° – the so-called Wadati-Benioff or subduction zones.

Paleomagnetism

Paleomagnetism is the study of the record of the Earth's past magnetic field as preserved in magnetic minerals in rocks. The principle is based on the fossilization of the magnetic field direction at the time of cooling of lavas or deposition of sediments. It is possible to measure the orientation, the polarity, and sometimes even the intensity of the magnetic field. Knowing the magnetic field at the given time allows us to reconstruct the apparent position of the pole and consequently the latitude and orientation of the studied region at a given time. This method has played a decisive role in obtaining a better understanding of the movement and rotation of plates, and the migration of continents over long periods of time. Further, the discovery of magnetic stripes on the ocean floor was decisive for understanding the opening of the oceans and helpful for formulating the new theory of plate tectonics.

Tectonic and Paleobiogeographic Reconstructions

Paleomagnetic studies are intimately connected with tectonic, paleobiogeographic, and paleoclimatological syntheses. It was shown that the drift of continents across paleo-latitudes was responsible for deposition of climatically sensitive sediments such as evaporites or tillites. In addition, continental drift played a decisive role in the distribution, diversity, and extinction of past life. Continents may break up, separate, and subsequently collide, thereby changing the disposition of faunal provinces and barriers to faunal migration. Paleobiogeographic studies bring key information about the isolation or connection of continents, the position of suture zones and

ancient oceans, and the paleogeographic position of lithospheric plates.

Structure of Lithospheric Plates

The outer layers of the Earth are divided into the ► **lithosphere** and ► **asthenosphere**. The distinction is based on differences in mechanical properties and in the process of heat transfer. The concept of lithosphere was introduced by Barell (1914) on the basis of geological and physical evidence suggesting the existence of a strong superficial layer (the lithosphere) floating above a weak zone (the asthenosphere). The lithosphere is defined as a mobile, near-surface, strong layer with a viscosity of about $10^{24} \text{ Pa s}^{-1}$ (Isacks et al. 1968) that supports high differential stress. The asthenosphere, in contrast, already flows under low stresses and has a disproportionally lower viscosity of 10^{20} – $10^{21} \text{ Pa s}^{-1}$. Consequently, earthquakes occur within the lithosphere but not in the asthenosphere, except where lithospheric slabs sink into the asthenosphere in subduction or collisional zones. As a first approximation, the lithospheric plate can be considered to be an elastic or viscoelastic sheet. The thickness of a plate is also the thickness of the lithosphere, which, at any location, is composed of continental (granitic to granodioritic) or oceanic (basaltic) crust and the subcrustal (peridotitic) mantle. The lithosphere loses heat by conduction, whereas the asthenosphere transfers heat mainly by convection and has a nearly adiabatic temperature gradient. Therefore, the contact between the lithosphere and the asthenosphere is not to a chemical or mineralogical boundary but a strong contrast of rheological behavior dependent on temperature. Two isotherms define this contact. The first, at 1,270–1,340 °C, corresponds to the temperature of the beginning of partial melting of the mantle peridotite as a function of lithostatic pressure. Partial melting of peridotite has been invoked to explain a layer with reduced seismic velocities – the low-velocity zone or LVZ – at the base of the lithosphere. The second isotherm, at 1,100–1,200 °C, corresponds to the temperature at which the deformation mechanism of mantle olivine changes from dislocation creep to diffusional creep.

In the oceans, the lithosphere thickens from the mid-ocean ridge (<20 km) to up to 100 km beneath older oceanic basins. It is even thicker beneath the continents, ranging from 120 to 250 km underneath old, cold, rigid Archean cratonic crust. The lithosphere under continents is thinner in tectonic regions such as active margins and intracontinental rifts where hot material may exist at shallow depth, and is thicker underneath orogenic belts where the lithosphere-asthenosphere boundary is depressed by thickening of the crust and mantle lithosphere.

Plate Boundaries and Hot Spots

Three main types of plate boundaries exist, each characterized by different relative motions of adjacent plates. Plate boundaries are marked by different tectonic processes and are associated with seismic and magmatic activities. The sites of localized mantle melting, called hot spots, are marked by chains of volcanoes aligned within plates in a direction parallel to plate movement.

Divergent Boundaries

Divergent boundaries occur where two plates move apart from one another. These boundaries, called mid-ocean ridges, are marked by bathymetric highs over the 4,000 m isobath within all the oceans. Here, new oceanic crust is formed by the eruption and crystallization of tholeiitic magmas (MORB, Mid Ocean Ridge Basalt), issued from 10% to 20% partial melting of mantle peridotite.

The thickness of the oceanic crust, as determined by seismic experiments (away from the fracture zones and from hot spot influence), varies between 2 and 8 km. With the exception of ultraslow-spreading ridges, the mean thickness of the oceanic crust is 6 km (White et al. 2001). Seismic activity on the ridges is superficial (the depth of earthquake hypocenters is 9 km, close to the brittle-ductile transition), with low magnitude (<6 M) and characterized by extensional focal mechanism. The ridge segments are truncated by transform faults that may reach tens to hundreds of kilometers long (see below). The larger transform faults exhibit high relief and intense seismic activity, with mainly strike-slip focal mechanisms between the ridge segments.

The spreading rate is calculated using magnetic anomalies. These originate from thermo-remnant magnetization of the basaltic crust, registered by Fe-oxides. Magnetic anomalies produce a striped pattern in the oceanic crust that results from changes from normal (in the same direction as the present magnetic field) to inverse (in the opposite direction compared to the present) polarity of the Earth's field at the time of crystallization. The ages of these anomalies have been established by dating of sediments deposited on magnetized blocks and collected during ocean drilling programs (DSDP, ODP, and IODP) or by dating of the volcanic rocks themselves. The anomalies are numbered from 1 to 34, corresponding to the period from the present to the Cretaceous normal quiet period from 84 to 118 Ma. For the older periods, the anomalies have been denoted M0 (118 Ma) to M41 (166 Ma). The anomalies are identified and modeled by measuring the direction of the regional magnetic field, its depth, and the thickness and direction of magnetization of the magnetic layer. Anomalies are present on both sides of the spreading zone but are not always symmetrical. The full spreading rate is calculated using the distance between isochrons of the same age on opposing sides of the ridge and the half spreading rate is defined using the isochrons on only one side (Hellinger 1981).

The spreading rate is variable from one ridge to another. Mid-ocean ridges are classified as ultraslow (0.8–1.5 cm year⁻¹), slow (1.5–5 cm year⁻¹), intermediate (5–9 cm year⁻¹), and fast (9–20 cm year⁻¹) (Fig. 1; plate velocities, from Westphal et al. 2002). Spreading rates increase along the ridge away from the position of the Euler pole to the equator. Spreading rates vary through time due to changes in plate motions (e.g., at 17–12 cm year⁻¹ during the period 70–45 Ma, to 4 cm year⁻¹ during the period 45 Ma to Recent on the SE Indian ridge as a result of the India-Eurasia collision).

Away from the influence of hot spots, the physical parameters of ridges depend on the spreading rate (MacDonald 1982). Slow-spreading ridges exhibit a narrow axial relief (below the 3,000 m isobath) with a pronounced axial valley and rugged transverse and along-axis

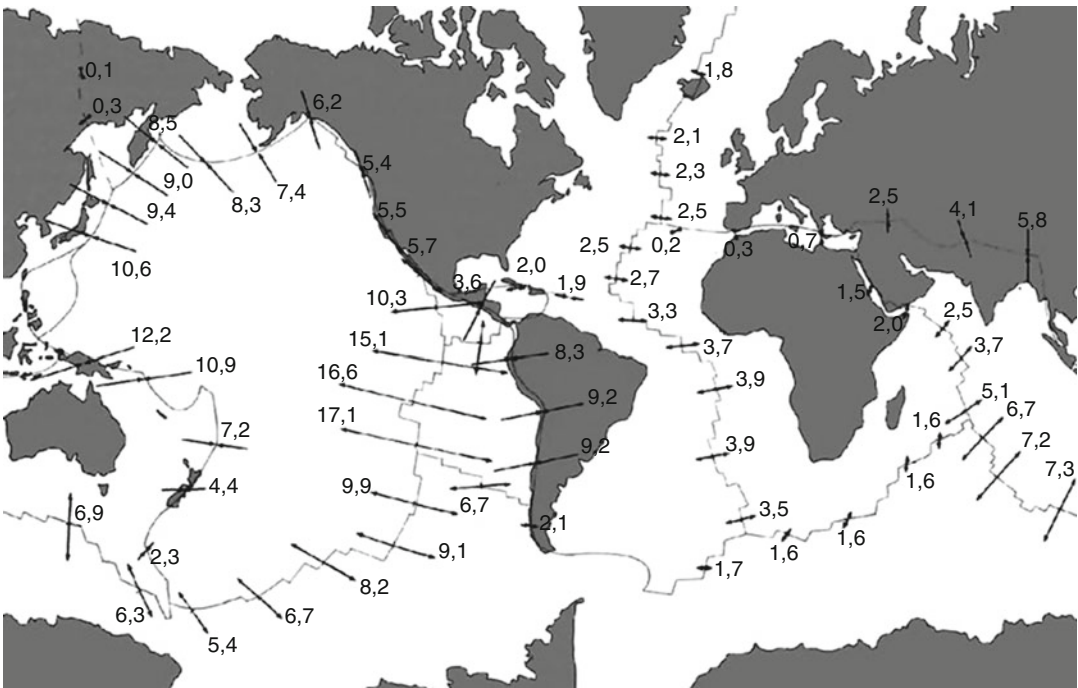


Plate Tectonics, Fig. 1 Directions and full spreading rates (cm year^{-1}) for ridges and direction and shortening rates for subduction zones (Westphal et al. 2002)

segmented morphologies with large variations in height (Fig. 2a; slow-spreading ridge from Pomerol et al. 2005). Their magma budget is low and mantle peridotite is frequently exposed at the surface. Axial magma chambers have not been detected. Large amplitude mantle gravity anomalies beneath slow-spreading ridges are of “bull eyes” shape. In contrast, fast-spreading ridges exhibit a large axial relief with an axial dome and smoother transverse and along-axis morphologies (Fig. 2b; fast-spreading ridges from Pomerol et al. 2005). Their magma flux is high and an axial magma chamber may be seismically detected. The lithosphere remains thin beneath the flanks of the ridge up to a distance corresponding to 40 Ma. Low-amplitude mantle gravity anomalies beneath fast-spreading ridges are parallel to the ridge. The differences between amplitudes of gravity anomalies indicate either variations in crustal thickness, or the presence of focused hot uprising mantle beneath slow-spreading ridges or along the ridge axis in the case of fast-spreading ridges. Slow-spreading ridges near hot spots

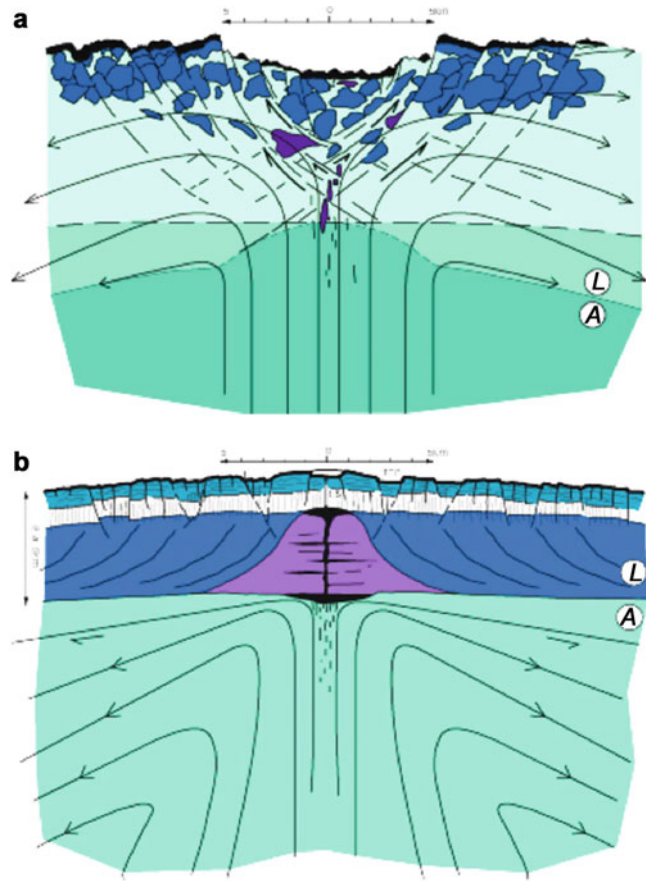
(e.g., Reykjanes ridge near Iceland) may have characteristics similar to fast-spreading ridges. This indicates that mantle temperature can also control the physical parameters of divergent boundaries.

Convergent Boundaries

A convergent plate boundary forms when a lithospheric plate, denser than the mantle, slides (subducts) beneath another plate. The oceanic lithosphere plunges beneath other oceanic lithosphere or beneath a continent. When two continents collide, some continental lithosphere may subduct and a mountain range is built (e.g., Himalaya). Broad and almost continuous zones of shallow seismicity, ductile deformation, and metamorphism characterize such zones. The distributed deformation of continents is due to the relatively low strength and low density of continental crust. Subduction zones are characterized by strong and localized seismic activity located within the plunging slab. Friction at the top of the plate causes earthquakes to form the so-called

Plate Tectonics,

Fig. 2 Ideal cross sections of: (a) slow-spreading ridge showing discontinuous small magma chambers (in violet) producing discontinuous oceanic crust (serpentinites in light blue containing gabbroic pockets in dark blue) and (b) fast-spreading ridge showing magma chamber, crystal mush (in violet), and magma sills and lenses (in black) producing a gabbroic (dark blue), sheeted dykes (white), and basaltic (dark green) crust. Flow directions and lithosphere/asthenosphere boundary are indicated in both diagrams (After Pomerol et al. 2005)



Wadati-Benioff zone. Intraplate compressional and extensional focal mechanisms are the responses to stresses generated by the subducting plate. This plate is separated from the overriding plate by deep trenches filled mainly by turbiditic sediments, pelagic sediments, cherts, and fragments of oceanic lithosphere that are internally imbricated in tectonic slices to form an accretionary prism.

Partial melting of the mantle overlying the subducting plate produces calc-alkaline magmas. Those magmas migrate upward and form archipelagos called volcanic arcs (chains of volcanic islands parallel to the subduction zone, f.i.: the “ring of fire” around the Pacific ocean). Two types of volcanic arcs are generally recognized: oceanic (island) arcs are formed by subduction of oceanic plate under another oceanic plate; continental magmatic arcs are formed by subduction of

oceanic plate underneath the continent. Arc magma forms when fluids expelled from the subducting slab (pore fluids at shallow depth or metamorphic dehydration of altered oceanic crust at greater depth) induce partial melting of the overlying mantle (the so-called mantle wedge). The magmas of continental arcs exhibit a wide range of calc-alkaline compositions (andesite and diorite, dacite and granodiorite, rhyolite and granite) due to fractional crystallization, continental contamination, and magma mixing in superposed magma chambers.

The distance of island arc volcanism from the trench is dictated by the inclination of the subduction zone, because appropriate temperature-pressure conditions for flux-induced melting occur at the same depth (about 100 km). Continental magmatic arcs are sites of high-temperature, low-pressure metamorphism, and

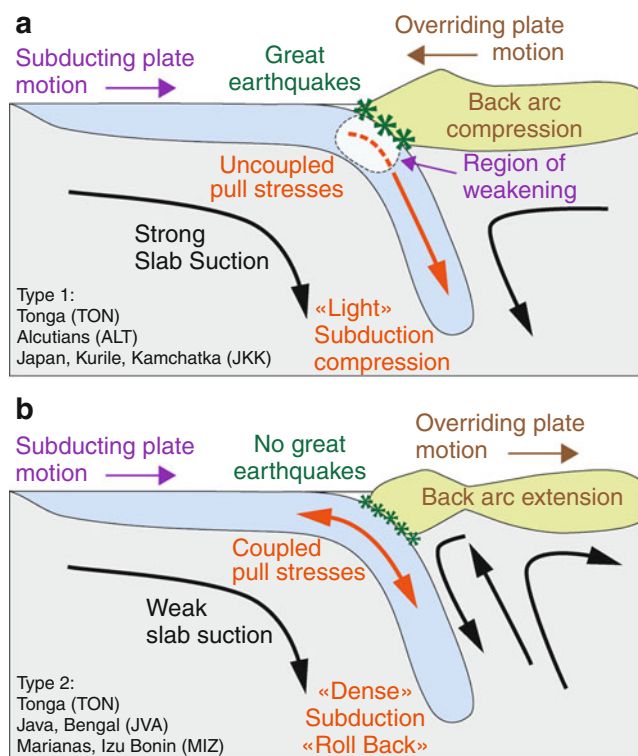
extensive crustal melting due to advection of heat by continuously intruding magmas.

Two types of subduction have been distinguished, depending on the age of the subducting lithosphere: (a) old, cold, and dense slabs subduct at a high angle or dip (e.g., Mariana subduction); and (b) young, hot, and less dense slabs subduct at a low angle (e.g., Chile subduction) (Fig. 3, from Internet). Mariana-type subduction exhibits deep trenches, short arc-trench distances, deep seismic activity (down to 670 km), and low-magnitude shallow seismicity indicating decoupling between the subducting and overriding plates. Retreat of the subducted plate and accompanying mantle flow (called “roll-over”) induces an extension in back-arc basins with eventual creation of new oceanic crust. Chile-type subduction is characterized as a seismic activity which does not exceed 200 km depth, shallow trenches, and long distance between the trench and the volcanic arc. The shallow inverse seismic activity is of high magnitude, indicating a high friction between the two plates that induces arc and back-arc compression.

Subduction zones are the sites of high-pressure, low-temperature metamorphism that develops at the base of the sedimentary prism and within the subduction channel. Thermal modeling shows variable depression of isotherms depending on the age of the lithosphere and rate of subduction. The subducting oceanic crust is metamorphosed progressively from blueschist (low-temperature, moderate-pressure) to eclogite (moderate-temperature, high-pressure) facies. Phase transformations within the subducting lithosphere induce intraplate seismicity and a large increase of density (by the transformation in eclogite of the subducting crust) which provides a major driving force for subduction.

Seismic tomography (two- or three-dimensional imaging of the Earth’s interior) shows that high-seismic-velocity, cold mantle from the subducting plate accumulates at the 670-km discontinuity when Mariana-type (steep-dip) subduction occurs. Tomographic imagery shows that cold material sinks episodically into the lower mantle, in some cases down to the core-mantle boundary.

Plate Tectonics,
Fig. 3 Two principal
architectures of Pacific
subduction zones



Transform Boundaries

A transform boundary (also known as conservative plate boundary) separates plates that move parallel to one another with no convergence and divergence, thereby conserving the areas of adjacent plates. The San Andreas Fault (California) or the North- and East-Anatolian faults (Turkey) and the Levant fault (Middle East) are good examples. These boundaries penetrate most of the lithosphere and generally are long-lived structures. They form deep valleys and pull-apart basins at the surface of the Earth. Transform boundaries link other plate boundaries, and can thus “transform” one type of tectonic boundary to another (e.g., from divergent to convergent boundary). Therefore, the stresses generated along the transforms originate from the relative motion of the two plates. Seismic activity can be intense with high magnitude (up to 7).

Ophiolites

An ► **ophiolite** is a slice of oceanic crust and underlying mantle thrust onto a continent by a process called obduction. Obducted ophiolites represent on-land relicts of oceanic lithosphere that escaped the subduction processes. Investigation of these structures has contributed greatly to our understanding of processes at divergent boundaries and tectonic processes related to transform faults. Two types of ophiolites have been described (e.g., Beccaluva et al. 2004): “Tethyan complexes,” which comprise complete mantle and crustal sequences (cumulates, dykes and basalts with mid-ocean ridge or island arc affinities) and “Cordilleran complexes” comprising dismembered calc-alkaline arc volcanic and plutonic suites.

The movement of oceanic plates away from the ridge toward the trench is associated with the development of ocean floor stratigraphy which consists, from base to top, or oldest to youngest, of pillow lavas overlain by bedded cherts, deep ocean pelagic sediments, and finally clastic sediments of the accretionary wedge. The interpretation of ocean floor stratigraphy has influenced significantly our understanding of the structure and age of oceanic lithosphere preserved in ophiolite sequences and accretionary orogens.

Hot Spots

Hot Spots are alignments of fossil to recent volcanoes (e.g., Hawaii and Louisville in the Pacific; La Réunion and Kerguelen in the Indian Ocean; Iceland, Azores, and Tristan da Cunha in the Atlantic Ocean) produced by the passage of a plate over a mantle plume (Fig. 4; position of hot spots from Westphal et al. 2002). These alignments of volcanic chains may exhibit a correlation between the age of the volcanoes and the distance from the active mantle plume. The duration of hot spot tracks varies from negligible to 90 Ma. Active volcanoes on the axis of the mantle plume can be situated near or on divergent plate boundaries, like Iceland on the Atlantic Ridge. Hot spots located near divergent plate boundaries influence the bathymetry and basalt chemistry for distances up to 800 km along the ridge axis. Large hot spots like Hawaii are situated over up-doming or swelling (100 km) of the lithosphere. The Polynesian Archipelagoes in the central Pacific are made up of numerous hot spot volcanoes and overlie a large positive 1,000-km-wide bulge called a “superswell.” Analysis of the main hot spot tracks leads to the conclusion that the deep-mantle source hot spots are fixed or move slowly relative to plate velocities. Tomographic images show that low seismic velocity hot mantle columns exist beneath hot spots and in some cases extend down to the core-mantle boundary, suggesting that mantle plumes may originate in the D'' seismic layer. These observations are at the origin of the mantle-plume concept.

Driving Forces of Plate Tectonics

It is generally accepted that plates move because of variations in the density of oceanic lithosphere and the weakness of the asthenosphere. Since more than 50 years, it is acknowledged that dissipation of heat from the mantle drives convection and implicitly also plate tectonics. Modern geophysical methods based on seismic tomography show large lateral variations in density throughout the mantle. These density variations are due in part to differences in rock chemistry and mineral structure, but mainly to changes of temperature that lead to the upwelling of hot regions and the

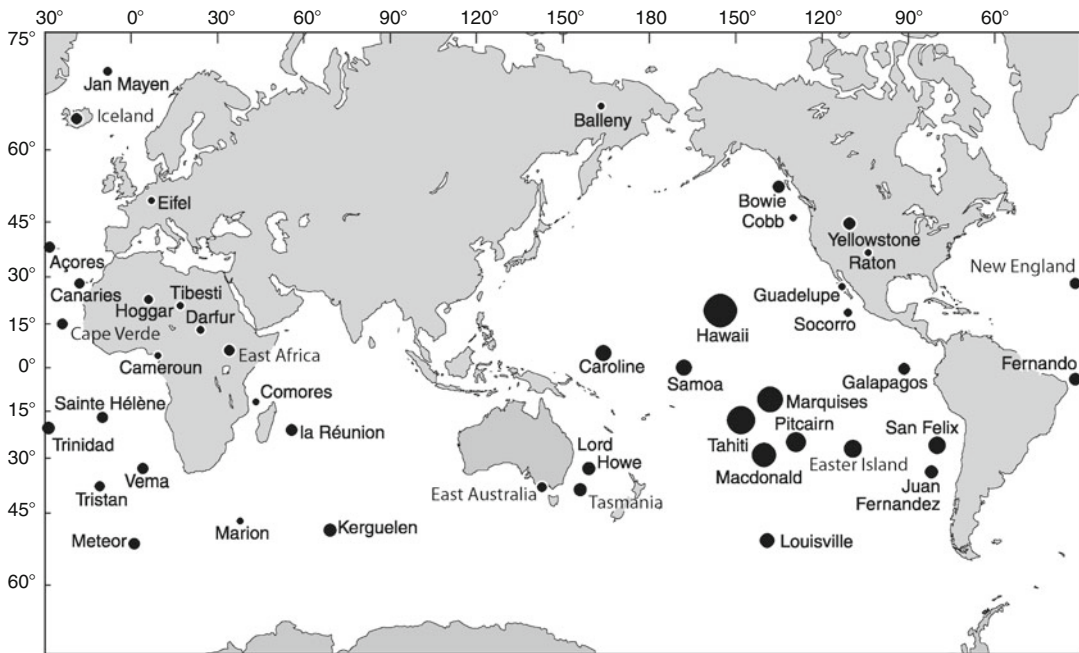


Plate Tectonics, Fig. 4 Position of recent hot spots. The diameter of *black circles* is proportional to the quantity of erupted magma

descent of cold regions. It is not entirely understood how plate tectonics is related to these motions. A major problem addressed by researchers since the 1960s is whether the driving force of plate tectonics is the mantle convection and/or the activity of mantle plumes, or whether plate tectonics is driven by surface boundary and plate forces such as slab pull and ridge push (see Gravitational Forces; Forsyth and Uyeda 1975). Any valid model has to reproduce the rigid behavior of plates, provide enough energy to produce stresses at the limits of plates, and produce continuous plate motion. Currently, two main types of forces are thought to drive plate tectonics: the friction (localized forces) and gravity (distributed forces) (Fig. 5, driving forces).

Frictional Forces

Basal drag results from friction between the asthenosphere and the lithosphere. It is supposed that the convection movement is transmitted through the asthenosphere and drags the overlying lithosphere. Trench suction occurs in subduction zones where the convection currents exert a

frictional pull on the subducting plate. This force results from small-scale convection in the mantle wedge which is driven by a subducting plate.

Gravitational Forces

Gravitational sliding (ridge push) is a distributed gravitational force produced by the higher elevation of oceanic plates due to upwelling of hot material at spreading ridges. Newly formed oceanic lithosphere at mid-ocean ridges is less dense than the underlying asthenosphere, but as the oceanic lithosphere moves away from the ridge it becomes colder, denser, and thicker (McKenzie 1969). Ridge push can be considered as a body force because the increasing thickness of the cold oceanic lithosphere creates a horizontal pressure gradient. However, lithosphere older than 90 Ma undergoes no further cooling and therefore does not contribute to ridge push. In other words, ridge push can be also regarded as a boundary force generated by the upwelling of young warm mantle beneath the ridge crest which causes a topography-driven horizontal pressure gradient that acts at the edge of lithospheric plate. If a hot

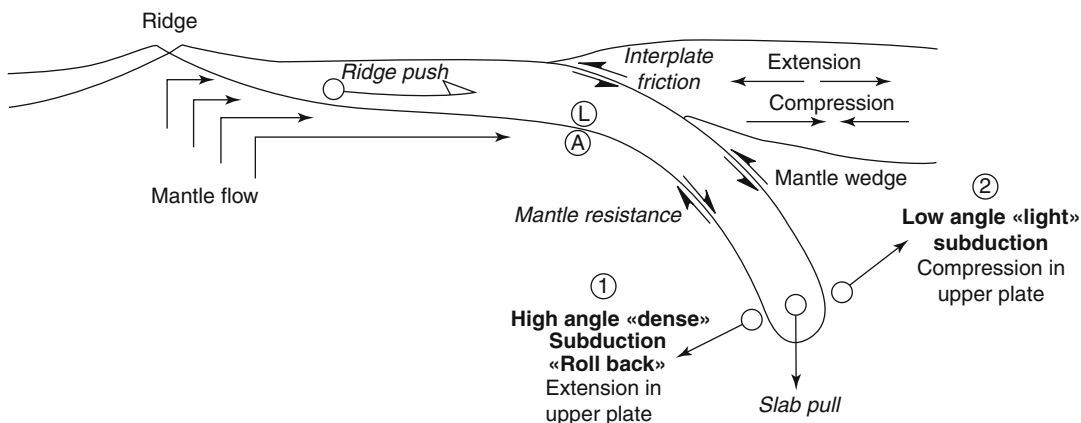


Plate Tectonics, Fig. 5 Schematic diagram for tectonic plate forces

spot is positioned at the spreading ridge axis, ridge push is amplified at least by a factor two (Ziegler 1993).

Slab pull results from the weight of the cold and dense subducting lithosphere. This force is dependent on the angle, age, and volume of this lithosphere, as well as the length of the trench (Chapple and Tullis 1977). The lateral distribution of dense and light masses deduced from seismic tomography led Davies (Vigny et al. 1991) to propose a model in which the excess density of the oceanic lithosphere in subduction zones is the most powerful source of plate motion. This hypothesis is supported by studies that show a positive correlation between plate velocities and age of subducting lithosphere. Collisional resistance, a force produced in high-viscosity ductile upper mantle material, is related to slab pull force.

Even if the slab pull is the most important force, it cannot be the only plate tectonic force, because some plates move without subducting boundaries, and other forces like basal drag are locally important. Therefore, plate movement results from the sum of forces acting upon the plate. A significant observation is that lithospheric plates attached to downgoing (subducting) plates move much faster than plates without subducting boundaries. The Pacific plate, which is surrounded by subduction zones, moves much faster than the plates of the Atlantic basin, which are continuous with the flanking continents.

Crustal Growth and Continental Construction

On the modern Earth, continental crust is created mainly at subduction zones. Here, release of aqueous fluid from dehydrating oceanic crust causes melting in the mantle wedge and generates the calc-alkaline magmas that evolve into granitoid continental crust. In other words, on the modern Earth, the formation of continental crust is linked directly to plate tectonics.

Two distinct processes are grouped under the term “continent growth.” To a geochemist or petrologist, it refers to the transfer of silicate material from the mantle into the continental crust. To a geodynamicist, the term refers to the construction of a continent, the process that assembles crustal segments of various types, compositions, and origins. This process combines the lateral accretion of island arcs, oceanic crust and oceanic plateaux, and microcontinents, with magmatic addition at convergent margins, to build a continent or ► [supercontinent](#). The term “continental crustal growth” or simply “crustal growth” is used for the first process and “continent construction” for the second.

The sites of both crustal growth and continent construction coincide with major accretionary orogens. The accretionary orogens comprise: (1) accretionary wedges, containing material accreted from the downgoing plate and eroded from the upper plate; (2) island arcs, back-arcs, dismembered ophiolites, oceanic plateaux, and old continental blocks; (3) post-accretion granitic rocks and metamorphic products up to the

granulite facies, exhumed high- or ultrahigh-pressure metamorphic rocks, and clastic sedimentary basins (e.g., Cawood et al. 2009). The concept of accretionary orogens is associated with the discovery of ocean-floor stratigraphy.

Crustal growth is linked directly to subduction and thus to the formation of oceanic lithosphere at spreading centers: if sea-floor spreading is a continuous process, continental crustal growth should also be continuous. According to many authors, the assembly of continents was an episodic process superimposed on quasi-continuous growth of the continental crust, at least through most of the Phanerozoic. The continental construction processes are commonly associated with large-scale plate reorganization that results from changes in the kinematics of plate motion and/or with superplume activity, which may account for the episodic character of lateral accretion (Vaughan and Searrow 2003). The fundamental cause of episodes of accelerated growth and construction of the continents can probably be related to changes in the activity of the mantle.

Mantle Convection

Mantle convection has been invoked as a fundamental process controlling plate tectonics (Davies 1999). Heat loss at the surface of the Earth and

calculations of heat dissipation in the mantle show that convection is an effective means of evacuating heat from the Earth's interior.

Experiments show that the mantle flows as a solid through two principal deformation mechanisms: diffusion and dislocation creep. The experimental laws of crystal deformation show that the mantle viscosity is a function of activation energy (activation enthalpy and volume), pressure, temperature, and differential stress. Many authors accept that diffusion creep is the major deformation mechanism in the mantle, in which case the viscosity is almost a linear function of depth, except at boundary layers (phase transitions). Reference viscosities of the upper mantle have been estimated using isostatic glacial rebound and subduction zone geoids. Viscosities of the order of 10^{20} Pa s are estimated for the asthenosphere and 10^{21} Pa s for the lower mantle.

The accepted model today describes the internal movement in the mantle as follows: active plunging of cold material in subduction zones, hot uprising mantle currents beneath hot spots, and discontinuous narrow passive upwelling of hot mantle beneath the ocean ridges (Fig. 6; from Westphal et al. 2002). Whether convection occurs in one cell or two depends on the properties at the 670 km depth discontinuity (Brunet and

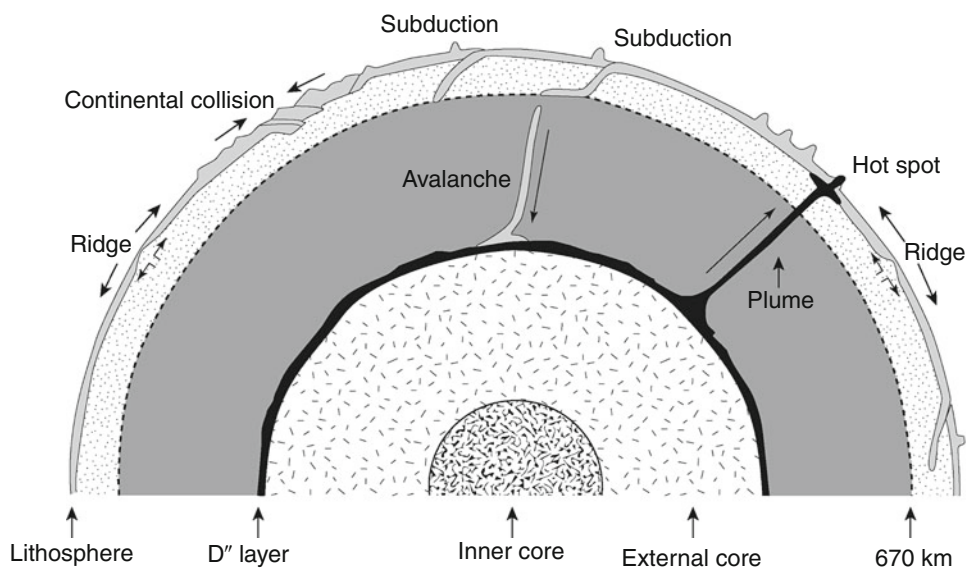


Plate Tectonics, Fig. 6 Schematic cross section of the Earth showing cold subducting plates down to D'' layer and upwelling mantle plumes from D'' layer

Machetel 1998). This limit corresponds to a phase transition (spinel-perovskite) which corresponds to a downward increase of density of 0.4 g cm^{-3} , or about 10%. This density change is greater than the density difference between a cold plunging slab and the surrounding mantle, which means that the slab does not penetrate the discontinuity until all the phases have been transformed.

Cross-References

- [Asthenosphere](#)
- [Continental Crust](#)
- [Continents](#)
- [Lithosphere, Planetary](#)
- [Mantle](#)
- [Mantle Plume, Planetary](#)
- [Mid-Ocean Ridge](#)
- [Plate, Lithospheric](#)
- [Supercontinent](#)

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Plate Tectonics, History of

Pierre Savaton

Université de Caen Basse-Normandie, Caen, France

Keywords

Continental drift · Isostasy · Mantle convection · Permanence theory · Polar wandering · Seafloor spreading

History

Plate tectonics is the paradigmatic theory of the modern geology since 40 years. It established that the major features of the Earth's surface depend on the dynamics of lithospheric plates, created from the ► mantle at the oceanic ridges and absorbed into the mantle at the oceanic trenches, except continental crust that can never sink and, thus, is condemned to be recycled in new mountain ranges. If moving plates are clear scientific evidence today, it was not at the beginning of the twentieth century when German meteorologist and geophysicist Alfred Wegener proposed his theory of continental translation (later translated with derisive sense in continental drift) against the leading theory on mountain formation.

In 1912, Alfred Wegener (1880–1930) proposed to consider that all continents might once have formed a single continent (today called a supercontinent) he named Pangea that might have been broken. Then, these continental masses might have drifted over oceanic crust. Their front margins (like a ship's bow), compressed and folded by the resistance of the ocean floor, might have formed mountain ranges (like Andes or the Rocky Mountains), and on the opposite, fragments of continents might have been detached in their wake as string of islands. Continents and ocean basins would not be permanent features of the Earth. Horizontal motions were more important than vertical motions defended by the theory of a cooling earth.

The model of mountains by contraction of a cooling Earth was suggested and developed in France by geologist Léonce Elie de Beaumont (1829) and defended in Great Britain by Henry De la Bêche. It found its best formalization at the end of the century in the work of the Austrian geologist Eduard Suess. According to Suess's theory, vertical motions of its crust explained the features of the Earth. As the globe cooled and began to sink, outer crust collapsed creating ocean basins and continents. Successive collapses changed the face of the Earth: ocean basins elevated into continents and continents collapsed to form ocean basins. Suess's theory was centered on "the breaking up of terrestrial globe." But this

model of "the shriveling apple" could not explain longer the compression rate calculated to unfold folding strata of the Alps or of the Himalayas. In the Alps, the horizontal extent of strata has been shortened to one quarter to one eighth of its original length, which would have required a shrinking of the circumference of the Earth by 3%, which means that Earth has cooled of about 2,400 °C.

At the end of the nineteenth century, geological views of Eduard Suess and of the European geologists were not shared by the American scientific community, which widely accepted the "permanence theory" developed by James Hall and James Dana. Oceans and continents were permanent features of the Earth's surface and change confined to limited areas on continental margins (*geosyncline*).

Wegener broke up with the secular cooling theory, collapsed by the discovery of natural radioactivity in 1896, and the assumption of a heating Earth. In contrast, he used the theory of isostasy, suggested by John H. Pratt and George B. Airy and named by Clarence E. Dutton in 1892, to interpret the Earth's crust in two layers. A light continental crust would float and drift on heavy oceanic crust and would never sink. The horizontal motions and deformations of the continents would cause the major geological features. Wegener's theory tried to unify data from paleontology, biogeography, geophysics, stratigraphy, geological mapping, and paleoclimatology to propose a synthetic model. He tried to unify European and American opposite views. The explanation of the rejection of his continental drift by most of the geologists of the 1920s and 1930s is complex and could not be justified only by the lack of a causal explanation of drift. The death of Wegener in 1930 and the inability to prove or disprove his theory closed the controversy. Debate was put aside in spite of the causal models proposed in the end of the 1920s by the Canadian geologist Reginald Daly and the British geologist Arthur Holmes. Daly in *Our Mobile Earth* published in 1926 proposed a gravity sliding as drift mechanism. Holmes in his paper of 1929 about *Radioactivity and Earth movements* proposed subcrustal convection currents to evacuate heat from the interior of the Earth. He

proposed continental drift as consequence of thermal convection. But the question of continental drift was not settled.

Because of his studies about earthquake waves, Sir Harold Jeffreys was persuaded that the Earth possessed a considerable strength, incompatible with models of drifting continents. The transmission of seismic waves could be imagined only within a stiff Earth. The study of the earthquake of Kupa of October 8, 1909, allowed Serbian geophysicist Andrija Mohorovicic to bring to light a brutal acceleration of the speed of propagation of the waves toward 50 km deep and to establish a seismic boundary between the crust and the mantle. Five years later, German seismologist Beno Gutenberg determined a major discontinuity at the depth of 2,900 km: the seismic boundary between mantle and core was discovered. In the 1920s, Gutenberg, through his works about deep-focus earthquakes and identification of a low-velocity zone, concluded to a weak crustal substrate and joined those who defended the possibility of subcrustal currents. In 1934, Gutenberg and an American seismologist Charles Francis Richter published new travel-time curves, which contributed to specify a seismic model of the globe. The discovery of an inner core's discontinuity by Inge Lehman, in 1936, and its interpretation by Beno Gutenberg and Richter as a separation between a fluid outer core and a solid inner core conducted in few years to establish a structural model of Earth's interior. The model of Harold Jeffreys and Keith E. Bullen little changed since 1940. In the 1950s, David Griggs, Harry Hess, and Félix Venig-Meinesz proposed convection models. Like that of Arthur Holmes, their models offered finally a physical reliable cause to the drifting continents of Wegener.

After the Second World War, the development of paleomagnetic studies was going to shake the trust in the continental permanence and revive the idea of drifting continents. The work of Bernard Brunhes in the early 1900s showed that old basaltic lavas are magnetized in directions making sometimes large angles with the present Earth's magnetic field. Basalt acquires its magnetization from the geomagnetic field when it crystallizes and passes under the Curie point of their magnetic

minerals (580 °C for magnetite). Considering that the mean geomagnetic field can be compared with an axial dipole situated at the Earth's center, the magnetic field's characteristics, recorded in the rocks, should be those of their geographic localization. Patrick Blackett, Stanley K. Runcorn, Edward Irving, and K. Creer, by the mid-1950s, observed that the geographic North Pole fossilized in lavas changed with geological time. The angle of polar difference increasing with time, a migration either of the poles or of the continents was clearly suggested. Wegener's hypothesis of polar wandering based on paleoclimatic data seemed to be confirmed. Polar wandering paths were determined for North America and Europe by Stanley Runcorn. A systematic difference appeared between the polar wanders of the two continents since the Triassic. But putting side by side North America and Europe, it disappeared. Paleomagnetic arguments strongly supported the idea of moving continents and the possibility of existence of supercontinents in the past, as Pangea, the old supercontinent imagined by Wegener, 30 years ahead. In the beginning of 1950, the American geologist Harry Hess used a magnetometer to record magnetic variations across the ocean floor. These magnetic variations are associated with the magnetite contained in oceanic basalts, which records the orientation and intensity of the Earth's magnetic field at the time of basalt extrusion. In the 1960s, magnetic studies revealed the existence of alternating stripes of normal and reverse polarity, which are symmetrically distributed on either side of the mid-ocean ridge. The alternation of direct and inverse magnetic polarity is related to periodic changes in the polarity of the Earth's magnetic field, which is recorded in the basaltic rocks. The marine geologists and geophysicists Frederick Vine and Drummond Matthews suggested in 1963 that the ► [mid-ocean ridges](#) mark structurally weak zones where the ocean floor was split in two along the ridge crest. It was suggested that pulses of magma rise along the ridge and create new oceanic crust, which then migrate laterally away from the ridge – the process called seafloor spreading. The explanation of the magnetic striping led to the rapid

acceptance of seafloor spreading as a key element of plate tectonics theory.

In the 1950s, geological and geophysical oceanographic explorations established a new physiography of the ocean floors. The ocean floor showed a world embracing mid-oceanic ridge system, cut by transverse faults, showed arc-trench system with extinct and active volcanoes, and revealed numerous seamounts, interpreted by Harry H. Hess as subsiding volcanoes. In 1959, Bruce Heezen, Marie Tharp, and Maurice Ewing published the first detailed bathymetric map of the North Atlantic Ocean. Campaigns of coring deep-sea sediment and dredging of rock samples from exposed scarps on the oceanic ridges revealed a great petrographic homogeneity of the seafloor (only basic and ultrabasic rock types) and lack of sedimentary rocks older than Cretaceous. In 1961, Robert S. Dietz expressed his hypothesis of a seafloor spreading, and a year later, Harry Hess, independently, published a paper where he proposed equally that the seafloor was created at mid-ocean ridges, then spread out toward the trenches where it sank into the mantle, driven by convection currents of the mantle. Canadian geophysicist Tuzo Wilson, studying transverse faults of the ridges, suggested in 1965 that they would limit several large, rigid crust areas that he called *plates*. The Earth's surface would be divided into plates limited by ocean ridges, ocean trenches, and transverse faults (such as the St Andreas fault in California) that would transform the one to the other one. Earthquakes and volcanic activity would characterize plate boundaries. In his model, the oceans are created, grow, and disappear; and the continents are fragmented, separated, and reassembled in what are now called "Wilson cycles." But Earth's crust was too thin to be stiff enough and required to extend about 100 km down that meant to the low-velocity zone of the mantle. Plates are lithospheric ones composed of what is called crust and the upper, rigid part of the mantle, the so-called lithospheric mantle. Further understanding of plate kinematics came from the work of the geophysicists William Jason Morgan and Dan McKenzie, who explained in 1968 relative displacements of adjacent plates. He showed that the movements

are parallel to transform faults and centered on a pole of rotation (the Euler pole) and that variations of seafloor expansion are a function of the distance from the pole of rotation. Using Jason Morgan's model of plates and Euler's theorem about translation of an area on a sphere, French geophysicist Xavier Le Pichon proposed the same year to divide Earth's surface into six major plates. Plate tectonics break with continental drift, because if continents move, they do not drift over ocean.

Geological aspects of the theory of plate tectonics were developed by the geologists John Dewey and John Bird, who showed in 1970 that the structure of active continental margins is dependent on the geometry and kinematics of subduction zones. This seminal paper showed geologists how the orogenic belts are linked to movements of the oceanic lithosphere and explained the relationship between plate tectonics and both the complex 3D movements at continental margins and the magmatic and metamorphic processes of mountain building. In 1977, the submersible vehicle Alvin observed hydrothermal vents on the east pacific ridge. Geologists were looking for deep-sea hot springs, which they predicted to exist along rifts. They discovered them, and in the same time, they made a greater discovery: vents were jammed with animals. Plate tectonics gave a new breath to understand the early beginning of the life on our Earth.

The early establishment of the theory of plate tectonics in the 1960s represented a revolution in Earth sciences, like British paleontologist Anthony Hallam wrote in 1972. For the first time, data from all of the branches of Earth sciences gathered in a unifying theory, which could explain past and present geological time and can also predict what will happen in the future.

Cross-References

- [Mantle](#)
- [Mantle Plume, Planetary](#)
- [Mid-Ocean Ridge](#)
- [Plate Tectonics](#)

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Cross-References

- ▶ [Asthenosphere](#)
- ▶ [Continental Crust](#)
- ▶ [Lithosphere, Planetary](#)
- ▶ [Mid-Ocean Ridge](#)
- ▶ [Oceanic Crust](#)
- ▶ [Plate Tectonics](#)

Plate, Lithospheric

Nicholas Arndt
ISTerre, University Grenoble Alpes, Grenoble,
France

Synonyms

[Tectonic plate](#)

Definition

A *lithospheric plate* is a large cohesive mass of oceanic or continental ▶ [lithosphere](#) which moves as a single element in the process of ▶ [plate tectonics](#). The outer layer of the solid Earth is composed of nine major lithospheric or tectonic plates and many minor plates. They are relatively rigid, and they float on and move atop the more deformable ▶ [asthenosphere](#) at speeds relative to each other varying from 2 to 10 cm/year. The largest, Pacific, plate is ~4000 km long and wide and up to 100 km thick. The upper part of the lithosphere plates may consist of either ▶ [oceanic](#) or of ▶ [continental crust](#) and is then called “continental” and “oceanic lithosphere,” respectively. Oceanic plates are created at ▶ [mid-ocean ridges](#) and are destroyed at subduction zones. The Pacific and Nazca plates and several smaller plates consist entirely of oceanic lithosphere, but the majority contain both continental and oceanic lithosphere. Because of thick roots beneath Archean cratons, the maximum thickness of continental plates reaches several hundred kilometers.

Platinum Group Elements

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Acronyms

PGE; PGM

Definition

The platinum group elements (PGE) or metals (PGM) – ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt) – have similar chemical characteristics and behave as a group during geochemical processes. They are strongly siderophile (iron-loving) and chalcophile (sulfur-loving) and are therefore concentrated in the core of the Earth and in iron meteorites, in sulfide ore deposits, and to a much lesser extent in the Earth's mantle. An important geological application of the PGE is their use as tracer of meteoritic material, most famously Ir in the development of the meteorite impact hypothesis (▶ [Chicxulub Crater](#)), which caused the Cretaceous-Tertiary ▶ [mass extinction](#). The isotopic system rhenium-osmium is used to date mafic-ultramafic rocks, ore deposits, or some organic-rich sediments, and as tracer of processes in the Earth's mantle. The Os isotope ratio ($^{187}\text{Os}/^{188}\text{Os}$) is also used to trace changes in oceans through time, such as weathering flux. The occurrence of small excesses of PGE in the mantle has been often indicated as evidence of a

late contribution of chondritic material to the Earth (► [Late Veneer](#) hypothesis). In some environments, PGE can also indicate anthropogenic effects such as the use of catalytic converters in cars.

Cross-References

- [Chicxulub Crater](#)
- [Late Veneer](#)
- [Oceans, Origin of](#)
- [Water, Delivery to Earth](#)

PLATO 2.0 Satellite

Heike Rauer¹ and Malcolm Fridlund²
¹German Aerospace Center (DLR), Berlin, Germany

²Max-Planck-Institut für Astronomie, Heidelberg, Germany

Keywords

Exoplanet · Transit · Asteroseismology · Stars

Synonyms

[PLANetary Transits and Oscillations of stars](#)

Definition

PLATO 2.0 (PLANetary Transits and Oscillations of stars) is a mission for the detection and characterization (radius, mass, age) of transiting exoplanets at orbital distances up to the habitable zone of solar-like stars. In addition, PLATO 2.0 will study the stellar structure through asteroseismology.

Overview

PLATO 2.0 is the first space mission designed for the simultaneous search for transiting exoplanets and study of their host stars through

► [asteroseismology](#) (Rauer et al. 2014). Selected as the third mission of the cosmic vision science programme of ESA, it is planned for a launch in 2024, PLATO 2.0 will be developed in a partnership between ► [ESA](#) (providing the spacecraft, launch, and elements of the operation) and a scientific consortium (providing the payload, including the telescopes, elements of the operations, and scientific planning), led by Germany (DLR) and consisting of elements from essentially all of the ESA member states.

Basic Methodology

When an exoplanet travels between its host star and the Earth, it induces a weak drop of the star's brightness (a mini eclipse). The detection of this periodic ► [transit](#) in the star's light curve, together with its careful analysis (e.g., discerning the transit signature from, e.g., star spots), reveals the existence of the exoplanet and provides important characteristics such as the planet's radius, its orbit parameters, and the rotation period of the star. By also studying the properties of the star, such as its radial velocity, its radius, and its age, the absolute values of the mass, radius, and age of the planet can be determined.

Stars, acted on by gravity, pressure, and Coriolis forces, behave as oscillators with many specific modes. These oscillations are detectable through tiny variations in the stellar brightness, and their analysis provides important parameters on the stars' internal structure. Most importantly, parameters such as mass, radius, and age can be determined with significantly higher precision in this way than with classical methods such as spectroscopy.

If the stellar parameters of the planet's host star have been determined through asteroseismology, the planetary values can be determined with unprecedented accuracy.

PLATO 2.0 is designed to have an ultrawide field of 2250 square degrees that enables it to monitor the flux from hundreds of thousands of stars for uninterrupted periods of up to several years. This allows users of the spacecraft to detect and measure the tiny variations in the stellar flux that are caused either by stellar activity, stellar internal oscillations, and/or the possible transit

signature of an orbiting exoplanet. The satellite carries thirty-four (34) six-lens visible telescopes each with a clear aperture of 12 cm and each focusing the stars' light on an individual focal unit hosting four frame-transfer ► [CCD](#) matrices of 4510×4510 18 Micron Pixels. The detectors, whose temperature is cooled passively, have a high quantum efficiency in the visible wavelengths. Each telescope is equipped with an individual baffle to reduce the parasitic straylight, as well as the whole assemblage being sheltered by an efficient sun shield. In order to remain shielded from the scattered Sunlight, as the satellite travels around the Sun in its L2 Lissajou (Lagrange points) orbit, it is necessary to rotate the spacecraft 90° around its optical axis every 90 days. Thirty-two of the telescopes (referred to as "normal cameras") observe with a cadence of 25s and monitor objects fainter than visual magnitude 8. The two remaining telescopes (referred to as "fast cameras"), equipped with colored filters, observe with a cadence of 2.5s and observe stars between visual magnitudes 4 and 8.

Key Research Objectives

Exoplanets and Asteroseismology

PLATO 2.0 will monitor about 1,000,000 solar-like stars, during periods of between a few months and ~ 3 years, searching for the signature of the transit of a planet with the same size as the Earth.

While PLATO 2.0 will be able to detect quite easily super-Earths in short (less than 2 months) orbits, its major breakthrough will be for planets down to Earth size orbiting within the habitable zone (HZ) of large numbers of solar-like stars (which requires the detection capability of periods larger than approximately 6 months). This is a parameter range not explored by any past, current, or planned space mission.

PLATO 2.0 will determine albedo and atmospheric properties for a large number of objects by performing the bulk observation of secondary transits (Alonso et al. [2009a, b](#)), as well as by measuring the changes in illumination of exoplanets as their phases change.

For about 85,000 bright stars with magnitudes smaller than 11.3, the stellar light curve will be

recovered with a precision accurate enough to obtain the mass and size of the star with an error of a few percent through asteroseismology. This will allow the detailed characterization of any planet found orbiting those stars. Their ages will also be determined with unprecedented precision ($\sim 10\%$) and with information about orbital distributions, and from some of the atmospheric parameters we will get the first information about the evolution of exoplanets.

PLATO 2.0 and Stellar Physics

Through asteroseismology solar-like stars, stars hotter than the Sun, and red giants can be studied in detail through solar-like oscillations. Data from the CoRoT and Kepler space missions have demonstrated that the much more capable PLATO 2.0 will be able to open a new chapter in stellar physics, as well as carry out detailed galactic archeology for our part of the Milky Way galaxy.

Applications

PLATO 2.0 will be the next order-of-magnitude step, beyond CoRoT (Baglin et al. [2007](#)), Kepler (Basri et al. [2005](#)), ► [TESS](#), and ► [CHEOPS](#), in our search for exoplanets, enabling us to further our understanding of the distribution of sizes and masses of large numbers of small and "rocky" planets. This will enable progress in theories for the formation and evolution of stellar systems and also their host stars. The improvement in physical parameters of large numbers and kinds of stars will allow stellar physics to evolve and will impact on large areas of astrophysics.

PLATO 2.0 will bring together the European exoplanetary community and drive the evolution of ground-based follow-up which will itself impact many areas.

Future Directions

PLATO 2.0, together with the preceeding missions TESS and CHEOPS, will constitute the main steps in preparing for the spectroscopic missions that will follow. ► [JWST](#) will of course carry out spectroscopy at roughly the same time as PLATO 2.0, but it is equipped with only

simple coronagraphic capability. PLATO 2.0 results will map out the direction that the astronomical community will have to move toward in order to make progress in the search for extraterrestrial life.

Cross-References

- [Asteroseismology](#)
- [Atmosphere, Temperature Inversion](#)
- [Brown Dwarf](#)
- [CoRoT Satellite](#)
- [Habitability, Effect of Eccentricity](#)
- [Habitable Zone, Effect of Tidal Locking](#)
- [Hot Jupiters](#)
- [Hot Neptunes](#)
- [Kepler](#)
- [Planetary Migration](#)
- [Radial Velocity](#)
- [Red Giant](#)
- [Spectroscopy](#)
- [Stellar Pulsation](#)
- [Stellar Rotation](#)
- [Super-Earths](#)
- [Transit](#)
- [Transiting Planets](#)
- [VLT](#)

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Plenum Formarum

- [Principle of Plenitude](#)

Ploidy

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Ploidy refers to the number of sets of chromosomes in a biological ► [cell](#). Sex cells, also called gametes, combine to produce somatic cells. The haploid number is the number of chromosomes in a gamete. A somatic cell has twice that many chromosomes. However, many organisms have more than two sets of homologous chromosomes and are called polyploidy.

Cross-References

- [Cell](#)
- [Chromosome](#)
- [Fungi](#)

Plug-Flow Reactor

- [Flow Reactor](#)

Plume

Doris Breuer and Ralf Jaumann

German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

A plume is a column of one type of matter moving through another one, driven by momentum, diffusion, and buoyancy. The flow can be driven by buoyancy derived from differences in temperature or chemistry between the plume and the surrounding medium. ► [Mantle plumes](#) are upwelling hot

rocks within a planetary mantle driven by a temperature difference of a few hundred Kelvin. Mantle plumes are thought to feed volcanic centers known as hotspots. Plumes also form in planetary atmospheres, e.g., above volcanic eruptions. Umbrella-shaped plumes are eruption columns that eject gas and dust from volcanic vents into space. The most impressive eruption plumes in the ► [solar system](#) occur on the Jovian satellite Io, reaching more than 400-km height before falling back. The mechanism of plume eruptions is similar to that of geysers.

Cross-References

- [Heat Flow, Planetary](#)
- [Interior Structure, Planetary](#)
- [Io](#)
- [Mantle](#)
- [Mantle Plume, Planetary](#)
- [Plate Tectonics](#)
- [Rock](#)
- [Solar System](#)

Plurality of Worlds

Florence Raulin-Cerceau
Maître de Conférences, Centre Alexandre Koyré
(UMR 8560-CNRS/EHESS/MNHN/CSI)
Muséum National d'Histoire Naturelle, Paris,
France

The plurality of worlds, regarded as other inhabited worlds in the universe, is a debated question since Antiquity. The Greek philosopher Anaximander considered that countless worlds succeeding one another could be born from an infinite universe. The atomist Democritus, as well as Epicurus and later Lucretius, maintained that worlds in infinite number have emerged from atoms and infinite void, a materialistic view of the universe. Following the heliocentric Copernican theory, new speculations were formulated. Inquisition rejected the infinity of worlds proposed by

the dissident Dominican friar Giordano Bruno. However, famous personalities expounded this idea (Kepler, Huygens, Fontenelle) which finally became a scientific topic during the nineteenth century (Flammarion, Proctor). Astrobiology revisits today this concept through space exploration and the continuous discoveries of exoplanets.

Cross-References

- [Bruno, Giordano](#)

Pluricellular Organisms

- [Multicellular Organisms](#)

Pluto

Tanguy Bertrand and Emmanuel Lellouch
Laboratoire d'Etudes Spatiales et
d'Instrumentation en Astrophysique (LESIA),
Observatoire de Paris, CNRS, UPMC Univ. Paris
06, Univ. Denis Diderot, Sorbonne Paris Cite,
Meudon Principal Cedex, France

Keywords

Dwarf planet · Resonant orbit · Satellite
system · Trans-Neptunian object · Terrestrial
atmosphere

Definition

Pluto (formal designation: 134340 Pluto) is the largest known object of the Kuiper belt, a ring of bodies beyond the orbit of Neptune. From its discovery in 1930 to 2006, it was considered the solar system's ninth planet. However, the International Astronomical Union's (IAU) reclassification of solar system objects in 2006 puts Pluto in the category of dwarf planets, that is, objects large enough to satisfy the condition of

hydrostatic equilibrium but that do not dynamically dominate their surrounding population. Pluto has been visited for the first time by the New Horizons spacecraft during a flyby on July 14, 2015, which allowed for detailed observations of its surface, atmosphere, and moons.

History

Pluto was discovered on February 18, 1930, by a 23-year-old farmer and amateur astronomer Clyde Tombaugh. Tombaugh was employed at Lowell Observatory with the task of searching for a putative massive (several Earth masses) object, known as “planet X.” Planet X had been predicted by Percival Lowell (and independently by others) on the basis of analyses of Uranus’ motion, in much the same manner Neptune had been discovered in 1846. After about 1 year of search, Tombaugh spotted a moving object on plates recorded on January 23 and 28, 1930. The discovery was announced on March 13 (for the 75th anniversary of Lowell’s birth) in the form of an observation circular cautiously entitled “The Discovery of a Solar System Body Apparently Trans-Neptunian.” Inspection of archive observations of the world’s major observatories confirmed the detection of the object on no less than 136 plates, the earliest of these “prediscovery” images dating from January 1914. This allowed an accurate orbit to be quickly established, confirming that the object, then at 41.3 AU from the Sun, was indeed trans-Neptunian. However, Pluto was immediately realized not to be the object that was looked for. With its faint magnitude (about 15 at discovery) and unresolved appearance, Pluto must have been very small. Initial estimates showed it to be less massive than the Earth (and measurements in subsequent decades only aggravated the problem), indicating that the new object was unable to perturb the motion of Uranus. Tombaugh continued his quest of Planet X for another 10 years, without success. The mystery was not solved until 1993, when updated calculations of Uranus’ motion, using the accurate mass of Neptune provided by Voyager 2, made the perturbations vanish, and with them the need for a planet.

Overview

Mass, Size, and Internal Structure

Pluto’s radius is 1188.3 ± 1.6 km and its mass is $1.303 \pm 0.003 \times 10^{22}$ kg, which is 0.22% that of Earth. Its surface area is about 17.7 million km² (equivalent to the surface area of Russia). Its surface gravity is 0.62 m/s², which is about 1/15th of the surface gravity on Earth. Pluto is smaller and less massive than seven moons of the solar system: Ganymede, Titan, Callisto, Io, the Moon, Europa, and Triton. However, Pluto may be the largest object in the Kuiper Belt (dwarf planet Eris approximate radius is 1163 km) and the second-most massive after Eris.

Based on its mass and size, Pluto’s density is 1.860 ± 0.013 g/cm³. The interior of Pluto is thought to be differentiated, with rocky material having settled into a dense silicate core (corresponding to two-third of Pluto’s radius) surrounded by a mantle of water ice (one-third of Pluto’s radius). It is possible that heating produced by the decay of radioactive elements continues today, creating a subsurface ocean of liquid water 100–180 km thick at the core–mantle boundary. Many modeling studies support the presence of a past or still existing subsurface ocean.

Pluto has no magnetic field.

Orbital and Spin Parameters

Orbit

With a semimajor axis of 39.5 AU, Pluto orbits the Sun in a mean 248.1-year period. Its highly elliptical (eccentricity = 0.249) and inclined ($i = 17.1^\circ$ over the ecliptic) orbit is distinctly different from those of the planets. The large eccentricity brings Pluto to 29.7 AU from the Sun at perihelion (lastly on September 5, 1989) and 49.7 AU at aphelion, which leads to the normal incident solar flux varying by a factor of ~ 3 over the course of its orbit. Pluto is therefore occasionally closer to the Sun than Neptune (lastly between February 1979 and February 1999), but the inclination of Pluto’s orbit is such that the two orbits do not intersect; when Pluto is near

perihelion, it is also far from the ecliptic plane. Moreover, Pluto and Neptune appear to be in 3:2 mean motion resonance, that is, for every two orbits that Pluto makes around the Sun, Neptune makes three (each cycle lasts about 495 years). The consequence of this synchronism is that the minimum distance between Pluto and Neptune is 17 AU. Ironically, Pluto can come closer to Uranus (12 AU). More fundamentally, these large distances imply that Pluto's orbit cannot be destabilized by the giant planets.

Pluto's orbit evolved over long timescales. First, its eccentricity oscillates between 0.222 and 0.266 with a 3.95 million years (Myr) period. Second, its argument of perihelion (the angle between the point where Pluto crosses the ecliptic and the perihelion) liberates by 24° with a period of 3.96 Myr. Third, the longitude of the ascending node (the point where Pluto crosses the ecliptic when passing from below to above the plane) is in near-resonance with the above liberation and regresses over 360° with a period of 3.7 Myr.

Computer simulations have predicted Pluto's orbital motion over the past and the next 10–20 million years, but beyond that timescale, calculations become speculative because of chaotic behavior.

Obliquity and Rotation

One day on Pluto lasts 6.387 Earth days, which is intermediate between fast rotators like Earth and Mars and slow rotators like Venus and Titan.

In Pluto's current orbit, the obliquity (angle between the planet's spin axis and its orbital axis) is 119.51° , equivalent to 60.49° in retrograde rotation. This high obliquity means that the annually averaged insolation is highest at the poles and lowest in the equatorial regions, in particular at 25°N and 25°S . Pluto's obliquity varies by about 23° between 104° and 127° over a period of 2.8 Myr. Consequently, over this timescale, the latitude of minimum insolation moves from $\pm 30^\circ$ to the equator, and the difference between the annually averaged insolation at the equator vs. the poles varies accordingly.

The reason for the high obliquity of Pluto could be related to a polar wander mechanism.

Satellite System

Pluto possesses five satellites, by order of increasing distance to Pluto: Charon, discovered in 1978 by J. Christy, Styx, Nix, Kerberos, and Hydra, detected over 2005–2012 in Hubble Space Telescope (HST) images. The five satellites lie in the equatorial plan of Pluto and have orbital periods of 6.387, 20.2, 24.9, 32.2, and 38.2 days, forming a 1:3:4:5:6 sequence of near (but not exact) mean motion resonances with Charon. Charon and Pluto form a remarkably "balanced" pair, with Charon's radius and mass being approximately one-half and one-eighth of Pluto's (606.0 ± 0.5 km, $1.586 \pm 0.015 \times 10^{21}$ kg, which is 12.2% of Pluto's mass). The barycenter of the Pluto–Charon system lies outside Pluto, justifying the use of the wording "binary system." Strictly speaking, Charon does not orbit Pluto; rather, the two bodies orbit their common barycenter. The system is also unusual among planetary systems in that each body is tidally locked to the other, which means that the period of mutual revolution is exactly equal to Pluto's and Charon's rotation periods, with each body having the same hemisphere facing the other. This synchronous motion is the consequence of mutual tidal forces.

The other four moons are not spherical (but instead elongated) and their dimensions are $16 \times 9 \times 8$ km, $49.8 \times 33.2 \times 31.1$ km, $19 \times 10 \times 9$ km, and $50.9 \times 36.1 \times 30.9$ km for Styx, Nix, Kerberos, and Hydra, respectively. They orbit the common barycenter rather than Pluto itself and are in stable dynamic resonances with Charon and with each other, with orbital periods close to a 3:4:5:6 ratio, respectively. These resonances may have been forced when Charon became tidally boosted into its current synchronous orbit. Unlike Charon, they are not in tidal lock with Pluto. Instead, they tumble chaotically. For instance, Hydra rotates 89 times on its axis for every orbital revolution.

Similar to the giant impact that formed the Earth's Moon, Pluto satellite system is thought to have resulted from a giant impact, that occurred early in the solar system history, between Pluto and a similar-sized body. The main clues are the

large masses of Pluto and Charon, the great specific angular momentum of the pair, and the coplanar system of the smaller satellites. After the collision, which may well have formed Charon intact, tidal forces over timescales of only a few tens of millions of years would have led to Charon's current circular and synchronous orbit. The collision also released material that consolidated into small moons in the Pluto–Charon orbit. However, it remains unclear what yields the large orbit distances of the moons and how they came to be near resonances with Charon.

Surface

Pre-New Horizons Knowledge

Pre-New Horizons Earth-based near-infrared spectroscopy indicated that Pluto's surface is covered by a variety of ices: volatiles N_2 , CO , CH_4 , with most of the CO and CH_4 occurring in dissolved form in N_2 , and non-volatile H_2O . Regions covered by essentially pure CH_4 were also evidenced. Charon's surface was found to be covered by H_2O ice, with possible evidence for ammonia hydrates. The bulk densities of Pluto and Charon were estimated to be 2.0 and 1.7, respectively, indicating a mixture of rocks and ices in approximately equal proportions.

Thermal measurements indicated that Pluto's surface temperature varies from ~ 37 K in the bright regions (temperature of the N_2 -rich ice) to ~ 60 K for the darkest areas when illuminated, with a low surface thermal inertia (~ 20 – 30 $J\ m^{-2}\ s^{-0.5}\ K^{-1}$ for the CH_4 -rich and volatile-free terrains). For pure N_2 , this implies that N_2 is in its β -crystalline phase with a temperature above the 35.62 K phase transition. The low thermal inertia implies a porous structure for the top few cm, which are affected by the diurnal temperature cycle.

Surface Appearance and Geology

The flyby of Pluto by New Horizons revealed a variegated surface, with a large number of surface features, brightnesses, and colors. New Horizons images also showed evidences of a complex geological history on Pluto's surface, with a

surprisingly pronounced topography, with 5-km deep depressions and 5-km high water-ice mountains, and a wide variety of geological landforms, including those resulting from glaciological and surface–atmosphere interactions as well as impact, tectonic, possible cryovolcanic, and mass-wasting processes.

The main prominent structure is Sputnik Planitia, a 1000 km-wide and several-km deep impact basin filled by a crater-free (and therefore geologically young, less than 10 Myr) ice sheet made of nitrogen ice, with traces of methane and carbon monoxide. The plains of the ice sheet display polygonal cells, suggested to be convective cells, obvious signs of glacial flows, sublimation pits, icy dunes, and wind streaks, thus hinting for significant surface–atmosphere interactions.

The largest dark feature on Pluto is Cthulhu Macula, located west of Sputnik Planitia at the equator. Its dark color results from the absence of exposed volatile ice and instead the accumulation of complex hydrocarbons, called tholins, onto the surface. These tholins possibly formed in the atmosphere from methane and nitrogen photolysis by solar ultraviolet light and cosmic rays. Cthulhu presents a large number of craters, which suggests that it may be billions of years old.

Normal reflectance of Pluto's surface ranges from 0.08 to 1.0, with the lowest values associated with the dark region of Cthulhu and the highest values to the bright volatile-covered Tombaugh Regio and the north pole. Pluto's mean Bond albedo is 0.72 ± 0.07 .

Surface Composition

New Horizons confirmed that most of Pluto's surface is covered by volatile N_2 , CH_4 , and CO ices in various mixtures. Less volatile methanol (CH_3OH) and hydrocarbon ices have been detected near the dark region of Cthulhu and are thought to be derived ultimately from both UV photochemistry and ion irradiation at Pluto's surface (see below). Non-volatile “bedrock” H_2O and NH_3 -hydrate ices were also detected on the surface. H_2O ice and ammoniated species dominate the surfaces of Charon and of the small moons. Molecular O_2 (abundant in the coma of comet 67P/Churyumov-Gerasimenko) and CO_2

ice (common on many icy satellites and abundant on Triton) were not detected.

Several processes could possibly have impacted Pluto's surface composition (and geology): cryovolcanism and tectonic activity over astronomical, darkening and contamination by haze sedimentation and by direct photolysis/radiolysis of the ices on seasonal or multi-seasonal timescales. The topography also impacts the volatile sublimation/condensation rates and therefore the ice distribution: N_2 favors low altitudes (e.g., Sputnik Planitia), whereas CH_4 favors high altitudes (e.g., Bladed Terrain, Pigafetta Montes, etc.).

Outside Sputnik Planitia, maps of surface composition (but also of albedo and color) show latitudinal banding, with non-volatile material dominating the equatorial region and volatile ices at mid- and polar latitudes. This pattern is driven by the seasonal cycle of insolation. The composition of terrains in the Sub-Charon hemisphere or south of $30^\circ S$ was not measured because these terrains were plunged into darkness (night-time and polar winter, respectively).

Atmosphere

Atmospheric Composition

Pluto's atmosphere is mainly N_2 , due to its high volatility and dominance on Pluto's surface, with minor amounts of methane (0.5%) and CO (0.05%), all in (quasi) solid–gas equilibrium with their ices on the surface. Methane is much less volatile than N_2 , and its relatively elevated abundance probably reflects sublimation from pure methane patches at Pluto's surface, that are warmer than N_2 ice, whose temperature is controlled by sublimation cooling.

In the upper atmosphere, solar ultraviolet radiations and cosmic X and gamma-rays drive N_2 and CH_4 destruction, yielding photochemical reactions that form more complex compounds in trace amounts (and not volatile at Pluto's surface temperatures), including ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), heavier hydrocarbons, and hydrogen cyanide (HCN).

Atmospheric Pressure

Since 1985, ground-based stellar occultation observations have indicated that Pluto's atmosphere is tenuous and time-variable. In particular, they showed that the atmospheric pressure increased by a factor ~ 2.5 between 1990 and 2015. In 2015, New Horizons measured a surface pressure of about 1.1 Pa in 2015, roughly 100,000 times less than Earth's atmospheric pressure. This value should be close to its annual maximum, according to models, due to seasonal effects, with regions covered by N_2 ice moving into summer and warming. The pressure should decrease during the next decades, with a minimum of a few mPa near aphelion. Larger variations can be expected during other obliquity or orbital conditions. Pluto's atmosphere is thick enough to be global, that is, the surface pressure and N_2 ice temperature are (except for topography) essentially independent of location on Pluto.

Atmospheric Haze

New Horizons also revealed a blue haze surrounding Pluto, structured in roughly 20 regularly spaced haze layers in the first 200 km above the surface. These 1–10 km thick layers could be the result of atmospheric waves, possibly generated by the volatile sublimation–condensation cycles or by air masses flowing over Pluto's mountains. The visible haze extends to ~ 600 km altitude.

The normal optical depth of the haze is estimated to be within 0.004–0.013. Different observations give different answers regarding haze particle sizes. Although the blue color points to particle radii near 10 nm, the ratio of brightnesses observed at different phase angles point to radii larger than 100 nm. These findings can be reconciled by invoking the aggregation of small (tens of nm) particles into larger (hundreds of nm) clusters, a situation already encountered on Titan.

The haze may consist of “tholin-type” solid particles, as on Titan. Their formation originates in the upper atmosphere, where N_2 , CH_4 , and CO are photolyzed by UV and cosmic high-energy radiation, leading to photochemical production of hydrocarbons (such as C_2H_2 , C_2H_4 , and C_2H_6) and nitriles (such as HCN) and then to the formation of these solid aerosols through

mechanisms of coagulation and aggregation. An alternative scenario suggests that the haze particles are mostly made of hydrocarbon ice (C_2H_4) that condenses on small tholin nuclei. Finally, there is no unambiguous evidence for condensation clouds in Pluto's atmosphere.

Atmospheric Temperatures

The Radio experiment (REX) on-board New Horizons measured a thermal profile consistent with those derived from Earth-based stellar occultations. REX showed a cold, dense layer in the lowest 3 km above the N_2 ice-covered surface in Sputnik Planitia, with a mean temperature (38.9 ± 2.1 K) close to the condensation temperature of N_2 . The cold layer is capped by a strong inversion with a peak gradient of $+9.5 \pm 1.2$ K km^{-1} (i.e., a stratosphere), mainly due to methane absorption. The temperature reaches its maximum at height 20–40 km (100–110 K) and then slowly decreases (about 0.2 K/km), reaching 70 K in the upper atmosphere (>400 km). Causes of this decrease are unclear, as the identified gases seem to provide insufficient cooling. It has been suggested that the organic haze has a significant radiative impact and is responsible for the cooling of the upper atmosphere but this remains to be explored in more details.

Atmospheric Escape

New Horizons detected the presence of atmospheric gases up to 1670 km altitude. Post-New Horizons models suggest that Pluto's atmosphere is currently (2015 conditions) losing only 1×10^{23} molecules of nitrogen and 5×10^{25} molecules of methane every second. Over the age of the solar system (~ 4.5 Gyrs), this corresponds to several centimeters of nitrogen ice and several tens of meters of methane ice lost to space. This may not be significant compared to the estimated reservoirs of nitrogen and methane ice on Pluto's surface. Nonetheless, Pluto's weakly escaping atmosphere may be at the source of Charon's poles' red coloration, interpreted as due to the capture of CH_4 gas escaping from Pluto and attendant condensation and chemical processing on Charon's cold poles.

Climatic Evolution

The climate of Pluto is a complex system in which the atmospheric dynamics are coupled with the N_2 cycle (sublimation and condensation processes induce surface pressure variations with time and control the winds) and the CH_4 and CO cycles (both partly control the radiative properties of the atmosphere and additionally CH_4 drives atmospheric photochemistry and haze formation). These cycles strongly depend on surface ice distribution and temperatures, themselves controlled by insolation changes and contamination by dark haze particles.

Changes in insolation and surface temperatures occur on diurnal, seasonal, and astronomical timescales. The astronomical timescale is dominated by changes in obliquity, solar longitude of perihelion, and eccentricity, also known as the Milankovitch mechanism, which also occurs on other planetary bodies such as the Earth, Mars, and Titan.

These variations force the volatile ices that form glaciers, frost, or lakes to migrate in different regions over time and causes meter-sized changes of their thickness. For instance, the N_2 -rich Sputnik Planitia ice sheet and the surrounding terrains exhibit numerous evidences of climate variation: active glacial flow on the edges of the sheet, icy dunes, fluvial features and ponds (that could have been shaped by liquid flows at the base of thick N_2 glaciers, now disappeared), deep sublimation pits, and erosions of water ice mountains. A variety of terrains outside Sputnik Planitia are also thought to have been carved by ancient glaciers. The major CH_4 deposits include the massive Bladed Terrain at the equator and several ice mantles at mid-northern latitudes. Climate models have been able to relate the formation of these geologic features to the Milankovitch parameters history of Pluto.

The atmosphere is also impacted by seasonal and long-term changes insolation. For instance, climate models have shown that surface pressure and atmospheric abundances of CH_4 and CO should have been minimal during very high obliquity periods ($\sim 104^\circ$, i.e., 76° in retrograde rotation) and maximal during low obliquity periods ($\sim 127^\circ$, i.e., 53° in retrograde rotation), with surface pressures remained in the range of 0.01 μbar

to 1 mbar and CH₄ atmospheric mixing ratio in the range of 0.001–10%. Higher pressures up to ~100 mbar (close to the triple point allowing liquid N₂ or CH₄ on the surface) have also been suggested but require extreme conditions including large and very dark volatile ice deposits covering Pluto's poles and low thermal inertia. These changes in surface pressure and trace gas abundance over time also impact photochemistry, haze and cloud amounts and composition, and therefore thermal structure and surface contamination.

Origin and Relation to Other Kuiper Belt Objects

Once thought to be an escaped satellite of Neptune (but we now know, it is impossible for Pluto to originate from a planet that it never approaches), the true place of Pluto in the solar system was revealed by the discovery of the Kuiper Belt from 1992 onward. Many resonant objects have been discovered (about 30% of the trans-Neptunian population); those located in the 3:2 resonance have been termed “Plutinos.” According to a popular model known as the “Nice model,” the overall structure of the Kuiper Belt results from mutual interactions between an initially massive and “cold” disk (i.e., bodies with low eccentricity and low inclination orbits) of planetesimals and the migrating giant planets. The initial Kuiper disk may have contained ~30 Earth masses and have harbored a thousand of Pluto-sized bodies. Neptune's outward migration may have involved a brief chaotic phase that expelled most of the planetesimals from the disk, leaving a Kuiper Belt of only ~0.03 Earth masses. Subsequent and gentler migration of Neptune would then have captured “cold” objects into mean motion resonances. While Pluto satellite system is particularly rich, multiple systems are common (~15%) in the Kuiper Belt.

Finally, it should be noted that, for both its atmosphere and surface, Pluto shows a clear similarity with Neptune's satellite Triton. Triton's atmosphere, as revealed by Voyager 2, is also very tenuous, nitrogen dominated with some traces of methane. Near-infrared spectra of Triton show that the ice composition, at its surface, is

very similar to that of Pluto. This goes along with dynamical arguments that indicate that Triton is a Kuiper Belt object captured by Neptune.

Cross-References

- ▶ [Charon](#)
- ▶ [Dwarf Planet](#)
- ▶ [IAU](#)
- ▶ [Kuiper Belt](#)
- ▶ [Orbit](#)
- ▶ [Trans-Neptunian Object](#)
- ▶ [Triton](#)

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PNA

Peter E. Nielsen
The Panum Institute, ICMU, University of
Copenhagen, Copenhagen, Denmark

Keywords

Genetic material · Nucleic acids · Peptides ·
Replication

Synonyms

[Peptide nucleic acids](#)

Definition

Peptide nucleic acid (PNA) is a DNA mimic that was first described in 1991. Although it is chemically remote from natural ▶ [nucleic acids](#) like DNA, being based on a pseudo peptide backbone

with pendant nucleobases, it is an effective structural DNA mimic capable of forming stable Watson-Crick sequence complementary duplexes with DNA, RNA, or itself. Furthermore, its chemical structure is uncharged, achiral, and based on “simple” chemistry being compatible with primordial (Earth and meteorite) conditions. Thus, it may be speculated that PNA type of (genetic) informational molecules could have preceded ► [RNA](#) in prebiotic evolution of life.

Overview

It is often hypothesized that our contemporary life based on DNA, RNA, and protein through the “central dogma” was preceded by a primordial life-form based solely on RNA being both the genetic material and providing enzymatic (catalytic) activity (the ► [“RNA world”](#)), and that this RNA world subsequently evolved into contemporary life by introduction of proteins and DNA. However, due to the very limited stability of RNA as well as lack of robust prebiotic synthesis routes for RNA precursors (in particular ► [ribose](#)), it is difficult to imagine how RNA molecules could have formed on the primitive Earth and how they would have survived long enough to allow creation of life. Thus, the idea of a pre-RNA life based on a more stable and prebiotically compatible genetic material has been entertained by many researchers. PNA is an example of one such material. It is extremely stable, precursors have been found in “prebiotic soup” experiments as well as in meteorites, and PNA is able to communicate genetic information with both RNA and DNA via Watson-Crick duplex formation. Furthermore, simple model experiments have demonstrated that chemical PNA replication as well as PNA to RNA transcription type processes may take place. So far, we are lacking evidence that a PNA world and a PNA to RNA world transition did take or even could have taken place at the early stages of the origin of life, but the data should encourage further experiments to investigate the (chemical) feasibility such a scenario. Indeed, a prerequisite for a

“PNA world” – in analogy to the RNA world hypothesis – would be the discovery of catalytically active PNA oligomers (“PNazymes”), which might have driven metabolic and replication life processes, and upon which evolutionary selection could have operated.

Cross-References

- [Nucleic Acids](#)
- [Origin of Life](#)
- [Ribose](#)
- [RNA World](#)
- [Prebiotic Chemistry](#)

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PO

- [Phosphorus Monoxide \(PO\)](#)

Polar Axis

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Rotational axis](#)

Definition

The polar axis of a planet is its axis of rotation. It is perpendicular to the planet's equatorial plane. The inclination of the Earth's polar axis with respect to the plane of its orbit about the Sun is responsible for the phenomenon of seasonal variations. Telescopes with an equatorial mount have one axis, also called the polar axis, which is parallel to the Earth's rotation axis. The slow (26,000 year period) conical motion of the Earth's polar axis is responsible for the ► [precession](#) of the equinoxes.

Cross-References

- [Precession](#)
- [Rotation Planet](#)
- [Rotational Velocity](#)

Polar Caps (Mars)

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, Paris, France

Definition

The Martian polar caps are layers of water ice or ► [carbon dioxide](#) ice accumulated in the Martian polar regions because of the cold polar temperatures. Several distinct objects may be labeled "polar caps" on ► [Mars](#). (1) The ► [polar layered deposits](#), made of ice and sediments, accumulated at both poles to a

depth of several thousand meters and about 1,000 km in diameter. (2) The northern water frost, a layer of relatively pure water ice interacting with the atmosphere and covering the northern layered deposits. (3) The perennial southern ice cap, about 400 km across near the south pole and composed of carbon dioxide ice several meters thick sitting upon a substrate of water ice (the rest of the southern polar deposits is covered by dry sediments). (4) The seasonal polar caps, a layer of carbon dioxide ice a few tens of centimeters thick covering both Mars high latitude in fall, winter, and spring.

Cross-References

- [Carbon Dioxide](#)
- [Mars](#)
- [Polar Layered Deposits \(Mars\)](#)

Polar Layered Deposits (Mars)

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, Paris, France

Definition

The polar layered deposits are landforms made of thousands of layers of ice mixed with a few percent of mineral sediments that have accumulated over more than 3,000 m in thickness and 1,000 km in diameter at both poles of ► [Mars](#). These deposits are thought to preserve a record of the seasonal and climatic cycling of atmospheric CO₂, H₂O, and dust over millions of years. It has been speculated that a liquid water ► [Habitat](#) could form at high pressure and temperature at the base of the deposits. However, radar sounding has not confirmed this hypothesis.

Cross-References

- [Habitat](#)
- [Mars](#)
- [Polar Caps \(Mars\)](#)

Polar Molecule

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A Polar Molecule possesses a permanent electric dipole moment and, therefore, in the gas phase has allowed electric dipole transitions between its rotational energy states. Most molecules observed in space have their rotational transitions in the millimeter and submillimeter domains.

Cross-References

► [Apolar Molecule](#)

Polar Motion

► [True Polar Wander, Theory of](#)

Polar Shift

► [True Polar Wander, Theory of](#)

Polarized Electron

Jun-ichi Takahashi

Faculty of Engineering, Yokohama National University, Yokohama, Japan

Synonyms

[Spin-polarized electron beam](#)

Definition

Polarized electrons can be defined as an electron ensemble in which the average of the spin angular

momenta of the electrons is distributed in a specified direction (spin-polarized electrons). The typical spin-polarized electrons existing in nature are beta ray electrons from radioactivity decay of elements. The spin of electrons in beta rays is longitudinally polarized due to parity non-conservation in the weak interaction mediated by charged W particles.

In general, the helical behavior of energetic quantum beams can be characterized with “helicity,” that is, the spin angular momentum projection onto the kinetic momentum direction. The spin of beta ray electrons is polarized to the opposite direction of the beam propagation; that is, the helicity of beta electrons is $-1/2$. Expressing positive spin vector as a right-hand helix, positive helicity electrons correspond to right-handed and negative helicity to left-handed symmetries, by analogy to right- and left-handed circularly polarized light.

From the standpoint of astrobiology, one of the hypotheses for the origin of biomolecular chirality is called the “cosmic scenario.” In this scenario, asymmetric energy sources in space, such as beta rays, induced asymmetric chemical reactions of precursors in interstellar dust, resulting in the enantiomeric excess of terrestrial bioorganic compounds.

Cross-References

► [Beta Rays](#)
► [Enantiomeric Excess](#)

Polarized Light and Homochirality

Louis d’Hendecourt

Institut d’Astrophysique Spatiale, Université Paris-Sud 11, Orsay Cedex, France

Keywords

Circular dichroism · Enantioselectivity · Linearly and circularly polarized light · Optical activity

Definition

Natural light is composed of an oscillating electromagnetic field traveling in vacuum at a speed of c . It can thus be represented by a wave vector k indicating its direction of propagation, to which are associated two perpendicular vectors, the electric (E) and magnetic (B) fields, each oscillating at the frequency of the wave, and both at right angles from k . Natural light is not polarized, that is, the E vector orientation and amplitude are random. If the electric vector is always in the same plane, the light is said to be linearly polarized. If it rotates around its axis of propagation, with constant amplitude, the light is said to be circularly polarized with two possible helicities, right or left, compared to the direction of the wave vector k . Ultraviolet circularly polarized light (UV-CPL) is suspected by some to be at the origin of enantioselectivity of chiral molecules, an idea originally proposed by Louis Pasteur as early as 1848.

History

Although the proper description presented above dates back to Maxwell with his theory of electromagnetism (1864), the idea that light behaves as a wave, as opposed to a collection of particles (Newton and later Einstein) had been discussed at length by Huygens. Following the famous interference fringes and diffraction experiments from Fresnel and later Young, most if not all the physicists of the nineteenth century admitted the theory of light waves. Polarization was well known at the time of Pasteur, especially linear polarization, a relatively easy to observe phenomenon. It was noted that some substances are able to rotate the plane of polarization when they are traversed by linearly polarized light. Schematically, Pasteur discovered that some “living” substances, molecules extracted from living organisms, systematically deflect the plane of polarization to the left. Abiotic substances of the same nature do not deviate at all this plane. In physics, this is explained by the symmetry of the chiral molecule responsible for the effect, where the term chiral refers here to organic molecules containing an

asymmetric carbon, a carbon whose four valences are bonded to different molecular subgroups. Most amino acids are chiral. Abiotically synthesized amino acids are generally racemic (composed equally of left- and right-handed molecules). In living systems, they are mostly homochiral, and left-handed, a property noted by Pasteur that he attributed at the time to “unknown forces at work in the cosmos,” somehow linked to the origin of life.

Overview

Although many ideas have been proposed to explain ► [homochirality](#) with a deterministic origin (Bonner 1991), the most commonly cited is the interaction of UV-CPL with asymmetric (chiral) organic molecules (Bailey 2001). Indeed, this can be simply understood by considering the reverse effect observed by Pasteur. If polarized light can turn its polarization plane while passing through a homochiral assembly of molecules, an action called optical activity, the reverse, obtaining an enantiomeric excess while passing UV-CPL through a racemic mixture, must be true. This refers to Curie’s Principle (Curie 1894) who was the first to coin this term “chiral photons” or “racemic light.” At a molecular level, asymmetric molecules are known to possess a property called circular dichroism, which ensures that a given molecule (e.g., a left or right enantiomer) reacts differently when submitted to UV-CPL with L or with R helicities. Thus, interaction of UV-CPL with chiral molecules may help enantioselective processes to obtain nonracemic molecular materials. To be meaningful for prebiotic chemistry, a scenario has been proposed in which interstellar organic molecules are illuminated by UV-CPL radiation that exists in some places in space (Cronin and Risse 2006; Meierhenrich 2008). Selection of one enantiomer (L) over the other (D) is certainly possible in astrophysical environments, since some amino acids in meteorites display slight enantiomeric excesses (e.e.) only of the L form. Amplification to homochirality (Soai et al. 1995) is considered as a viable and common phenomenon, as even a slight enantiomeric excess

(around 1%) is able to start this amplification. Thus, UV-CPL experiments on amino acids have shown since 1974 (Balavoine et al. 1974) that asymmetric photolysis can create some excesses, and more recently this effect has been confirmed in the solid state (Meierhenrich et al. 2005). For a valid astrophysical application, these experiments have been transposed to photochemical simulations on interstellar “dirty” ices using UV-CPL from a synchrotron radiation beam to obtain non-racemic amino acids. These difficult experiments, up to now inconclusive, are still under development (Nuevo et al. 2006). Recently, these experiments on analogues of dirty interstellar ices have succeeded to produce a significant enantiomeric excess in one amino acid, alanine, the sign of which (L or D) changing with the helicity of the UV-CPL is used at the beamline DESIRS of the SOLEIL synchrotron (France). This result, described by de Marcellus et al. (2011), gives some support to the idea that interstellar molecules such as amino acids of a given enantiomeric excess (L, such as the ones found in meteorites) may have seeded the Earth, prior to the onset of homochirality. This scenario is still in the making with running experiments now dedicated to sugars.

Cross-References

- [Amino Acid](#)
- [Asymmetric Reaction, Absolute](#)
- [D/L-Ratio](#)
- [Homochirality](#)
- [Polarized Electron](#)

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Polycistronic Transcript

- [Operon](#)

Polycyclic Aromatic Hydrocarbon

Els Peeters and Jan Cami
Department of Physics and Astronomy &
Institute for Earth and Space Exploration,
The University of Western Ontario, London,
ON, Canada
SETI Institute, Mountain View, CA, USA

Keywords

Infrared emission features · Infrared · Ultraviolet · Radio · Spectroscopy · Interstellar chemistry · Interstellar medium · Molecules in space · DIBs

Synonyms

PAH

Definition

Polycyclic aromatic hydrocarbons (PAHs) are organic molecules containing two or more fused ► [benzene](#) rings that are arranged in a honeycomb structure with hydrogen attached to the edges of the molecule. When used in the context of astrophysical research, the term “PAHs” often refers to a broader class of related molecules, including fully or partially hydrogenated or dehydrogenated PAHs, and chemically modified PAHs where one or more hydrogen or carbon atoms are replaced by another element (e.g., nitrogen) or metallocomplexes.

Overview

Polycyclic aromatic hydrocarbons (PAHs) are a large class of organic molecules containing – strictly speaking – only carbon and hydrogen. On Earth, they are found as tarry materials that are naturally present in, for example, coal and crude oil. They are formed by combustion processes of many carbonaceous substances and are thus also found in auto exhaust, candle soot, and tobacco smoke. Although some PAHs are used in medicine, public awareness of PAHs is most often raised because of their known carcinogenic properties and their long-term stability, which thus implies a persistent detrimental effect on their environment, for example, when present in soil.

In space, PAHs are observed at high abundances in our ► [Milky Way](#) galaxy wherever ultraviolet radiation is present, and they pervade the universe far beyond, as is clear from their detection in galaxies at high ► [redshifts](#). PAHs are primarily observed through their emission features at infrared wavelengths – the so-called → unidentified infrared (UIR) bands – that dominate the infrared (IR) spectra of almost all environments, including the ► [interstellar medium](#) (ISM), ► [reflection nebulae](#), star-forming regions, evolved stars, and entire galaxies. No less than

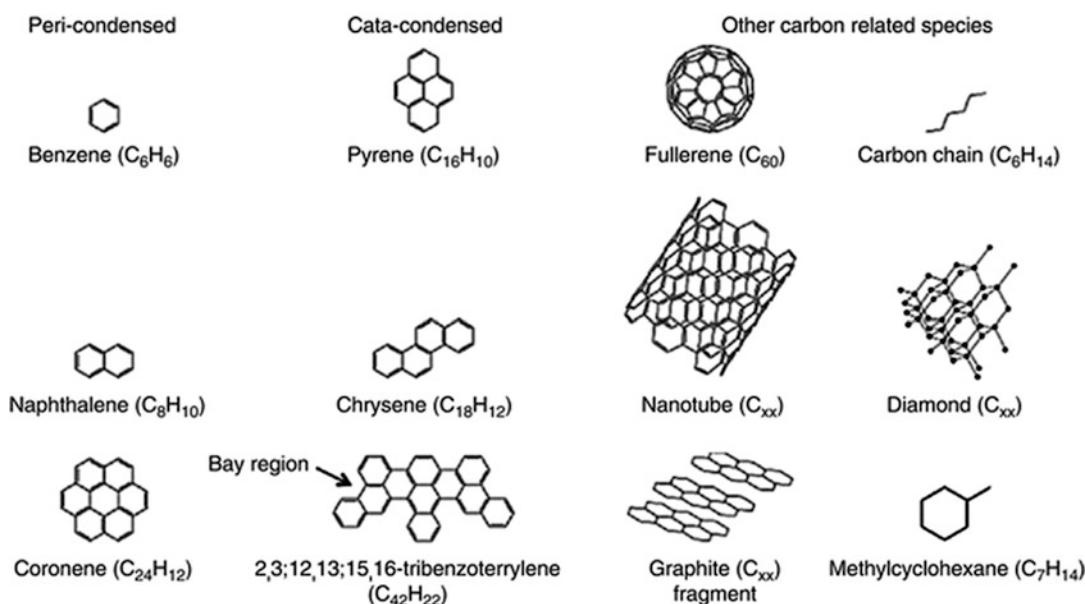
20–30% of the galactic IR radiation is emitted in these PAH bands, and it is estimated that about 10% of the cosmic carbon is locked up in these molecules. PAHs thus represent a large class of complex ► [molecules in space](#).

PAHs form in the outflows of evolved and dying carbon-rich stars and are further processed as they voyage out to the ISM and become part of protostellar environments. In addition, PAHs can also form in the ISM. Given their large abundance, their stability, and their presence in these diverse environments, it is clear that they play a crucial role in many physical and chemical processes in circumstellar and interstellar media. Furthermore, their strong IR emission features are easily observed and show subtle variations in their spectral appearance that depend on various parameters. PAHs are thus ideal tools to probe the environmental conditions in a wide range of astronomical objects.

There is an extensive body of literature about PAHs in astrophysical environments; we refer in particular to the reviews by Allamandola et al. (1989), Puget and Léger (1989), Tielens (2005, 2008, 2021), the proceedings: “PAHs in the Universe” (2011; further referred to by JTPAHs), Li (2020), and Peeters et al. (2021).

Structure

The ability of carbon atoms to have four chemical bonds allows them to form complex structures. Carbon atoms can be configured into planar hexagonal rings – benzene rings – where each carbon atom is bound to three neighboring atoms (either C or H) by covalent σ -bonds (Fig. 1). These bonds result from overlapping sp^2 -hybridized orbitals in the same plane, and thus, a planar molecular structure results. The remaining six electrons (one belonging to each carbon atom) in a benzene ring correspond to p orbitals that have lobes perpendicular to this plane. Overlap of these orbitals then results in a delocalized π -bond with molecular orbitals above and below the plane of the molecule. Such a configuration is called an aromatic bond. Hydrocarbon molecules that do not contain aromatic bonds are called aliphatic compounds.



Polycyclic Aromatic Hydrocarbon, Fig. 1 The chemical structure of benzene, some cata- and peri-condensed PAHs, and other forms of carbon and PAH-related species.

A bay region is indicated, and irregular PAHs are exemplified by 2,3;12,13;15,16-tribenzoterrylene ($C_{42}H_{22}$; adapted from Boersma 2009)

Benzene rings are then the basis for much larger molecules that are composed of several fused rings and therefore called polycyclic. If these polycyclic molecules contain only carbon and hydrogen, they are called polycyclic aromatic hydrocarbons (PAHs, chemical definition). Some chemical modifications might be common in astrophysical environments and change the molecular and spectral properties. For example, when a hydrogen atom is replaced by deuterium, the deuterated PAHs are sometimes called PADs. A PAH molecule where one or more carbon atoms are replaced by nitrogen is a polycyclic aromatic nitrogen heterocycle (PANH).

PAHs are thus a large family of different molecular species with a similar (honeycomb-like) structure. The PAH molecules themselves can be used for even larger structures. PAH platelets are stacks of PAH molecules ordered in parallel layers; PAH clusters contain several PAHs in various ordered configurations. ► [Amorphous carbon](#) is then a random combination of PAH platelets and PAH clusters.

Note that in an astrophysical context, the term “PAHs” is not only used to refer to the strict

chemical definition of PAHs but also includes PAH-like species such as, for example, PAHs in which an H is substituted by D or a functional group and PAHs in which an atom is replaced by another atom, metallocomplexes, etc. Also, there are many other molecular species made of carbon, such as carbon chains, ► [fullerenes](#), nanotubes, ► [\(nano-\) diamond](#), etc. (see Fig. 1), and many of these exist in space.

Basic Methodology

At astronomical distances, we can only study PAHs through their interaction with electromagnetic radiation. PAHs exhibit electronic transitions in the ultraviolet (UV) and at optical wavelengths, but the presence of PAHs in space is thus far primarily established through their bright emission at IR wavelengths where they have strong vibrational transitions. Some PAHs have pure rotational transitions at radio wavelengths, and indeed, two small PANHs and a pure PAH have recently been detected at radio wavelengths (see below).

Infrared Spectroscopy of PAHs

Given the emphasis on the IR characteristics of PAHs, a good understanding of the fundamentals of ► [infrared molecular spectroscopy](#) is in place here.

The energies associated with the vibrational motions between the atoms that make up a molecule are quantized and are such that the transitions between two vibrational levels occur at IR wavelengths. A molecule composed of N atoms is characterized by a unique set of $3N - 6$ allowed vibrational modes (and thus a unique IR spectrum), which allows astronomers – at least in principle – to identify specific molecules by means of IR spectroscopy. Moreover, the bandwidths and intensity ratios between different vibrational bands depend on various parameters (e.g., temperature, density); thus, the IR spectra of molecules contain information on the physical properties of the environments in which they reside. This makes IR molecular spectroscopy a very powerful tool.

However, there is a complicating factor when dealing with collections of large molecules that have a similar structure, such as PAHs. In that case, certain vibrational modes are present in each species. This is typically the case for stretching modes (where the vibrations correspond to changes in bond length between two atoms) and bending modes (where the bond angle between two atoms changes) involving only C and H atoms. The energy required to excite, for example, the C-H stretching mode is similar in all PAH molecules, and thus all PAHs will have a C-H stretching transition at nearly the same wavelength. Although each species in the set will still have its own unique vibrational spectrum, the features due to the common modes will overlap. Typically, a combined spectrum then has strong features where these common modes overlap, but the weaker features that are specific to individual molecules are washed out.

The Unidentified Infrared (UIR) Bands

In the early 1970s, new IR instruments on ground-based and airborne telescopes revealed broad emission features at 3.3, 6.2, 7.7, 8.6, and 11.2 μm in ► [planetary nebulae](#), star-forming

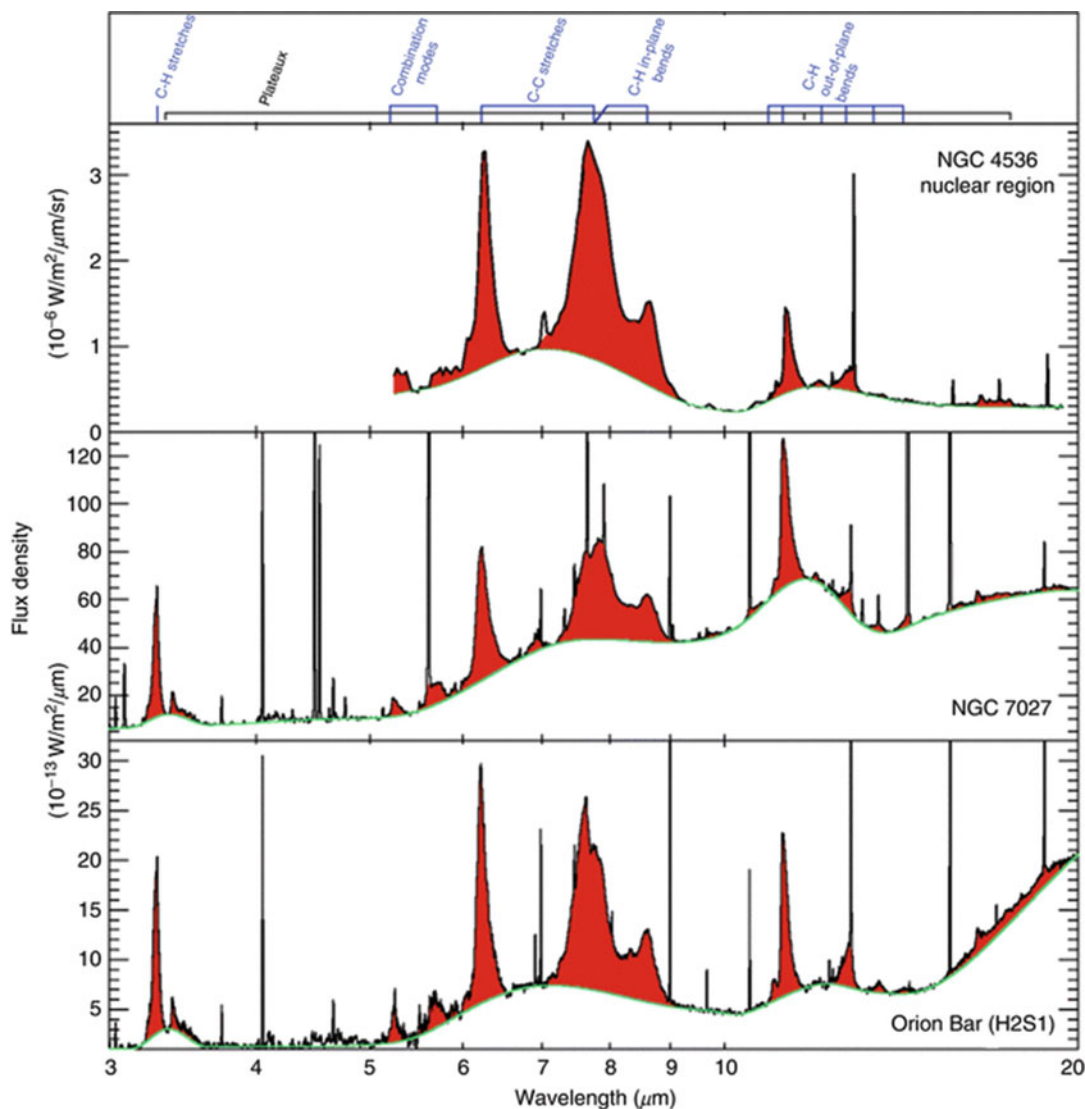
regions, and ► [reflection nebulae](#) (Fig. 2). Since the carriers of these features remained unknown for almost a decade, they were dubbed the unidentified infrared (UIR) bands, a name still in use today.

In the past two decades, the unprecedented views of the IR universe offered by the ► [Infrared Space Observatory](#) (ISO) and the ► [Spitzer Space Telescope](#) showcased the spectral richness of the UIR spectrum. Observations with these facilities and ground-based telescopes revealed additional weaker bands (at 3.4, 3.5, 5.25, 5.75, 6.0, 6.6, 6.9, 7.2–7.4, 8.2, 10.5, 10.8, 11.0, 12.0, 13.5, 14.2, 15.8, 16.4, 16.6, 17.0, 17.4, and 17.8 μm) perched on top of broad emission plateaus (at roughly 3.2–3.6 μm , 6–9 μm , 11–14 μm , and sometimes 15–20 μm); these weaker features are apparent in some – but not all – astronomical objects. A band at 19 μm was at one point considered to be part of the PAH spectrum; however, it shows a different spatial distribution than the PAH bands in the reflection nebula NGC 7023 (Sellgren et al. 2007) and is now generally assigned to C_{60} (Cami et al. 2010; Sellgren et al. 2010; see entry on ► [Fullerene](#)). The 17.4 emission feature is due to both PAHs and C_{60} .

The UIR bands have now been observed in almost all astrophysical environments where UV radiation is present, including the diffuse ► [interstellar medium](#), the edges of ► [molecular clouds](#), ► [reflection nebulae](#), young stellar objects, star-forming regions, C-rich Wolf-Rayet stars, C-rich post-AGB stars, C-rich ► [planetary nebulae](#), novae, nuclei of galaxies, normal galaxies, starburst galaxies, and ultra-luminous IR galaxies (ULIRGs) out to redshifts of ~ 4 . The carriers of the UIR bands are thus ubiquitously present throughout the universe, must be stable, and represent an important cosmic component in the astronomical mixtures of gas and dust.

The UIR Bands and PAHs

In the early 1980s, it was recognized that the UIR features coincide with the vibrational modes characteristic of aromatic materials (Duley and Williams 1981). Since then, many different carriers have been proposed, such as ► [hydrogenated amorphous carbon \(HAC\)](#), ► [quenched carbon](#)



Polycyclic Aromatic Hydrocarbon, Fig. 2 The ISO-SWS spectra of the planetary nebula NGC7027 and the photodissociation region (*PDR*) at the Orion bar and the Spitzer-IRS spectrum of the nuclear region of the galaxy NGC4536 illustrate the richness and variety of the PAH spectra (shown in *red*). Also indicated are the aromatic

mode identifications of the major PAH bands and the broad plateau emission on which the PAH bands are located. Other spectral features (not labeled) are atomic and H_2 emission lines. (Reproduced from Peeters in JTPAHs with permission from EDP Sciences)

composites (QCC), PAHs (e.g., Allamandola et al. 1989; Puget and Léger 1989) and coal, and more recently ► **nanodiamonds**, locally aromatic polycyclic hydrocarbons, and mixed aromatic-aliphatic organic nanoparticles (MAONs; Kwok and Zhang 2011). Indeed, the vibrational spectrum of almost any (purely) aromatic material can provide a global fit to the observed UIR

bands since – at the smallest scales – they have the same aromatic structure as PAHs.

However, the UIR bands are generally attributed to free aromatic molecules in the gas phase rather than to aromatic dust grains (such as HAC and QCC). This is primarily because emission at mid-infrared wavelength requires excitation temperatures of at least several hundred K, yet

the UIR bands have been detected in “cold” environments such as in ► [reflection nebulae](#) far away from the illuminating stars and in the diffuse ISM where dust temperatures are of the order of only tens of K. Furthermore, it is seen, for example, in reflection nebulae that the UIR band ratios show little variation with distance from the star. That indicates that the carriers of the UIR features can be excited to very high “temperatures” in such cold environments upon absorption of a single far-ultraviolet (FUV) photon (Sellgren 1984). This, in turn, requires the emitting species to be small. Indeed, classical 0.1 μm size grains are too large and do not become hot enough to emit at mid-infrared wavelengths in these environments; typically, sizes of the order of 10 Å are inferred (Sellgren 1984). A molecular origin is further supported by the anharmonic band profiles of several of the main UIR features and the high feature-to-continuum ratio. However, spectral variations have been observed in various environments (see below) that are not compatible with a single molecular species as carrier for the UIR bands. Thus, the general consensus is that the UIR bands originate from a family of aromatic molecules with sizes of <50–100 carbon atoms (e.g., Tielens 2005, 2008, 2021).

The physical processes that cause PAH molecules to produce the IR emission bands are relatively well understood qualitatively. Absorption of a far-ultraviolet (FUV) photon by a PAH molecule that is originally in the electronic and vibrational ground state induces a transition to an excited electronic state. The excited molecule then makes rapid isoenergetic transitions to a lower-lying electronic state, leaving most of the initial excitation energy in the form of vibrational energy. Subsequently, this highly vibrationally excited molecule cools down, mainly by IR emission in its vibrational modes. After it has cooled down, it will remain cold (~ 10 K) for a long time until it absorbs another FUV photon. For a typical interstellar (IS) PAH with 50 carbon atoms ($N_{\text{C}} = 50$; throughout this text, we will use N_{C} to denote the number of carbon atoms), photon absorption occurs once a year in the diffuse interstellar medium and every 10 min in typical

► [photodissociation regions \(PDRs\)](#) such as the Orion bar (Tielens 2005).

The main UIR bands at 3.3, 6.2, 7.7, 8.6, and 11.2 μm are then attributed to various stretching and bending vibrations involving the C-H and C-C bonds in PAH molecules with $N_{\text{C}} \approx 50$ –100. In particular, the 3.3 μm band is due to C-H stretching modes, and the 6.2 μm band to C-C stretching modes. C-H in-plane bending modes are responsible for the 8.6 μm band and coupled C-C stretching and C-H in-plane bending modes for the 7.7 μm complexes. The 11.2 μm band is caused by C-H out-of-plane bending modes. Vibrational transitions at wavelengths longward of 15 μm involve motions of the entire molecular skeleton and hence are more specific to each molecule.

Laboratory measurements and theoretical calculations indicate that the PAH molecules have low-frequency vibrational modes at far-IR wavelengths (Boersma, Joblin in JTPAHs). These low-frequency vibrational modes of PAHs are skeleton or drumhead modes sensitive to the entire structure of the molecule. Detecting these modes would further constrain the PAH population and could possibly lead to the identification of a single molecule. As these far-IR modes are intrinsically very weak (about 1% of the strong mid-IR modes, Mulas et al. 2006) and do not overlap with different molecules, they have not been detected yet.

It is important to realize that the carriers of the UIR bands may not all be “pure” PAHs (following the strict chemical definition). Stable PAH-like structures can be made, for example, by substituting one or more C atoms for N, O, or Si. Similarly, H atoms could be replaced by deuterium, by aliphatic carbon chains, or by molecular side groups. However, such substitutions leave a clear spectral imprint (see below), and spectroscopic analyses of the UIR bands in the interstellar medium show that at most 2% of the aromatic H can be substituted by methyl groups ($-\text{CH}_3$) and at most 6% by superhydrogenated PAHs (i.e., PAHs with an extra H attached to a peripheral C), both based on the strongest aliphatic emission feature observed in the interstellar medium (at 3.4 μm ; Tielens 2021).

Although the assignment of the UIR bands to vibrational modes from a collection of PAH molecules is now generally accepted, specifics of the emitting population remain elusive. This is due to the fact that the clear spectral signatures of the vibrational modes of PAHs are primarily governed by the physical conditions of the environment (which is the same for all PAHs) and show only a weak dependence on size and structure.

Electronic Transitions of PAHs

The electronic transitions of PAHs occur at UV and optical wavelengths, where the precise transition properties depend primarily on size (and somewhat on charge). Given their large abundance in the interstellar medium inferred from their infrared emission, PAHs are thus often suggested to play a role in various observational phenomena related to interstellar extinction. In particular, PAHs are at least a contributing species to the 217.5 nm extinction hump (see ► [UV Absorption Bump](#)) and are also considered as possible carriers of the ► [diffuse interstellar bands \(DIBs\)](#). They might furthermore also be responsible for the ► [extended red emission \(ERE\)](#) and the blue luminescence.

The 217.5 nm band is by far the strongest feature in the interstellar extinction curve and exhibits a fairly constant wavelength but a variable width in different lines of sight. Many individual species have been proposed as carriers of this feature, but the consensus is that this extinction hump is due to a plasmon resonance in carbonaceous material. PAHs must thus contribute to this feature. Laboratory experiments have shown that mixtures of PAHs with sizes larger than 22 carbon atoms result in a 217.5 nm hump that is as smooth as the observed interstellar hump, while mixtures of smaller PAHs exhibit many narrow features. The exact wavelength of the hump depends on the average size of the PAHs, and calculations show that an average interstellar PAH size of 50–60 carbon atoms is required to reproduce the observed peak wavelength of the 217.5 nm hump.

The DIBs are a set of hundreds of absorption lines observed from the near-UV to the near-IR

in the spectra of reddened stars (Herbig 1995; Sarre 2006). Their interstellar origin is now well established, but their carriers remain unidentified, with the exception of two strong and three weaker DIBs in the near-IR that have been recently identified as due to C_{60}^+ (Campbell et al. 2015; Linnartz et al. 2020). Many observational studies point to abundant gas-phase molecules that are able to survive the interstellar radiation field. PAHs (and especially PAH cations) are thus very promising candidates, although the same arguments could favor carbon chains and fullerene compounds. Some consensus is now growing that “normal,” pure PAHs cannot be the carriers of the strong DIBs (Cami and Cox 2014). Note that this does not exclude PAH radicals and PAH-metal complexes as DIB carriers.

Rotational Spectroscopy

Neutral PAHs generally have no permanent dipole moment, and thus, they exhibit no allowed rotational transitions. Exceptions are open-shell species (e.g., the polycyclic aromatic nitrogen heterocycles or PANHs) and nonplanar molecules (e.g., the bowl-shaped corannulene, $C_{20}H_{10}$). Also, PAH cations exhibit rotational transitions. Rotational properties have been reported for a few molecules (Tielens 2008 and reference therein) facilitating dedicated searches for these species. Recently, ► [benzonitrile](#) ($c\text{-C}_6\text{H}_5\text{CN}$; McGuire et al. 2018), 1- and 2-cyanonaphthalene (a derivative of the two-ring PAH naphthalene ($C_{10}H_8$) in which a H-atom is substituted by a nitrile ($C \equiv N$) functional group; McGuire et al. 2021), and indene ($c\text{-C}_9\text{H}_8$, Cernicharo et al. 2021, Burkhardt et al. 2021) have been detected in emission towards the molecular cloud TMC-1 constituting the first identification of individual PAH molecules in space.

PAHs might also contribute to the galactic anomalous foreground emission. This excess microwave emission at frequencies from 10 to 100 GHz has an interstellar origin and is strongly correlated with the dust IR emission. Its origin is still somewhat debated but is generally attributed to emission from spinning ► [interstellar dust grains](#) (Draine and Lazarian 1998). The

anomalous emission can be well reproduced by theoretical models of spinning PAHs that adopt PAH properties that are in good agreement with those derived from their mid-IR emission (Ysard et al. 2010).

PAHs in the Solar System

For completeness, we note that PAHs have also been observed and found in situ in various objects in the Solar System (e.g., ► [meteorites](#), interplanetary dust particles, ► [comets](#), ► [Titan](#)).

Key Research Findings

Characteristics of the Astronomical PAH Family

We have learned most of what we know about PAHs in space from detailed analyses of their IR emission features – the UIR bands. The UIR bands observed in a large variety of environments are remarkably similar, and in first order, a generic UIR spectrum emerges. Detailed observational studies, however, have revealed a multitude of spectral variations in peak positions, shapes, and (relative) intensities from source to source, and also spatially within extended sources. The interpretation of the UIR bands and these spectral variations is strongly based upon theoretical and experimental spectroscopy of PAHs and related species. Laboratory experiments and theoretical models reveal how PAH spectra change as a function of parameters such as temperature, charge, size, and the precise molecular (edge) structure. This information can then be used to determine the cause of the observed spectral characteristics in astronomical observations. This comparison uncovers some properties of the astronomical PAH family, as well as their relation to specific environmental parameters.

Distribution and Abundance

As is unequivocally evident from the observations, PAHs pervade the universe: they are found in almost all sources with associated gas and dust within our ► [Milky Way](#) and in many galaxies near and far (up to a redshift of ~ 4). Exceptions are regions with extreme radiation fields or fast

shocks, since PAH molecules cannot survive in these environments, and regions well shielded from UV radiation, as in the dense interiors of molecular clouds where PAHs get frozen into the ice mantles on the grain surfaces. Furthermore, the UIR bands generally dominate the IR spectra of these sources. The total emitted power in all the UIR bands combined ranges from a few percent to about 10% of the total power budget of galaxies. Hence, PAHs are very abundant in space: for a typical PAH size of 50 carbon atoms, the total PAH abundance by number is $\sim 3 \times 10^{-7}$ relative to the number of hydrogen atoms (Tielens 2005).

Charge State

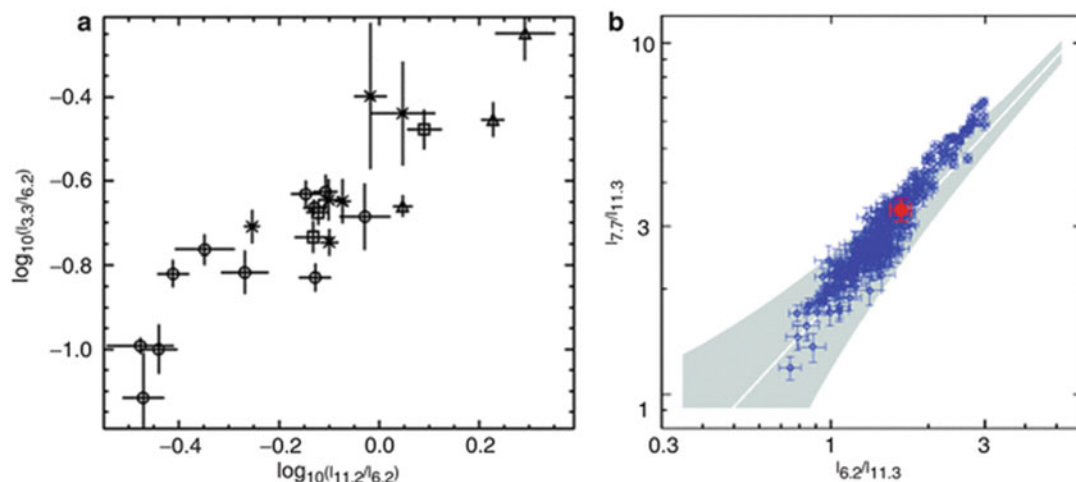
One of the early pivotal results of the laboratory and theoretical studies on PAHs is the remarkable effect of ionization on the infrared spectra. While peak positions are only modestly affected, the influence on intensity is striking: the C-C bands in the 5–10 μm regions grow from the smallest features to become the dominant bands upon ionization. Although anions and multiply charged large PAHs are less studied, they exhibit a similar increase of emission in the C-C modes in the 5–10 μm regions relative to the C-H modes at 3.3 and 11.2 μm .

The corresponding C-C and C-H modes of the UIR bands do show strong variations in their relative strengths from source to source, and even within extended sources, suggestive of changes in the charge state of the astronomical PAHs (Fig. 3). The CH out-of-plane bending modes, however (in the 10–15 μm regions), do not behave consistently: the 12.7 μm PAH band correlates well with the 6–9 μm modes and not with the 11.2 μm PAH.

Note that several other parameters may influence the observed C-C/C-H intensity ratio; however, several studies indicate that changes in the degree of ionization of the PAHs are the main factor in these different environments (e.g., Hony et al. 2001; Galliano et al. 2008).

Chemical Composition

The PAH band profiles show pronounced variability, in particular for the C-C modes (6.2 and 7.7 μm bands). These variations define four



Polycyclic Aromatic Hydrocarbon, Fig. 3 (Left) The correlation of the 3.3 and 11.2 μm band strengths normalized to the 6.2 μm band strength. Circles are HII regions, stars intermediate mass star-forming regions, squares are reflection nebulae, and triangles are planetary nebulae (Hony et al. 2001; reproduced with permission © ESO). (Right) The variation in the C-C/C-H band ratios (see

Fig. 2) within the starburst galaxy M82. The gray-filled area represents the correlation obtained for the integrated spectra of a large sample of galactic and extragalactic sources. The red symbol is the value of the global measurement over the entire galaxy. (Galliano et al. 2008, reproduced by permission of the AAS)

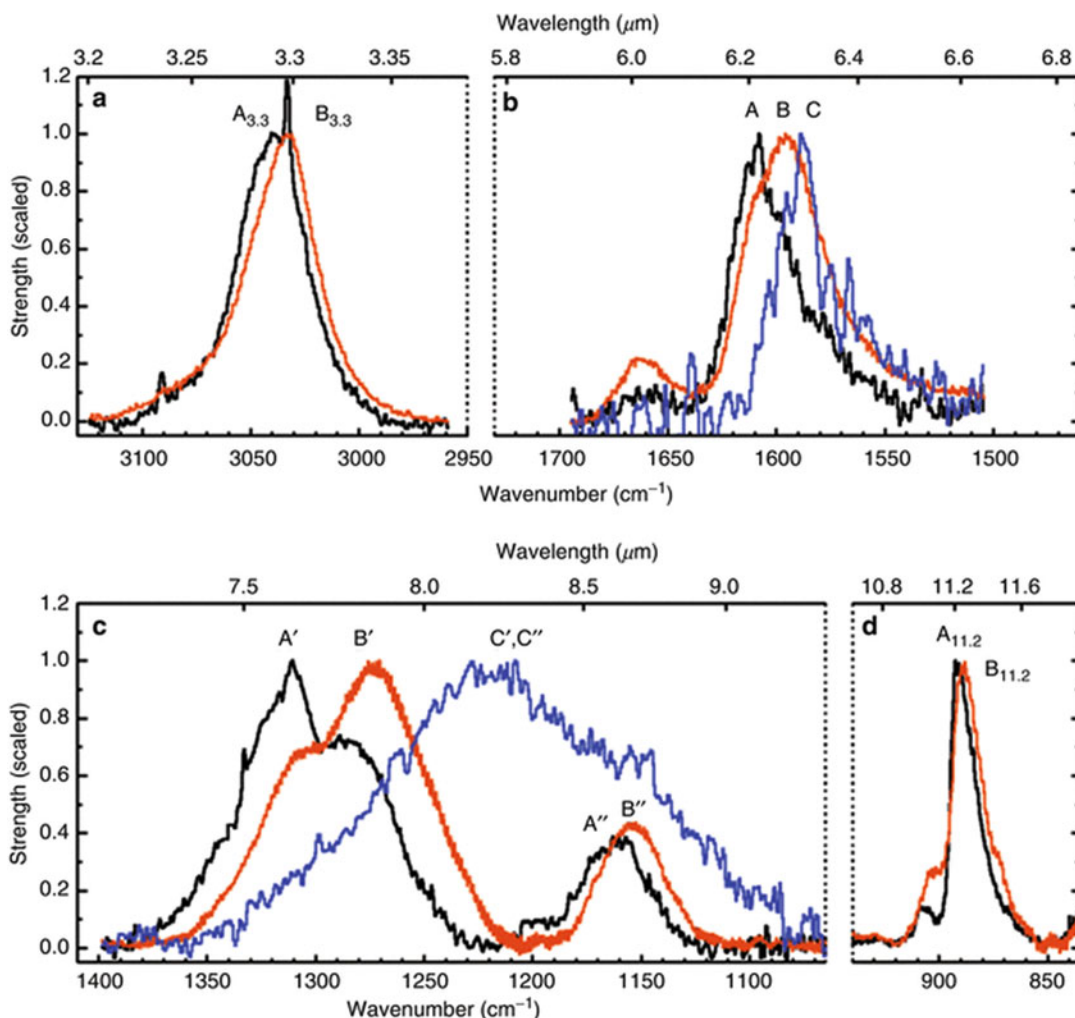
classes, A, B, C, and D (Fig. 4; Peeters et al. 2002; van Dienenhoven et al. 2004; Matsuura et al. 2014), each having different band profile characteristics. Class A and B sources show the “classical” UIR features at 6.2, 7.7, and 8.6 μm , but class B profiles are slightly redshifted compared to class A. Moreover, the 7.7 μm complex has a dominant 7.6 μm component in class A sources while class B sources show a dominant component in this complex peaking between 7.8 and 8 μm . Class C and D band profiles are significantly different from classes A and B: they show a very broadband peaking at $\sim 8.2 \mu\text{m}$ and $\sim 7.8 \mu\text{m}$. Class A and C sources show little variation in their profiles at these wavelengths, moderate variations are present within class D while large differences are present within class B. The observed variations in the UIR spectra seem to span a continuous distribution going from class A via class B to class D and C.

Although several properties could in principle determine the precise peak positions of the C-C stretching bands, a strong constraint is offered by the fact that the position of the 6.2 UIR band in

class A sources cannot be reproduced by the C-C stretching mode of pure PAHs (Peeters et al. 2002; Hudgins et al. 2005) using the currently available laboratory and theoretical data. The observed variations in the band profiles thus seem to reflect a (chemical) modification of the PAHs. Various PAH-related species have been proposed:

- PANHs: substitution of a C atom by an N atom in a PAH systematically shifts the position of the strongest C-C stretching mode toward shorter wavelengths while having no systematic effects or shifts on the position of other vibrational modes.
- Aromatic-aliphatic carbonaceous species with different degree of aromaticity (see below).
- PAH clusters: for example, PAH dimers and trimers.
- PAH-metal complexes: these are species in which a metal atom is located either below or above the carbon skeleton.

Additionally, structural modifications to PAHs may also involve the H atoms and include:



Polycyclic Aromatic Hydrocarbon, Fig. 4 An overview of the source-to-source variations in the position and profile of the main UIR bands in four wavelength bands. Large variations are evident in the 6–9 μm regions. Class A peaks at the shortest wavelengths and class B at

longer wavelengths. The C-C modes of class C peak at even longer wavelengths. (Peeters et al. 2002; van Dienenhoven et al. 2004, reproduced by permission of the AAS)

- Superhydrogenated and protonated PAHs: These PAHs contain peripheral C atoms bonded to two hydrogen atoms. Hence, these species have aliphatic CH bonds which emit near 3.4 μm (Fig. 2). This band is observed in many sources but is generally weak. Also, emission at this wavelength may be due to methyl side groups attached to PAHs.
- Deuterated PAHs: Peeters et al. (2004c) and Doney et al. (2016) detected weak emission bands at 4.4 and 4.6–4.8 μm , characteristics

of the C-D stretching mode in PADs and D_n -PAHs in 7 star-forming regions. While the aromatic C-D stretch is very weak, the derived D/H ratio for the aliphatic bands is very large compared to simple molecular species, suggesting that deuterium fractionation is very specific. However, many star-forming regions do not exhibit emission in these modes, implying that conditions necessary for deuteration are not common in the ISM. Nevertheless, the presence of deuterated PAHs can

still contribute to the observed variations in the gas-phase D/H ratios for different lines of sight.

- Side groups: Hydrogen can be replaced by chemical side groups. The most important one is methyl group ($-\text{CH}_3$), which causes a spectral signature of $3.4\text{ }\mu\text{m}$ (Fig. 2).
- Molecular edge structure (see below).

Size

When a PAH molecule absorbs a UV photon, the absorbed energy is distributed over the vibrational modes. Since larger PAHs have many more available modes, the average energy per mode is lower. As a consequence, smaller PAHs will reach much higher levels of vibrational excitation and thus will be more conducive to emitting at shorter (more energetic) wavelengths.

Thus, the size distribution of molecules that contribute to an observed UIR band will depend on the wavelength of the band. For example, the majority of the $3\text{ }\mu\text{m}$ UIR emission is due to PAHs made up of 30 to 70 carbon atoms, while emission in the $10\text{--}15\text{ }\mu\text{m}$ region originates from much larger PAHs, with sizes between 80 and several hundred carbon atoms (Schutte et al. 1993). Clearly, the astronomical PAH family must represent a size distribution. The best probe for PAH size is the $3.3/11.2$ intensity ratio as these bands cover the largest wavelength range, which is thus most sensitive to PAH size (and thus excitation), and both bands arise from CH modes in neutral PAHs. Observed PAH sizes are between 50 and 110 C-atoms in a handful of ISM sources (Croiset et al. 2016; Knight et al. 2021).

Laboratory and theoretical studies of PAHs also show clear spectral differences between small and larger PAHs. The spectra of small PAHs are rather diverse, while larger PAHs emit more consistently at the same wavelengths. However, very large PAHs ($N_{\text{C}} > 150$) exhibit complex spectra unlike those observed in space. In addition, small changes in peak position occur with changing PAH size and contribute to the band profile variations (primarily in class A and B).

At the same time, though, the astronomical PAH family is most likely somewhat limited,

since the astronomical observations are very similar to first order and do not show the numerous variations that could be expected for millions of PAHs with all possible sorts of structures. This is also clear from the emission in the $15\text{--}20\text{ }\mu\text{m}$ regions, which is due to carbon skeleton modes and hence more molecule-specific. However, the astronomical spectra only exhibit a limited number of bands and/or a broad emission feature. This led to the grand PAH hypothesis, that is, the idea that only a few large compact PAHs dominate the PAH family (Andrews et al. 2015).

Molecular (Edge) Structure

Laboratory studies show that the peak wavelength of the C-H out-of-plane bending mode depends strongly on how much the bond is influenced by the presence of neighboring hydrogen atoms and, more specifically to the number of adjacent peripheral C-atoms bonded to an H-atom (Bellamy 1958). While the details depend slightly on the charge state of the carrier, it is clear that the 11.0 and $11.2\text{ }\mu\text{m}$ features are due to solo C-H groups (i.e., there is no adjacent C atom that is bonded to an H atom), while both duos and trios (respectively two and three adjacent C-atoms each with an H attached to them) contribute to the $12.7\text{ }\mu\text{m}$ feature. Variations in the relative strength of these out-of-plane bending modes are thus indicative of variations in the molecular edge structure of the emitting PAHs. Indeed, the solo CH groups decorate long, straight, and smooth edges, while duos and trios are characteristic of corners and irregular edge structures.

Circumstellar PAHs associated with planetary nebulae have a very strong $11.2\text{ }\mu\text{m}$ band, and a much weaker $12.7\text{ }\mu\text{m}$ band (Fig. 2) and are therefore characterized by very compact molecular structures. On the other hand, the $11.2\text{ }\mu\text{m}$ band in interstellar PAHs is about as strong as the $12.7\text{ }\mu\text{m}$ band (Fig. 2), indicating that interstellar PAHs have more corners, either because they are (on average) smaller or they are more irregular larger species (Fig. 1, Hony et al. 2001; Bauschlicher et al. 2008, 2009).

Laboratory and theoretical studies also reveal that H atoms located in a bay of the edge structure (see Fig. 1) have emission at slightly shorter

wavelengths compared to that of non-bay H's. This difference can be used to estimate the smoothness of the edge structure (Bauschlicher et al. 2009). In addition, a varying degree of bay Hs has been put forward to explain variations in the 3.3 μm band profile (Candian et al. 2012). The degree of bay Hs also influences the 7–9 μm emission (e.g., Peeters et al. 2017).

Astronomical Observations Versus PAH Databases

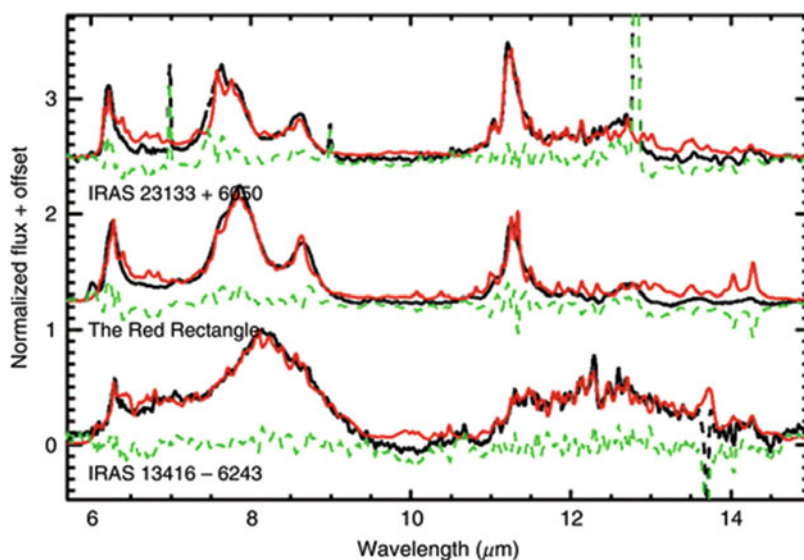
One of the strongest criticisms against the PAH hypothesis (i.e., the identification of the UIR bands with emission from PAHs and PAH-like species) has been the lack of a good match between a combination of experimental and/or theoretical PAH spectra, and the astronomical UIR spectra. This has been largely due to the limited availability of spectral properties for a large number of PAH species. Several databases now exist containing over 4000 spectra (Bauschlicher et al. 2010, 2014, 2018, Mattioda et al. 2020, <http://www.astrochem.org/pahdb/>; Mallocci et al. 2007), and good fits for astronomical observations of all three classes have been obtained (Fig. 5, Cami in JTPAHs [2011]). Spectral decomposition of the fits can be used to reveal the contribution of PAHs of different sizes, charge states, and differing compositions (e.g., Boersma

et al. 2013). Such work confirms and extends many of the conclusions discussed above.

The PAH Life Cycle

Carbon stardust is formed in the outflow of C-rich AGB stars and is believed to be comparable to terrestrial soot formation in flames – where PAHs are formed. Carbon star outflows are thus believed to be the birthplace of astronomical PAHs. Most of the carbon in these outflows is tied up in CO and C_2H_2 ($\blacktriangleright$ [acetylene](#)); chemical models then predict the formation of $\blacktriangleright$ [benzene](#), PAHs, and ultimately soot (Tielens 2008 and reference therein). There is little direct evidence of PAHs in the outflows of C-rich AGB stars though, possibly because of the absence of UV radiation from these stars. Indirect evidence, however, is provided by the ample detection of PAHs in the subsequent evolutionary stages characterized by much stronger UV radiation: the C-rich post-AGB stars, and C-rich $\blacktriangleright$ [planetary nebulae](#). Eventually, the material in these outflows becomes part of the $\blacktriangleright$ [interstellar medium](#) and conglomerates into $\blacktriangleright$ [diffuse clouds](#) that grow in size and evolve into $\blacktriangleright$ [molecular clouds](#). In the dense cores of molecular clouds, PAHs get frozen into the ice mantles covering grain surfaces. The cores of molecular clouds will eventually become proto-stars, at which point the PAH molecules are

Polycyclic Aromatic Hydrocarbon, Fig. 5 The astronomical UIR spectra (black) and the best fit PAH model spectra (red) for three types of PAH sources. Residuals are shown in green. This PAH model is able to fit all three classes. The HII region IRAS 23133 + 6050 (black) is a class A source; the Red Rectangle (red) a class B source; and the protoplanetary nebula IRAS 13416-6243 (blue) a class C object. (Cami in JTPAHs, reproduced with permission from EDP Sciences)



released into the gas phase and may be incorporated into a planetary system.

PAHs may undergo dramatic changes due to UV and collisional processing, coagulation, accretion, shattering, etc., that are associated with different phases of this life cycle. In addition, shattering of grains by shocks or UV processing of PAH clusters may form PAHs in the interstellar medium (top-down approach). Furthermore, the recent detections of small PAHs in the molecular cloud TMC-1 also suggest PAH formation in the ISM through a bottom-up approach.

There is ample observational evidence for these processes:

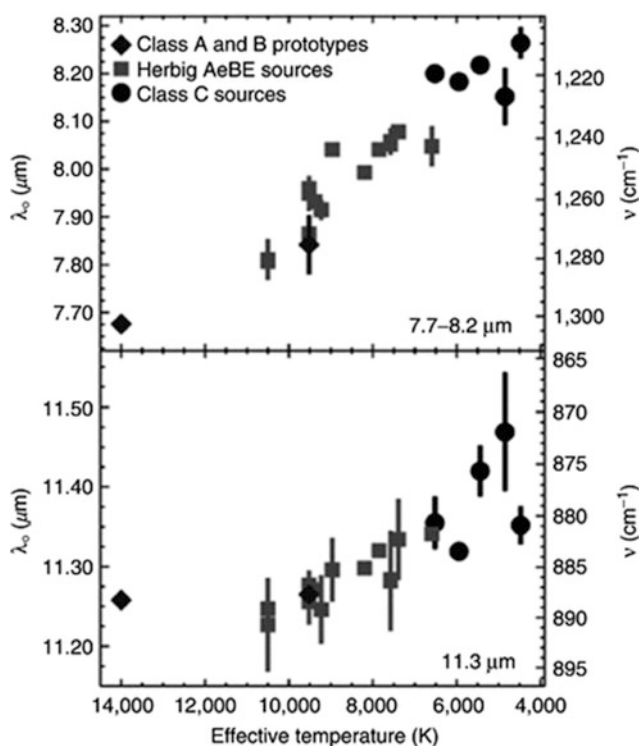
- Analysis of the spatial behavior of PAHs within extended sources reveals the photochemical evolution of the PAH family. We list a few examples here. PAHs are prominent toward the edge of PDRs but further inward the PDR (characterized by less UV radiation), larger species (such as PAH clusters) are found. These studies suggest that the destruction of PAH clusters by UV photons results in the formation of PAHs. These PAH clusters themselves may be reformed in the denser and more shielded environments of molecular clouds (e.g., Berné, Rapacioli in JTPAHs, Pilleri et al. 2012). In addition, the derived size of the PAH molecules increases with increasing FUV radiation field strength, indicating that small PAHs are destroyed in regions of high UV radiation (Croiset et al. 2016; Knight et al. 2021). Moreover, the PAH abundance decreases while the C_{60} abundance increases with increasing UV radiation field strength in NGC7023 suggesting that PAHs are converted to C_{60} under UV processing (Berné and Tielens 2015). In addition to PAH size, UV radiation also influences the charge balance and the molecular (edge) structure (e.g., Boersma et al. 2013; Peeters et al. 2017), revealing, amongst others, that different PAH subpopulations contribute to individual PAH emission bands.
- The specific profiles of the UIR bands depend directly on the type of object (Peeters et al. 2002; van Dienenhoven et al. 2004): class

A profiles represent ► **HII regions**, non-isolated Herbig AeBe stars, ► **reflection nebulae**, interstellar medium, and entire galaxies; class B contains most ► **planetary nebulae**, isolated Herbig AeBe stars, and a few post-AGB stars; and class C and D are mainly comprised of post-AGB stars. Thus, class A profiles are associated with interstellar material, while classes B, C, and D profiles correspond to circumstellar material; the differences between the classes are due to PAH processing. These spectral variations are also seen within spatially extended objects such as reflection nebulae and evolved stars (e.g., Peeters in JTPAHs, Candian et al. 2012, Rosenberg et al. 2011, and Boersma et al. 2013).

- In a sample of post-AGB stars and isolated HAeBe stars (all of PAH class B or C), Sloan et al. (2007) found a remarkable anticorrelation of the peak positions of several of the UIRs with the effective temperature of the exciting star (Fig. 6), suggesting that the components of the PAH family are susceptible to UV processing. This has been interpreted as a varying importance of aliphatics versus aromatics (e.g., Sloan et al. 2007; Boersma et al. 2008, Acke in JTPAHs, Kwok and Zhang 2011) instead of a change in size distribution of the PAH family. Aliphatic carbonaceous species are known to produce broader emission bands compared to PAHs and hence are put forward as the carrier of the class C 7.7 μm complex. An evolution to class B and then to class A is then the result of more UV processing (e.g., due to an increase in effective temperature) of these aliphatic carbonaceous species, destroying the aliphatic bonds and hence increasing the aromaticity of species. However, the observational relation does not hold in general. Indeed, several planetary nebulae and class A objects do not follow the correlation; moreover, the PAH bands of Herbig AeBe stars with the same effective temperature can belong to both classes A and B (Boersma et al. 2008). These exceptions seem to suggest that in addition to or in contrast with a dependence on effective temperature, other parameters may play a role such as, for example, the history of the material (prolonged

Polycyclic Aromatic Hydrocarbon, Fig. 6

The central wavelengths of the 7.7–8.2 and 11.3 μm UIR features versus the effective temperature of the host star. (Sloan et al. 2007; Keller et al. 2008, reproduced by permission of the AAS)



exposure to a strong radiation field in the photosphere of a disk; Tielens 2021).

- For galaxies harboring an active galactic nucleus (AGN, thought to indicate the presence of a supermassive black hole), the PAH emission differs considerably. The 6 to 9 μm emission is often suppressed relative to the 11.2 μm emission (Li 2020 and references therein). While still under investigation, this suppression has often been attributed to the preferential destruction of small PAHs by the hard radiation field of the AGN.
- For galaxies, the relative importance of PAHs with respect to dust grains in the spectra depends on the hardness of the radiation field and the ► [metallicity](#) (Li 2020 and references therein). These two parameters are related, and it is thus difficult to distinguish between an origin in a less efficient PAH formation process (since less carbon is available at lower metallicities) and increased PAH processing (modification and/or destruction of PAHs by the hard radiation field).

The Role of PAHs in Astronomical Environments

PAH Chemistry

Several chemical processes involve PAHs in the ISM. UV processing (► [photochemistry](#)) and collisional processing can significantly alter the PAH distribution (in terms of charge and size). PAHs can furthermore chemically react with abundant atoms such as H, C, N, and O. In ► [dense clouds](#), PAHs condense out onto ice mantles, and can subsequently undergo UV processing. The photo-products are later released into the gas phase by thermal heating in the star-forming environment, or in the PDRs and by shocks or cosmic-ray ► [sputtering](#). For a detailed account of PAH chemistry, see Tielens (2005, 2021), ► [Cosmochemistry](#), ► [Interstellar chemical processes](#), and ► [Interstellar Ices](#).

Photochemistry involves photoionization and photodissociation. The ionization potential of PAHs is around 6–7 eV (electron volts) and depends on the PAH size and geometry. PAHs

can be multiple ionized, but for a typical 50 C-atom PAH, the fourth positive ionization potential is larger than 13.6 eV, which limits the ionization stage in neutral hydrogen regions. Alternatively, absorption of a UV photon may lead to the loss of a H atom (dehydrogenation) or a side group. The rates for such reactions are highly dependent on the PAH size and the side group in question: for example, hydrogen loss from a methyl group is faster than aromatic hydrogen loss, which in turn is much faster than carbon loss (i.e., C_2H_2 ejection). The size below which PAHs may lose all H (because the re-hydrogenation rate is lower than the dehydrogenation rate) is estimated to be ~ 35 C-atoms. Following complete dehydrogenation, PAHs may isomerize into carbon chains, rings, or fullerenes (Zhen et al. 2014). This process removes small PAHs from the PAH family.

Collisional processing is as important as UV processing, especially for collisions with high-velocity electrons and ions originating in shocks, hot gas, and cosmic rays (Micelotta 2009). Interstellar PAHs (~ 50 C-atoms) are destroyed in shocks with velocities greater than 100 km/s. For lower velocity shocks, PAHs survive, but their structures, and thus characteristics are severely altered by the loss of carbon atoms (20–40%). In a hot gas ($T \sim 10^3$ – 10^8 K), PAHs are destroyed through consecutive C_2 loss on the periphery of the structure primarily by He collisions in low-temperature gas ($T < 3 \times 10^4$ K) and by electronic collisions in high-temperature gas ($T > 3 \times 10^4$ K). Finally, PAHs are destroyed by cosmic rays on various timescales (depending, e.g., on the collisional particle). Depending on the environment considered (and its physical conditions), different collisional processes dominate.

Gas-phase chemistry involves the following reaction types: electron recombination ($PAH^+ + e \rightarrow PAH$), electron attachment to PAHs ($PAH + e \rightarrow PAH^-$), charge-exchange reactions involving neutral PAHs ($PAH + M^+ \rightarrow PAH^+ + M$ with M a metal), mutual neutralization reaction of PAH anions with atomic or molecular cations ($PAH^- + M^+ \rightarrow PAH + M$), and reactions involving PAH cations and H, N, and O atoms.

Laboratory studies of UV processing of PAHs trapped in ice show that the processing is confined to the peripheral aromatic hydrogen and leaves the carbon skeleton intact. The aromatic hydrogen may be substituted by side groups (e.g., OH, CH_3 , COOH, CO, and CN) to form more complex organic compounds such as, for example, quinones (Bernstein et al. 1999). Some of these photoproducts are thus prebiotic molecules and may have relevance for the organic content in space. However, the importance of PAH processing in ices in actual molecular clouds is not yet established.

Shattering of solid carbon in shocks modifies the interstellar grain size distribution (Jones et al. 1996). Typical interstellar shocks may transform 10% of the solid carbon into small carbon clusters and hence provide a pathway for PAH formation in the ISM. However, faster shocks will destroy the PAHs. Currently, little observational evidence exists for PAH formation in shocks, although Rho (in JTPAHs [2011]) discerned 15–20 μm PAH emission in supernova remnant SNR N132D in the Magellanic Clouds, while Engelbracht et al. (2006) detected PAH emission associated with the superwind of the galaxy M82 and entrained by hot shocked gas.

PAH Physics

PAHs play an important role in the physics of the ISM, primarily through their influence on the charge balance and in the heating of the ISM.

The ionization balance of PAHs is set by the ratio of the ionization rate to the recombination rate, which is equal to $G_0 T^{1/2}/n_e$ in which G_0 is the far-ultraviolet (FUV; $6 \text{ eV} < \text{photon energy} < 13.6 \text{ eV}$) radiation field in units of the Habing field (see ► [Photodissociation Region](#)), T the gas temperature, and n_e the electron density (for details, see Tielens 2005, 2021). In typical interstellar conditions, several charge stages are present simultaneously, as is also indicated by the spectra attributed to PAHs. These include neutral PAHs and ionic PAHs (either cations or anions). PAH anions provide an alternative and effective recombination path for atomic and molecular cations compared to gas-phase recombination in ► [photodissociation regions](#) and ► [molecular](#)

clouds. PAHs thus influence the charge balance and – through their influence on the equilibrium state of chemical reactions – gas-phase abundances (Tielens 2005, 2021).

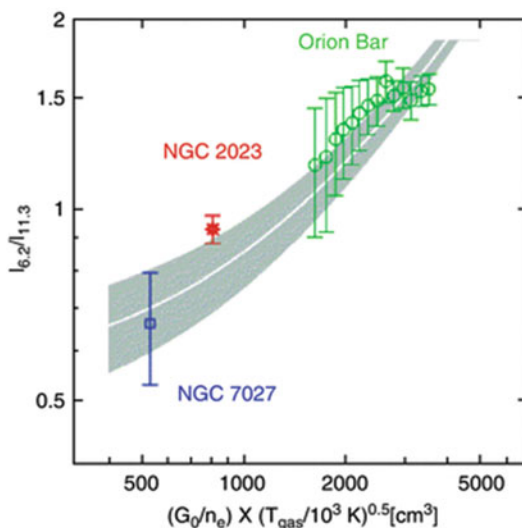
In addition, PAHs and very small grains dominate the photoelectric heating of the ISM (Tielens 2005, 2021). This photoelectric heating couples the gas energy budget with the radiation field of stars in PDRs and hence determines the physical conditions in PDRs.

Applications

The intensity ratios of the CC/CH modes of the UIR bands are determined by the charge balance of the PAHs. If variations in the physical conditions are known (e.g., derived from PDR models), the observed variations of the PAH bands can be used to establish an “empirical” calibration that relates the PAH bands to the local physical conditions. Once such a calibration is known, the physical conditions can be determined based upon the omnipresent PAH bands. This can serve as a diagnostic tool for regions where, for example, the main PDR coolants are not easily observable, such as galaxies at large distances. Such an approach has been tested on a sample of three well-studied objects and has been proven to be very promising (Fig. 7, Galliano et al. 2008). Similarly, physical conditions can be derived from combining the observed PAH ionization ratio and H₂ line ratios in dense, highly irradiated PDRs (Berné et al. 2009).

UIR emission bands are particularly bright in massive star-forming regions since they are excited by strong UV radiation. Combined with their ubiquitous appearance, this makes PAH a powerful tracer of star formation throughout the universe. PAHs are indeed widely used to derive star formation rates of galaxies (Calzetti 2020), one of the key indicators for understanding galaxy formation and evolution. In combination with emission lines, they serve as diagnostics for the physical processes powering galactic nuclei.

Finally, the presence of PAHs is used to distinguish between shocked gas and PDRs (van den



Polycyclic Aromatic Hydrocarbon, Fig. 7 Empirical calibration of the 6.2/11.2 UIR band ratio as a function of the ionization parameter, $G_0 T^{1/2}/n_e$ (Galliano et al. 2008, reproduced by permission of the AAS)

Ancker et al. 2000) and to determine redshifts in distant galaxies (e.g., Yan et al. 2007).

Future Directions

Several key questions regarding astronomical PAHs remain and require further investigations. In particular:

1. How exactly do PAH characteristics (e.g., size, charge state, chemical structure) interact with and reflect the physical conditions of their environment (e.g., density, radiation field, temperature, ► [metallicity](#))?
2. How can we use the UIR bands as a probe of the physical conditions in regions near and far?
3. Can we observe long-wavelength counterparts to the well-known mid-IR PAH bands? What are their characteristics?
4. What are the spectroscopic signatures of large PAH molecules, PAH clusters, and PAH complexes?
5. Which specific molecules make up the astronomical PAH family?

6. What can we learn from the electronic transitions of PAHs, and what is their relation to the
 ► [diffuse interstellar bands \(DIBs\)](#)?

Today, the wealth of IR PAH emission bands and the large variability of the IR PAH spectra prompt more questions than can be answered with the current experimental and theoretical data. Similarly, at optical wavelengths, there are now more observed unidentified DIBs than ever before. With the upcoming launch of the James Webb Space Telescope (JWST), we live in a golden era to address these questions from the observational perspective. Indeed, with its unprecedented combination of high spatial resolution, medium spectral resolution, and high sensitivity over the IR wavelength range of relevance for PAH research, JWST will spatially resolve the chemical frontiers where the photochemical evolution of PAHs occurs. However, if we intend to make significant progress in our understanding of the PAHs, the observational effort needs to be balanced with dedicated laboratory and theoretical studies. Indeed, we can only fully exploit the treasure trove of information that is hidden in the PAH spectra by a joint effort of the observational, experimental, and theoretical tools.

Cross-References

- [Acetylene \(C₂H₂\)](#)
- [Aliphatic Hydrocarbon](#)
- [Amorphous Carbon](#)
- [Aromatic Hydrocarbon](#)
- [Asteroid](#)
- [Benzene \(C₆H₆\)](#)
- [Cassini-Huygens Space Mission](#)
- [Comet \(Nucleus\)](#)
- [Cosmochemistry](#)
- [Diffuse Interstellar Bands](#)
- [Extended Red Emission](#)
- [Extinction, Interstellar or Atmospheric](#)
- [Fluorescence](#)
- [Fullerene](#)
- [Graphite](#)
- [Hydrocarbons](#)
- [Hydrogenated Amorphous Carbon](#)
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- [Interstellar Dust](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Metallicity](#)
- [Meteorites](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Nanodiamond](#)
- [Photochemistry](#)
- [Photodissociation Region](#)
- [Planetary Nebula](#)
- [Quenched Carbonaceous Composite](#)
- [Reflection Nebula](#)
- [Spitzer Space Telescope](#)
- [Stellar Evolution](#)
- [UV Absorption Bump](#)

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Polydeoxyribonucleic Acid

► [DNA](#)

Polydeoxyribonucleotide

► [Nucleic Acids](#)

Polygenetic Breccia

► [Polymictic Breccia](#)

Polyhedral Bodies

► [Carboxysomes, Structure and Function](#)

Polyolithologic Breccia

► [Polymictic Breccia](#)

Polymannuronic Acid

► [Alginate](#)

Polymer

Koichiro Matsuno

Nagaoka University of Technology, Nagaoka, Japan

Keywords

Catalytic cycle · Formose reaction · Oligonucleotides · Oligopeptides · Peptide cycle · Template-directed polymerization

Definition

Polymers of prebiotic significance are those to be found on the verge of the evolutionary onset of various catalytic cycles of chemical reaction. One typical example is the ► [formose reaction](#) of polymerizing formaldehyde into glycolaldehyde. When one glycolaldehyde molecule enters the cycle in the presence of formaldehyde, two glycolaldehyde molecules come out of the cycle at the end. Significant to the operation of the reaction cycle is that the synthesis of glycolaldehyde is not due to the direct dimerization of formaldehyde. The initiation of the cycle presumes the prior presence of trace amounts of glycolaldehyde. This convoluted nature of the cycle requiring the prior presence of the intended products symbolizes a difficulty facing the emergence of polymers of prebiotic significance.

Overview

One specific case demonstrating a simple cyclic, though not yet autocatalytic, polymerization of small organic molecules is found in the acceleration of polymerizing hydrogen cyanide in the presence of formaldehyde (Schwartz and Goverde [1982](#)). Under some fixed experimental conditions,

the initial rate of polymerization of HCN monomers up to an HCN tetramer is increased almost 100-fold within a very short period of time. Although the present cyclic polymerization up to HCN tetramer could be impressive especially in the respect of prebiotic synthesis of adenine, the reaction is also accompanied by a complex mixture of other products which might induce some deleterious effect on the focused reaction. The situation is almost similar to the formose reaction not yet sufficiently tailored enough to synthesize an adequate amount of ribose as the main ingredient of the backbone of RNA molecules. The difficulty comes from the interferences with other complex products available at the same time.

Destructive interferences between autocatalytic reactions in focus and the necessarily accompanied side-chain reactions can be conceivable even on a theoretical ground alone. A case in point is the peptide cycle (Kauffman 1986). It is one thing to expect an emergence of a set of autocatalytic peptides in a random mixture of amino acid molecules, while it is quite another to preserve the once appeared autocatalytic set for some indefinite period of time. If the random mixture is in thermal equilibrium, every forward reaction is counterbalanced by the reversed reaction as revealed in the principle of detailed balance. The appearance of a likely autocatalytic set, if any, is necessarily counterbalanced by its disappearance, with no net autocatalysis in the effect.

A rescue for saving the likelihood for the appearance of an autocatalytic set on an experimental ground may be sought in preparing specific initial conditions which are not in thermal equilibrium in themselves. If one can initially prepare appropriate peptides of 32-residue length that are carefully designed to self-associate to form stable coiled coils, they will facilitate the ligation of the accompanied N-terminal and C-terminal subsequences (Lee et al. 1996). The present ligation makes self-replication of peptides possible. An essence of the experimental operation of an autocatalytic peptide set is within the choice of uniquely designed initial conditions. This demonstration now invites us to face the issue of how the choice of the initial conditions can be naturalized.

One likely strategy for implementing the initial conditions is to update the experimental conditions frequently. A specific example for the present objective is the feeding experiment on the prebiotic synthesis of oligonucleotides and oligopeptides on mineral surfaces (Ferris et al. 1996). When the monomers activated by imidazole were fed successively onto the mineral surfaces (montmorillonite for nucleotides and elite or hydroxylapatite for amino acids), the formation of oligomers even up to 55 monomers long was confirmed.

Then the experimental endeavor for approaching polymers of prebiotic significance in a natural manner as much as possible will be found within how the experimental conditions could enhance their specificity as repeating their update without asking an intelligent help from the experimentalist every time in the process. Practicing this strategy exclusively on the theoretical ground is hardly conceivable because of the historical and evolutionary nature of the empirical or experimental counterpart. Even if molecular Darwinian process remains legitimate in its own light at least theoretically, one cannot rely upon the Darwinian process to figure out how self-replicating molecules could have got started. Some preliminary evolutionary process must have been in place so as to make the emergence of molecular Darwinian process tangible; otherwise the issue of the onset of self-replicating molecules would have to remain intangible.

One obvious clue for addressing how self-replicating molecules got started is sought within a reexamination of chemical reactions conceived in thermodynamics. Chemical reactions in thermal equilibrium certainly satisfy the principle of detailed balance, as implying that every forward reaction is counterbalanced by the reversed reaction as maintaining both the reactants and the products in equilibrium. No evolution could be in sight within the stipulation of detailed balance. However, once the condition of thermal equilibrium is lifted, the chemical reactions there may be set free from the theoretical stipulation of detailed balance.

Just for the sake of argument, let us imagine a reaction solution of monomers participating in their ligation and the resulting hydrolysis. If the reaction solution is in thermal equilibrium, the

population distributions of the monomers and the possible oligomers, especially their ratios, depend only upon the equilibrium constants or equivalently upon both the Gibbs free energies and temperatures, and not upon each rate constant. The situation would however be drastically changed if thermal equilibrium is not attainable. If the reaction solution happens to experience rapid decrease of its temperature as in the sudden transference from near hydrothermal vents in the ocean to the surrounding cold seawater, the likely products to remain must be the one that can survive the rapid quenching. The decisive factor for determining the likely product to survive is not the equilibrium constant, but is the rate constant measuring the extent of following the sudden temperature drops in the immediate neighborhood. Even if the material constituents remain the same, the most likely product to survive is the one whose internal configuration maximizes the rate constant for following rapid quenching. There is no chance of survival left for those products whose internal configurations fail in maximizing the rate constant for following rapid quenching. Only such an internal configuration that can be fastest in lowering its temperature as facing the rapid quenching while processing each of ligation and hydrolysis from within will win, and there is no chance left for the slower contenders.

Reaction kinetics is already selective internally in maximizing the rate constant for following rapid quenching, while the factor driving the internal selection is sudden temperature drops applied externally. Henceforth, once both the internal selection and the external driving factor are naturalized in an integrated manner, the outcome from the integration can be seen as a consequence of the selection of a natural origin even prior to the onset of Darwinian natural selection. A likely candidate for materializing pre-Darwinian natural selection on Earth could be chemical reactions riding on hydrothermal circulation of seawater through or near the hot vents in the ocean. Of course, the occurrence of hydrothermal circulation of seawater is exclusively of geological origin and totally external to biological processes and organizations. Nonetheless, chemical reactions riding on hydrothermal circulation of seawater, once happened to occur, could take advantage of pre-Darwinian natural selection.

What is specific to pre-Darwinian natural selection latent in chemical reactions riding on hydrothermal circulation of seawater is a frequent update of the reactants visiting the hot reaction spots. The reactants are only those products that could survive the rapid quenching to be experienced after visiting the hot spots the last time. It may look like a successive update of the reaction conditions in an increasingly specific manner progressively as repeating the visits, but no intelligence of external origin is involved. At the same time, how the surviving reaction products would manage the internal regulation of both ligation and hydrolysis could not be directly accessible to the external observer. Concrete factual aspects of pre-Darwinian natural selection associated with chemical reactions riding on hydrothermal circulation would have to be sought in the results of the corresponding experiments, while their actual objective and the likely target would also have to clearly be made as much as possible in advance.

One selective nature latent in the reaction solution of only monomers initially must be found in the selective scheme of the gradual buildup of oligomers through the internal regulation of both ligation and hydrolysis as repeating the cycle of heating and quenching. Further examination of the present conjecture on the selective elongation of oligomers requires consultation with a corresponding experiment. When a flow reactor simulating hydrothermal circulation of seawater equipped with rapid quenching from 250°C down to 0°C somewhere along the streamline was employed for studying elongation of glycine oligomers in the presence of copper ions, the elongation was found to proceed in the sequential order from ► [diketopiperazine](#), diglycine, tetraglycine, to hexaglycine along the time course of development (Imai et al. 1999). Both triglycine and pentaglycine were not identified. The result reveals that the chain elongation could be due largely to aminolysis of diketopiperazine. The elongation was already selective in eliminating the cases of adding monomeric glycine one by one onto the then surviving oligoglycine.

Polymerization of monomers through elongation of oligomers proceeding under the influence

of rapid quenching can be history-dependent and evolutionary in demonstrating a pre-Darwinian natural selection. The hydrothermal environments on the seafloor in the ocean must have been pivotal in keeping the cradle for nurturing the operation of pre-Darwinian natural selection for synthesizing polymers of prebiotic significance.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [Diketopiperazine](#)
- [Formose Reaction](#)
- [Hydrothermal Reaction](#)
- [Natural Selection](#)
- [Nucleic Acids](#)
- [Protein](#)

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Polymerase Chain Reaction

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Keywords

Amplification · DNA · Replication · *Taq* polymerase · Thermostable DNA polymerase

Synonyms

PCR

Definition

Polymerase chain reaction or PCR is an artificial method for the amplification of double-stranded ► [DNA](#) – dsDNA – fragments based on the action of a thermostable DNA polymerase. It allows for the quick, reliable, and highly sensitive in vitro amplification of DNA from any source. The reaction consists of a series of replication cycles of three successive phases: (1) *denaturation* of the parental dsDNA into two complementary single-stranded – ssDNA – molecules; (2) *annealing* or hybridization of two short ssDNA primers with their respective complementary region in each ssDNA strain; and (3) *elongation* or DNA replication of each primer-bound ssDNA strain by the DNA polymerase, rendering two identical dsDNA molecules. Cycles of exponential amplification are repeated 30–40 times, resulting in over a million-fold amplification of the initial material.

Overview

Since its invention in the mid 1980s (Saiki et al. [1985](#); Mullis and Faloona [1987](#)), PCR has revolutionized genetics and molecular biology by permitting rapid amplification of DNA of any length – up to 50,000 nucleotides, nt – and sequence. A general requirement for the target DNA is that the flanking sequences at both ends of the fragment to be amplified must be known, thus allowing the use of two short – usually 15–30 nt long – DNA primers complementary to them during the annealing phase of each cycle. Currently, PCR is a routine protocol that only requires the target DNA, forward and reverse primers, a thermostable DNA polymerase, triphosphate deoxynucleotides as monomers, and a buffer that provides the required pH and salts for the reaction.

Once the reaction mixture is prepared, PCR is performed automatically in equipment called thermocyclers or thermal cyclers, taking 2–3 h for completion. Alternatively, advances in microfluidics and microchip technology allow 20 cycles

of PCR to be completed in only 90 s (Innis et al. 1990; Sambrook and Russell 2001). The detection and characterization of the amplified product is done after the last cycle in traditional PCR. In turn, real-time quantitative PCR combines amplification and detection in a single tube, thus measuring the amount of amplified DNA at each cycle (Higuchi et al. 1992; Smith and Osborn 2009).

PCR amplification of DNA can be accomplished by DNA polymerases from different thermophilic microorganisms, able to withstand the high temperature – usually 90–94 °C – used during the denaturation phase of each cycle. The optimal DNA polymerization temperature of these enzymes – and thus the selected elongation temperature in PCR – is 68–74 °C. Different DNA polymerases show differences in efficiency (yield of DNA amplification per unit of the enzyme or per cycle), processivity (average length of the DNA amplified), and fidelity (frequency of polymerase-induced errors). These parameters also depend on the PCR conditions. The most widely used enzyme has been ► *Taq polymerase*, purified from the thermophilic bacterium *Thermus aquaticus*. Nevertheless, the high error rate associated with the DNA replication performed by this enzyme has encouraged the use of high fidelity DNA polymerases of some hyperthermophilic archaea such as: *Vent*, from *Thermococcus litoralis*; *Pfu*, from *Pyrococcus furiosus*; *Pwo*, from *Pyrococcus woesei*; and mixtures or genetically engineered versions of them (Pavlov et al. 2004; Lewin 2008).

Different experimental variants of PCR technology currently used include reverse transcription followed by PCR (also called RT-PCR), double or nested PCR, asymmetric PCR, multiplex PCR, mutagenic PCR, random PCR, inverse PCR, and ligation-mediated PCR (Innis et al. 1990; Lewin 2008). All of them enjoy an increasing applicability in different fields of biology and medicine.

- [Replication \(Genetics\)](#)
- [Taq Polymerase](#)
- [Thermophile](#)

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Polymict Breccia

- [Polymictic Breccia](#)

Polymictic Breccia

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Cross-References

- [Amplification \(Genetics\)](#)
- [DNA](#)

Synonyms

Polygenetic breccia; Polyolithologic breccia; Polymict breccia

Definition

A polymictic breccia is a clastic sedimentary rock composed of angular clasts from different lithologies intermixed and held in a consolidated matrix. The clast can be formed during tectonic events or meteorite impacts. In the latter case, they take the term of *polymictic impact breccia*. *Polymictic impact breccia* may be used as a generic term for *lithic breccia* and *suevite breccia*.

Cross-References

- [Breccia](#)
- [Crater, Impact](#)
- [Impact Basin](#)
- [Impact Melt Rock](#)
- [Impactite](#)
- [Monomictic Breccia](#)
- [Suevite](#)

Polynucleotide

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A polynucleotide is a repeating polymer composed of ► [nucleotide](#) monomers covalently bonded via phosphodiester bonds. DNA and RNA are examples of polynucleotides. The chain length at which an oligonucleotide becomes a polynucleotide is somewhat arbitrary, but some biochemists define the transition as occurring at lengths of 13 or more nucleotide residues.

Cross-References

- [Nucleic Acids](#)
- [Nucleotide](#)

Polyoxymethylene

Hervé Cottin
Univ Paris Est Creteil and Université Paris Cité,
CNRS, LISA, F-94010 Créteil, France

Keywords

Comet · Distributed source · Formaldehyde · Polymer

Synonyms

[Paraformaldehyde](#); POM

Definition

Polyoxymethylenes (POM) are polymers of formaldehyde. They can exist either in cyclic (trioxane $C_3O_3H_6$ and tetroxane $C_4O_4H_8$) or linear form. The latter includes a wide range of chain lengths with the formula $(HO(CH_2O)_nH)$. The low molecular weight polymers (typically ranging from 10 to 100 monomers units) are commonly known as paraformaldehyde and are readily thermally degraded into pure formaldehyde. They are used in chemistry as a source of pure H_2CO . High molecular weight polymers (a few hundreds to a few thousands monomer units) are extensively used in the plastics industry for their remarkable mechanical properties (Walker 1964). POM could have had a key role in prebiotic chemistry as a source of concentrated formaldehyde for the ► [formose reaction](#).

Overview

The presence of polyoxymethylene in comets has often been proposed to interpret various puzzling

observations in their comae, although it has not been directly unambiguously detected yet. The presence of polyoxymethylene in the interstellar medium has been discussed since the middle of the 1970s. However, no clear observational evidence of its presence has ever been reported, either because it is not synthesized in such environments or because its detection is compromised by the presence of silicates, the infrared signatures of which are similar to those of POM. In 1987, its detection was reported in the comet 1P/Halley by mass spectrometry (Huebner 1987). However, a few years later, it was demonstrated that the mass spectral characteristics attributed to POM could also be the signature of a complex mixture of organic compounds (Mitchell et al. 1992). This does not rule out the presence of POM, but makes its detection ambiguous. In the early twenty-first century, it was demonstrated that the distribution of formaldehyde in the comae of comets 1P/Halley and C/1995 O1 (Hale Bopp), which could not be explained by a direct production of formaldehyde from the nucleus, could be explained by the presence of a few mass percent of POM in the nucleus of the comet, ejected on grains in the coma, and then slowly degraded into gaseous formaldehyde by photo and thermal degradation processes. POM would then be the parent compound of the so-called distributed source of formaldehyde in comets (Cottin et al. 2004; Fray et al. 2006). Though this is not a direct detection, this demonstration strengthens the probability of the presence of this polymer in some comets in the form of relatively small polymeric units similar to laboratory paraformaldehyde. This idea is backed by laboratory experiments showing that POM can be synthesized in cometary ice analogs under certain conditions (Schutte et al. 1993; Duvernay et al. 2014). The presence of POM at the surface of the nucleus of comet ► [67P/Churyumov–Gerasimenko](#) has been proposed to interpret a pattern of peaks in mass spectra measured by the Ptolemy instrument in the *Philae* lander (Wright et al. 2015). However, its presence could not be confirmed or quantified by other instruments either in the lander or the main spacecraft.

If POM is present in comets, it could have played an essential role in synthesizing sugars on the primitive Earth bombarded by comets, being a

source of concentrated formaldehyde for the formose reaction.

Cross-References

- [67P/Churyumov–Gerasimenko](#)
- [Comet](#)
- [Formaldehyde](#)
- [Formose Reaction](#)
- [Rosetta Spacecraft](#)

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Polypeptide

Shin Miyakawa

6-1-7 Minami Hatsutomi, Kamagaya, Japan

Definition

A polypeptide is a ► [polymer](#) formed by the covalent bonding of a certain number of amino acids. The

exact lengths for peptides, oligopeptides, polypeptides, and ► [proteins](#) are not clearly defined; however, oligopeptides < polypeptides < proteins. Most naturally occurring polypeptides are composed of the 20 proteinogenic L-amino acids, although many microbial polypeptides contain unusual noncoded amino acids, such as ► [sarcosine](#), β -amino acids, and D-amino acids. Some examples of biological peptides are calcitonin (32 amino acid long) and adrenocorticotrophic hormone (39 amino acid long).

Cross-References

- [Amino Acid](#)
- [Covalent Bonds](#)
- [D-Amino Acids](#)
- [L-Amino Acids](#)
- [Oligopeptide](#)
- [Polymer](#)
- [Protein](#)
- [Sarcosine](#)

Polyribonucleotide

- [Nucleic Acids](#)

Polysaccharide

Shin Miyakawa
Kamagaya, Chiba, Japan

Definition

A polysaccharide is a polymeric ► [carbohydrate](#) composed of repeating ► [monosaccharide](#) or disaccharide units. Some of them contain uronic acids or ester sulfates. Examples are starches, cellulose, and heparin. Polysaccharides are constituents of plant and bacterial cell walls.

Cross-References

- [Carbohydrate](#)
- [Monosaccharide](#)

POM

- [Polyoxymethylene](#)

Poorly Oxygenated

- [Suboxic](#)

Population Genome

- [Metagenome](#)

Porphyrin

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Porphyrins are heterocyclic organic macrocycles composed of four modified pyrrole rings connected by their α -carbon atoms via methine [-CH=] linkages. Porphyrins are aromatic and thus obey Hückel's $4n + 2 \pi$ electron rule. Porphyrins are highly conjugated and have very intense absorption in the visible region and may be deeply colored. The name porphyrin derives from the Greek word for purple. Porphyrins are the conjugate acids of ligands that form complexes by binding metal ions, which are usually in the +2 or +3 oxidation state. Some porphyrins, such as ► [heme](#), coordinate iron; other porphyrins chelate cobalt, magnesium, manganese, or nickel. Porphyrin-like compounds have been reported in meteorites, and a prebiotic synthesis has been proposed starting from pyrroles and aldehydes. Acidic conditions are required for this synthesis.

History

F. M. Johnson proposed in the 1970s that porphyrins were the carriers of the ► [diffuse interstellar bands](#). This proposal has not been supported by subsequent observations, although large organic molecules remain prime candidates for the still-unidentified carriers of these absorption features in stellar spectra.

Cross-References

- [Aromatic Hydrocarbon](#)
- [Chlorophylls](#)
- [Diffuse Interstellar Bands](#)
- [Heme](#)

Porpoise Cove Greenstone Belt

- [Nuvvuagittuq Greenstone Belt](#)

Positional Astronomy

- [Astrometry](#)

Postimpact Plume

Henderson James Cleaves II^{1,2,3} and Nicholas Arndt⁴

¹Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

²Blue Marble Space Institute of Science, Washington, DC, USA

³Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

⁴Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

A postimpact plume is the cloud of gas and fine debris ejected by the impacts of ► [comets](#) and ► [meteorites](#) on the surfaces or atmospheres of

planetary bodies. One example is the plume released by the impact of fragments of the comet Shoemaker-Levy on Jupiter; another is that produced by the impact of an artificial satellite and booster rocket on the moon. Spectral analysis of plumes provides information about the composition at the surface of the target and of the impactor. Such plumes could also be responsible for significant atmospheric chemical synthesis during the early formation of planets.

Cross-References

- [Comet](#)
- [Meteorites](#)

Power-Law Networks

- [Scale-Free Networks](#)

Poynting-Robertson Drag

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A particle in orbit around a star absorbs stellar radiation and, assuming that it is rapidly rotating and hence has an isothermal surface, it reradiates energy isotropically in the particle's rest frame. Consequently, in the star's rest frame the particle radiates preferentially in the direction of its motion, so that it loses momentum, energy, and angular momentum, and thus spirals inward toward the star. This effect, the predominant perturbation on centimeter-sized particles in otherwise ► [Keplerian orbits](#) around a host star such as the Sun, is called Poynting-Robertson drag.

History

John Henry Poynting gave a classical physics description of this effect in 1903. In 1937, the more complete relativistic description was published by Howard Percy Robertson.

Cross-References

- [Keplerian Orbits](#)

References and Further Reading

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pppA

- [ATP](#)

Prasad-Tarafdar Mechanism

Steven B. Charnley
Solar System Exploration Division,
Code 691, Astrochemistry Laboratory,
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

The gas phase chemistry inside dark ► [molecular clouds](#) is driven by cosmic ray and ultraviolet ionization of atomic and molecular constituents. External UV radiation is largely blocked by dust grains, but a flux of UV photons is derived from the de-excitation of H₂ molecules following the impact of cosmic-ray-produced electrons. This is called the Prasad-Tarafdar mechanism.

History

First quantified by Prasad and Tarafdar (1983).

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Ion-Neutral Reaction](#)
- [Molecular Cloud](#)

References and Further Reading

Prasad SS, Tarafdar SP (1983) UV radiation field inside dense clouds – its possible existence and chemical implications. *Astrophys J* 267:603–609

Pre-main-sequence Star

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Protostar · Star formation

Definition

A young star, which has reached its final mass by accreting material from its surrounding ► [molecular cloud](#), but which is not yet fusing hydrogen into helium at its center, is called a pre-main-sequence star. Such a star is slowly contracting, and is actually larger and more luminous than a main-sequence (hydrogen fusing) star of the same mass. The relatively high luminosity stems from the conversion of gravitational potential energy during contraction. Our Sun spent 30 million years in this phase. Current pre-main-sequence stars of two solar masses and below are known observationally as ► [T Tauri stars](#), while more massive ones are Herbig Ae/Be stars. Even younger objects, called protostars, are optically invisible and still gathering mass from their surrounding molecular clouds.

Cross-References

- [Birthline](#)
- [Molecular Cloud](#)
- [T Association](#)
- [T Tauri Star](#)

Prebiotic Chemistry

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Chemical evolution](#)

Definition

Prebiotic chemistry is the study of the abiotic synthesis of organic compounds that may have been necessary for the origin of life. Although many syntheses that are now considered to be likely prebiotic processes, such as the Strecker synthesis, were demonstrated in the nineteenth century, few experiments were conducted with the express intent of demonstrating how organic compounds could have formed in primitive environments until the 1950s, beginning with the work of Calvin and coworkers, but more notably by Stanley Miller. This remains an ongoing area of investigation.

Cross-References

- [Abiogenesis](#)
- [Evolution, Chemical](#)

Prebiotic Phosphorylation

Bruno Mattia Bizzarri
Biological and Ecological Sciences Department
(DEB), University of Tuscia, Viterbo, Italy

Keywords

Prebiotic Chemistry · Nucleotide ·
Nucleoside · Origin of Life · Phosphates,
Formamide, Meteorites

Synonyms

[Abiotic phosphorylation](#)

Definition

Prebiotic phosphorylation is defined as the phosphorylation process of the nucleoside with a phosphate source to obtain a nucleotide in a prebiotically plausible routes for phosphorylation reactions.

Overview

Phosphorylation, a fundamental process for cellular growth and metabolic pathways (Xing et al. 2017), still remain argument of debate in prebiotic chemistry (Whicher et al. 2018). The attention has been focused on thermal conditions in the presence of various phosphorus reagents, such as ortho-phosphate (Osterberg and Orgel 1972; Chang et al. 1968; Yamagata et al. 1979), condensed phosphates (Schwarz and Ponnampertuma 1968), mineral phosphates (Mullen and Sutherland 2007), reduced phosphorus(III) compounds, and hydroxyapatite (Graaf et al. 1995). These reactions required the presence of catalysts and condensing agents to overcome the unfavorable activation energy in water. Vacuum ultraviolet (VUV) radiation and γ -radiation have been also reported as alternative energy sources

(Simakov and Kuzicheva 2005). In addition, the phosphorylation of adenosine in dry-film condition was described by using proton beam as energy source in the presence of sodium orthophosphate (Simakov et al. 2002). Similar results were obtained in real space experiments by satellite exposure of 2'-deoxy adenosine and NaH_2PO_4 (Kuzicheva and Simakov 1999). More recently, the role of deep eutectic solvents (Mamajanov et al. 2010; Gull et al. 2014; Welton 1999) and formamide (NH_2CHO) (Schoffstall 1976; Schoffstall et al. 1982) have been explored using ortho-phosphate and hydroxyapatite, NH_2CHO being able to solubilize both nucleosides and phosphorus reagents (Bizzarri et al. 2020). In this latter case, the process was activated by high energy proton beam irradiation mimicking the solar wind, the reaction being catalyzed by meteorites of the chondrite type. Reactive radical species have been identified as key intermediates of the process by computational studies. Thus, nucleotides may form in the same physical-chemical frame in which the formation of nucleic bases and nucleosides has been reported (Saladino et al. 2012; Saladino et al. 2017; Botta et al. 2017).

Cross-References

- Nucleoside
- Nucleotide
- Origin of Life
- Phosphates
- Prebiotic Chemistry

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Prebiotic Photosynthesis

- ▶ [Abiotic Photosynthesis](#)

Prebiotic Soup

- ▶ [Primordial Soup](#)

Prebiotic Soup Hypothesis

- ▶ [Heterotrophic Hypothesis](#)

Precambrian

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The *Precambrian* is the informal name given to the first part of Earth's history before the Cambrian Period of the Standard Global Chronostratigraphic Scale. It includes the (informal) ▶ [Hadean](#) eon, and the formal Archean and Proterozoic eons. It spans ca. 4 billion years, or 90% of the lifespan of our planet. The Precambrian began with the formation of the Earth at about 4.56 Ga; it ended with the first appearance of a trace fossil (*Phycodes pedum*) at about 543 Ma ago, shortly after the proliferation of hard-shelled fossilizable organisms. Due to this absence of macrofossils, before the middle of the twentieth century, the Precambrian was also called Azoic Eon. The Precambrian was marked by a series of major events – the formation of the Moon and the ▶ [Late Heavy Bombardment](#), the filling of the ocean basins, the emergence of ▶ [life](#), the start of plate tectonics and growth of the ▶ [continents](#), the ▶ [great oxygenation event](#), and the ▶ [“Snowball” Earth](#) glaciations.

Cross-References

- ▶ [Archean Eon](#)
- ▶ [Earth, Formation, and Early Evolution](#)
- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Great Oxidation Event](#)
- ▶ [Hadean](#)
- ▶ [Oceans, Chemical Evolution of](#)
- ▶ [Oceans, Origin of](#)
- ▶ [Proterozoic Eon](#)
- ▶ [Snowball Earth](#)

Precambrian Oceans, Temperature of

François Robert
Institut Origine et Evolution (O&E), Muséum
National d'Histoire Naturelle, Sorbonne
Université, IMPMC-UMR 7590 CNRS, 57 rue
Cuvier 75005 Paris, France

Keywords

Ocean · Temperature · Stable isotopes ·
Oxygen isotopes · Silicon isotopes · Archean ·
Isotope paleothermometry

Synonyms

[Ocean](#)

Definition

The most ancient traces of life dated from about 3.8 Ga. At that time, earth's surface was no longer the magma ocean that solidified 4.35 Ga ago or earlier. The primitive atmosphere inherited from the presolar nebula had disappeared, being replaced by a secondary atmosphere derived in part from the outgassing of the mantle and in part brought to the surface by extraterrestrial impactors and micrometeorites. This atmosphere was dominated not only by N₂ but also by several greenhouse gases such as carbon dioxide,

methane, and water vapor. The extent of surfaces covered by the oceans is unknown, but it can be postulated that – since the continents had not yet formed – the absence of the present-day bimodal distribution of elevations on earth caused water to cover most of the surface of the Archean earth. Undoubtedly, sedimentary rocks existed on earth since at least 3.85 Ga ago as shown by unambiguous sedimentary structures recorded from rocks in South Africa and Greenland. The temperature of the first oceans, however, has always been a subject of debate.

Overview

Cherts: Surviving Witnesses of Early Oceans

In the early 1950s, geochemists showed that the isotopic compositions of sedimentary rocks could be used to reconstruct the temperature of the oceans provided (1) the isotopic composition of seawater from which these rocks precipitated was known and (2) the geological evolution of these rocks had not altered their pristine isotopic compositions. These two points are key issues in reconstructing paleotemperatures in all types of environments and samples. Siliceous sediments (cherts) are common in the Precambrian. Since microplanktons (e.g., diatoms) able to fix soluble silica for building their skeletons did not exist in the Precambrian, it appears plausible that silica precipitated in Precambrian oceans in the form of amorphous silica deposited at the surface of the sediments. Today, this abiotic precipitation still exists in some rare terrestrial environments.

During burial of the marine sediments and subsequent diagenesis, the increase in pressure and temperature caused the progressive elimination of connate water along with mineralogical transformations of the silica. These transformations always involve the dissolution and reprecipitation of preexisting silica crystals. At the top of the sedimentary column, the first form of deposited silica is amorphous opal that is progressively transformed to microcrystalline silica (“opal-CT”), then to chalcedony and fibrous quartz. These transformations take place *in situ*, i.e., with almost no migration of silica; they are

caused by the large amount of liquid water trapped in the rocks and that is progressively expelled during the compaction of the sediment (e.g., Knauth 1992, 1994). We shall see below that this diagenetic evolution has important consequences on the significance of the temperature recorded by silica.

Compaction yields a rock exceptionally resistant to weathering in which the diffusion of water is negligible. The cryptocrystalline nature of chert, combined with its average ability to resist weathering, recrystallization, and metamorphism, has made it an ideal rock for the preservation of indigenous geochemical tracers such as isotopic compositions or the chemical fossils of early life (e.g., Hayes et al. 1983; Beaumont and Robert 1999). During metamorphism, fluids may nevertheless circulate along cracks or veins that are still clearly visible at the spatial resolution of tens of micrometers. However, the spatial isotopic and chemical exchange between the matrix and these veins is restricted to a few hundred microns. Unless a chert is extensively percolated by fluids during metamorphic events, their pristine geochemical compositions are preserved in their nanocrystalline silica matrix since deposition and crystallization. In this respect, cherts can be regarded as the best-preserved sedimentary rocks on earth.

Early studies reported oxygen isotopic compositions of cherts with the aim of reconstructing the temperature of the Archean oceans (e.g., Knauth and Epstein 1976; Knauth and Lowe 1978).

Measuring the Temperature of the Early Oceans

The oxygen isotopic composition of cherts shows a systematic decrease with geological time: the older the sample, the lower the isotope ratio ($\delta^{18}\text{O}$) (e.g., Knauth and Lowe 1978, 2003). Assuming that the isotopic composition of seawater did not change with time, this trend was interpreted as resulting from the progressive cooling of the oceans since 3.5 Ga. The partition of oxygen isotopes between water and silica was determined in the laboratory, and accordingly, a temperature of up to 80 °C was derived for the Archean oceans (Knauth and Lowe 1978). More

quantitatively, there is 1.6% more ^{18}O relative to ^{16}O at 20 °C than at 80 °C. The routine precision on the isotopic proportion being $\pm 0.02\%$, such a difference is easily detectable by modern isotope mass spectrometers. Precambrian cherts older than two billion years have oxygen isotopic compositions corresponding to crystallization temperatures higher than 40 °C. In contrast, Phanerozoic cherts have an isotopic composition corresponding to markedly cooler temperatures. It was thus concluded that the Precambrian oceans were hotter than today (Knauth and Lowe 1978, 2003).

This interpretation has been challenged. First, it was argued that the isotopic composition of oxygen in seawater from which these rocks precipitated has changed with time (Perry 1967) and therefore that the isotopic trend observed as a function of time reflects this evolution of the ocean but not its temperature (Kasting et al. 2006). The progressive reset in ^{18}O would have taken place during the interaction of seawater with the mantle via the intense hydrothermal circulation at mid-ocean ridges (Kasting et al. 2006). The half-life for recycling the entire oceans through these ridges is less than ten million years, and oxygen isotopes should be quickly equilibrated with the mantle with respect to the three billion years of ^{18}O evolution observed in cherts. However, no evidence of such change appears in the geological record.

Several studies have shown that Precambrian pillow lavas – i.e., volcanic lavas cooled rapidly in contact with seawater – did not show any specific isotopic compositions at their interface with seawater compared with their modern counterparts. In addition, in some cases, the phosphates contained in cherts have provided an independent estimate of the seawater isotopic composition that appears constant through geological times. Although a few theoretical models have reopened the issue of a possible drift of ^{18}O with time (Kasting et al. 2006), the general consensus is that the seawater isotopic composition remained constant within reasonable uncertainties, corresponding to a precision of ± 15 °C.

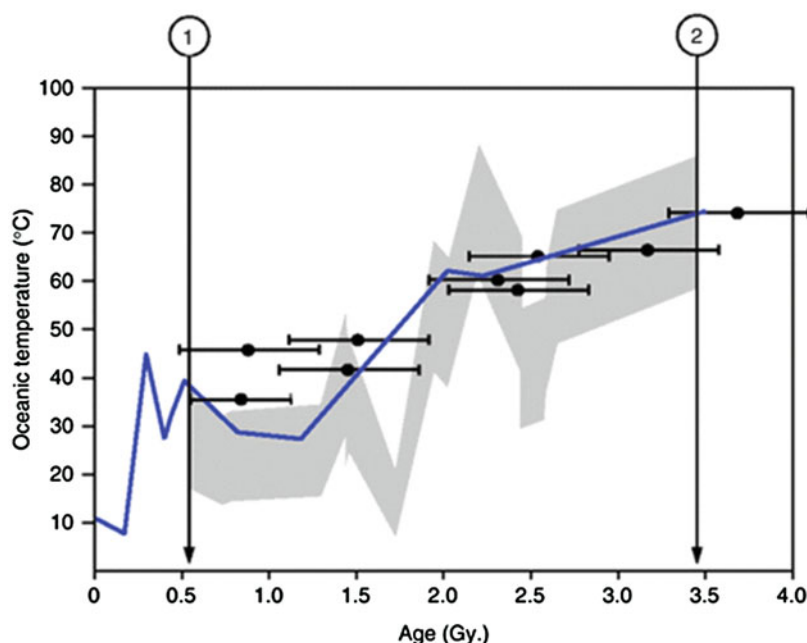
The second criticism of the thermometric interpretation deals with the problem of the

preservation of the chert isotopic compositions, by arguing that the older the cherts, the more disturbed are their compositions. This second aspect is more difficult to circumvent on the basis of oxygen isotopes and the petrology of cherts. Silicon isotopes shed new light on this issue.

Measuring the Silicon Isotope Composition of the Early Oceans

Based on the analyses of more than 100 chert samples covering the whole Precambrian period, it was shown that silicon and oxygen isotopic compositions exhibit some covariation (Robert and Chaussidon 2006), a priori unexpected since silicon isotopes are – unlike oxygen – insensitive to temperature. The alteration processes for these two chemical elements – through which isotopic resets may take place – are completely decoupled. Indeed, during alteration, the carrier of silicon is the dissolved silica whose concentration rarely exceeds 200 ppm, while the carrier of oxygen is the water itself. In addition, once under the form of silica, the isotopic exchange of silicon could occur only in solution via the dissolution – reprecipitation of silica. Consequently, in order for the relation between the isotopic compositions of silicon and oxygen to be maintained, secondary effects post-dating the chert formation must be limited. Some cherts, however, clearly show late disturbance in their oxygen isotopes with no counterpart for silicon (Marin-Carbonne et al. 2014).

These silicon and oxygen isotopic covariations are well accounted for by the solubility of silica in the oceans and hence are ultimately related to seawater temperature. The results of such a model are reported in Fig. 1 as variations in oceanic temperatures between 3.5 and 0.5 billion years. For samples younger than 0.5 billion years (arrow 1 on the Fig. 1), the silicon and oxygen isotopic covariation disappears, which indicates that silicon isotopes stop recording oceanic temperatures. This is attributed to the appearance of silica fixators in the oceans – siliceous planktons (diatoms) – that have maintained so far silica under saturation. In other terms, during the Phanerozoic, the concentration in silica dissolved in the ocean was no longer dictated by



Precambrian Oceans, Temperature of, Fig. 1 The temperature of the oceans is reconstructed from three independent proxies: (1) the solid line stands for oxygen isotopes (After Knauth and Lowe 2003); (2) the gray area stands for silicon isotopes (After Robert and Chaussidon 2006); and (3) the data points with error bars stand for the

elongation factors of a selection of proteins in microorganisms (After Gaucher et al. 2008). Arrows 1 and 2 designate (1) the emergence of silica-fixing organisms in oceans and (2) the oldest siliceous marine sediments found on earth, respectively. Time is in Ga

the temperature but by the metabolic activity of the plankton (De la Rocha et al. 1997). The oldest preserved cherts on earth (dated at 3.5 Ga; cf. 2 on Fig. 1) exhibit the lowest silicon and oxygen isotope ratios, corresponding to the highest oceanic temperatures.

Robustness and Limits of the Secular Oceanic Temperature Evolution Model

Following the publication where the covariations in silicon and oxygen isotopes in the Precambrian were interpreted as a seawater temperature evolution (Robert and Chaussidon 2006), the assumptions of this conjecture were re-questioned by several authors. These assumptions are (i) the seawater $\delta^{18}\text{O}$ did not evolve during these last 3.0 billions years (addressed by Jaffrés et al. (2007)) and (ii) the temperature of crystallization of silica is registered by cherts with limited post-depositional alteration (addressed by Sengupta and Pack (2018)).

- (i) On the basis of a thorough review of existing data on this question, Jaffrés et al. (2007) constructed a detailed model accounting for the secular increase of marine carbonates with decreasing age. The carbonate trend is parallel to the one defined by cherts but yield higher seawater temperatures at the Archean (up to 100 °C). In this model describing the geological water cycle, the seawater $\delta^{18}\text{O}$ increases by $\approx 13\text{‰}$ over a period of 3.4 Ga. This secular increase of $\delta^{18}\text{O}$ seawater values would result from both an enhanced weathering on the newly emerged continents as well as the diminishing impact of the high-temperature alteration taking place at the mid-ocean ridges. This increase in seawater $\delta^{18}\text{O}$ implies that the Precambrian oceans temperature were similar to that of the present day.
- (ii) On the contrary, Sengupta and Pack (2018), using the combined $\delta^{17}\text{O}/\delta^{18}\text{O}$ variations in

cherts, argued that the seawater $\delta^{18}\text{O}$ was constant in time but that the evolution in chert $\delta^{18}\text{O}$ values during the Precambrian is explained by the diagenesis of silica involving low $\delta^{18}\text{O}$ meteoric water. Accordingly, the Precambrian silica would have precipitated in cool oceans. Note that Bindeman et al. (2018), using the same $\delta^{17}\text{O}/\delta^{18}\text{O}$ criteria on shales, reconstructed a Precambrian temperature evolution similar to that proposed in the Fig. 1.

In summary, both approaches, although somewhat contradictory, conclude that there is no natural evidence for an oceanic temperature change during geological times.

These two arguments have been examined with two distinct analytical protocols. For (i), the $\delta^{18}\text{O}$ of the kerogen embedded in Precambrian cherts has been measured and for (ii) the isotopic homogeneity of silica in cherts has been determined at a 20 μm spatial resolution.

- (i) Precambrian kerogen can only be derived from marine plankton. Consequently, oxygen atoms in this biological organic matter came from water. The isotopic composition of biomolecules is largely determined by metabolic exchange between living organisms and their environment and is almost insensitive to temperature (within 2–3‰ in $\delta^{18}\text{O}$). The $\delta^{18}\text{O}$ of marine organisms define an isotopic fractionation factor between water and organic oxygen of $+25 \pm 5\%$. Tartèse et al. (2018) show that $\delta^{18}\text{O}$ in the Precambrian kerogen embedded in cherts has a constant value of $+20 \pm 4\%$. The difference between living organism and their remnants, i.e., between $+25\%$ and $+20\%$, is likely caused by an isotopic evolution of the insoluble organic matter during its diagenetic evolution in cherts. Nevertheless, this study indicates that the seawater $\delta^{18}\text{O}$ value was constant during geological times within $\pm 4\%$. Propagating $\pm 4\%$ on the temperature of the precipitation of silica gives $\pm 20^\circ\text{C}$.
- (ii) Marin-Carbonne et al. (2010, 2014) have shown that the oxygen isotopic compositions are highly heterogeneous at a micrometric

scale. The $\delta^{18}\text{O}$ variations can reach 6.6‰ at a 20 μm scale. During the removal of water from the siliceous sediment, microdomains grown up and prevent a large-scale circulation of water during the final compaction of the rock. Each microdomain had its own isotopic evolution governed by a close reservoir water–silica fractionation. This isotopic heterogeneity (6.6‰) likely reflects this progressive closure. This observation contravenes models where the circulation of meteoric water would have lowered the $\delta^{18}\text{O}$ of the silica. Any water circulation would have erased such isotopic heterogeneity. Note that Phanerozoic cherts that precipitated from large-scale water circulation in their parent carbonate rocks do not exhibit such an isotopic heterogeneity.

The discovery of this isotopic heterogeneity has shown that the bulk $\delta^{18}\text{O}$ of chert cannot be taken as a face value to derive the precipitation temperature of silica. A correct thermometric interpretation of the chert oxygen isotopic compositions requires an assessment of the extent of diagenetic alteration. Although such an effect cannot erase the relative variations reported in Fig. 1, a Rayleigh distillation model calculated to account for the $\delta^{18}\text{O}$ micrometer distribution suggests that the seawater temperatures could be as lower as 10–15 $^\circ\text{C}$ compared to the temperatures reported in Fig. 1.

Interestingly, this model was independently supported by biological studies on proteins in which the elongation factors can be scaled to estimate the age of the last mutation responsible for this elongation (Gaucher et al. 2008). The timescale of resurrected proteins provides a palaeotemperature proxy for the environments that hosted life from 3.5 to 0.5 billion years ago. The thermostability of several phylogenetically dispersed ancestral elongation factors suggests that these environments cooled progressively during the last 3.5 billion years. It seems that ancient life has continually adapted to changes in environmental temperatures throughout its evolutionary history. The corresponding variations in temperature versus time are reported in Fig. 1 (data points with error bars) for comparison with

isotopic temperatures. The resemblances in the trends are quite compelling.

A general consensus seems now to emerge: as suggested by Jaffrés et al. (2007) and Sengupta and Pack (2018), variations in the seawater $\delta^{18}\text{O}$ and the contribution of low $\delta^{18}\text{O}$ water in diagenesis are expected but their magnitudes do not erase the temperature signal. From all these observations, the suggestion that early Precambrian oceans were several tens of degrees warmer than the modern ocean has definitively gained some acceptance. Nevertheless, the exact significance of this temperature remains an open issue.

Cross-References

- [Chert](#)
- [Earth, Formation, and Early Evolution](#)
- [Oceans, Chemical Evolution of](#)
- [Oxygen Isotopes](#)

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Precession

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Precession is the change in the orientation of the rotational axis of an astronomical body, such as a star or a planet, under the gravitational forces due

to one or several nearby massive bodies. The change is slow and continuous and the axis, like in a wobbling top, describes a cone.

Earth's precession of the equinoxes is one of the best-studied effects of this kind: it results from the combined action of the Sun and the Moon on the equatorial bulge of the Earth, the bulge itself being created by the centrifugal force induced by the rotation. The Earth ► [polar axis](#) traces a cone of half-angle 23.4° in about 26,000 years.

Exoplanets as well are capable of precession, and it is not unlikely that the effect could be observed in some particular cases.

Cross-References

- [Polar Axis](#)
- [Rotation Planet](#)
- [Rotational Velocity](#)

Precursor

Kensei Kobayashi
Yokohama National University,
Yokohama, Japan

Synonyms

[Parent molecule \(ion, species\)](#)

Definition

When a compound A gives rise to another compound B after some simple chemical reaction, A is called a precursor of B. For example, aminoacetonitrile is a precursor of glycine since hydrolysis of aminoacetonitrile gives glycine. This term is also used in astronomy (e.g., chemical species found in cometary nuclei are precursors of the species in cometary comae) and in biology (e.g., metabolic pathways).

Cross-References

- [Amino Acid Precursors](#)
- [Parent Molecule, Comet](#)

Predissociation

Stefanie N. Milam
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Predissociation is the break-up of a molecule in an excited state without the emission of radiation. Predissociation occurs when there is a radiationless transition from the excited energy level (electronic, vibrational, or rotational) to an overlapping dissociation continuum.

Cross-References

- [Spectroscopy](#)

Pre-planetary Nebulae

- [Protoplanetary Nebula](#)

Primary Atmosphere

- [Atmosphere, Primitive Envelope](#)

Primary Eclipse

- [Eclipse](#)

Primary Kingdom

- [Domain \(Taxonomy\)](#)

Primary Producer

- [Autotroph](#)

Primary Production

- [Autotrophy](#)

Primer

Juli Peretó
 Institut Cavanilles de Biodiversitat i Biologia
 Evolutiva, Universitat de València, València,
 Spain

Definition

Primer is a short oligonucleotide allowing the initiation of replication by a DNA polymerase. In vivo, usually the primer is a short RNA strand synthesized on the DNA strand and near the initiation site of replication. In vitro, primers are used in the PCR used for DNA amplification (or cloning).

Cross-References

- [Amplification \(Genetics\)](#)
- [DNA](#)
- [Polymerase Chain Reaction](#)
- [Replication \(Genetics\)](#)
- [RNA](#)

Primitive Atmosphere

- [Atmosphere, Primitive Envelope](#)

Primitive Broth

- [Primordial Soup](#)

Primitive Mantle

- [Bulk Silicate Earth](#)

Primitive RNA Catalysis

- [Abiotic Recombination](#)

Primordial Heat

Doris Breuer
 German Aerospace Center (DLR), Institute of
 Planetary Research, Berlin, Germany

Definition

Primordial heat is the internal heat energy accumulated by dissipation in a ► [planet](#) during its first few million years of evolution. The main contributions to the primordial heat are accretional energy – the energy deposited by infalling ► [planetesimals](#) – and ► [differentiation](#) energy. The latter is mainly released by core formation and is basically potential energy that is dissipated upon formation of a gravitationally stable layering of the planet. In addition to the primordial heat, the planet’s internal heat source is mainly provided by the radioactive decay of long-lived unstable isotopes such as ²³⁸U, ²³⁵U, ²³²Th, and ⁴⁰K and by latent heat.

Cross-References

- [Core, Planetary](#)
- [Differentiation, Planetary](#)
- [Planet](#)
- [Planet Formation](#)
- [Planetesimals](#)
- [Radioactive Heating](#)

Primordial Nucleosynthesis

- [Big Bang Nucleosynthesis](#)

Primordial Soup

Antonio Lazcano

Facultad de Ciencias, UNAM, Cd. Universitaria, Mexico, DF, Mexico

Keywords

Abiotic organic synthesis · Oparin-Haldane · Origin of life · Primordial heterotrophs

Synonyms

[Prebiotic soup](#); [Primitive broth](#)

Definition

The primordial soup is a generic term that describes the aqueous solution of organic compounds that accumulated in primitive water bodies of the early Earth as a result of endogenous abiotic syntheses and the extraterrestrial delivery by cometary and meteoritic collisions, and from which some have assumed that the first living systems evolved.

Overview

The term “primordial soup” and its synonyms are linked to the proposal of the heterotrophic theory

of the origin of life, which was suggested independently in the 1920s by Alexander I. Oparin, John B. S. Haldane, and few others. Based on the simplicity and ubiquity of fermentative reactions, Oparin and Haldane proposed that the first organisms must have been heterotrophic bacteria that could not make their own food but obtained organic material present in the primitive milieu. In order to support his proposal, Oparin appealed not only to astronomical observations that had shown that hydrocarbons and other organic material were present in meteorites and cometary nuclei but also to the nineteenth-century experimental syntheses of organic molecules by Wohler, Butlerow, and Mendeleyev, among others (Lazcano 2010a).

Similar ideas were being developed independently at the same time by other researchers. Like Oparin, the British biochemist and geneticist John B. S. Haldane argued in 1929 that the origin of life had been preceded by the synthesis of organic compounds. Based on experiments by E. C. C. Baly, an English chemist who had reported the formation of amino acids and sugars as a result of the UV irradiation of a solution of CO₂ in water, Haldane suggested that the absence of oxygen in a CO₂-rich primitive atmosphere led to the synthesis of organic compounds and their accumulation in the primitive waters of the Earth, which he wrote had “the consistency of hot dilute soup.” The discovery of phages led Haldane to argue that viruses represented an intermediate step in the transition from the prebiotic broth to the first heterotrophic cells (Farley 1977; Lazcano 2010a).

A Darwinian Warm Little Pond

In 1871, Charles Darwin mailed a letter to his close friend Joseph Dalton Hooker in which he mentioned Pasteur’s work on the absence of spontaneous generation and added that “It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive, in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity, and c. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured,

or absorbed, which would not have been the case before living creatures were formed.”

However, the “hot dilute soup” concept formulated by Haldane developed independently of Darwin’s warm little pond. During the first part of the twentieth century, most authors assumed, at least implicitly, that the origin of life had taken place in an aqueous environment. When Winslow Herschel discussed the consistency of colloids, which by then were assumed to explain many of the properties of protoplasm (Podolsky 1996), he wrote that “How many factors determine consistency is a matter of controversy, but the colloquial meaning of the word is well understood and may be illustrated by the description, from a recent novel, of ‘Flanders mud after a thaw’. As the flow increased, the side of the trenches began to fall in; the earth thus mixed with the water thickened it to a consistency which might be liked to a very rich soup” (Herschel 1926).

There is nothing that suggests that Herschel, Haldane, or Oparin had read Darwin’s remarks about the origin of life and the warm little pond. Darwin’s letter was included by his son Francis as a footnote in the 3rd volume of his father’s book *Life and Letters* published in 1887, but it was not until 1969 that Melvin Calvin published it in his book on chemical evolution (Calvin 1969), calling it to the attention of the origins-of-life community (Peretó et al. 2009). By then, the concept of a prebiotic broth and a heterotrophic origin of life, which had been developed by Oparin and Haldane within the framework of an evolutionary perspective, had gained considerable support from the development of a multidisciplinary research program on the emergence of the first living systems.

Defining the Soup

The proposal that life was the outcome of prebiotic chemistry and the evolution of precellular systems was further elaborated and refined by Oparin in a more extensive book that was published in Russian in 1936 and translated 2 years later into English (Oparin 1938). In his new book, Oparin suggested that the primitive Earth was a highly reducing milieu in which iron carbides of geological origin would react with steam to form ► [hydrocarbons](#). Their oxidation

would yield alcohols, ketones, aldehydes, etc., that would then react with ► [ammonia](#) to form amines, amides, and ammonium salts. The resulting protein-like compounds and other molecules would form a hot dilute soup, in which they would aggregate to form colloidal systems such as coacervates, from which the first heterotrophic microbes evolved. Others, like John D. Bernal, argued that the compounds were concentrated on the surfaces of minerals like clays, where the higher density would favor their chemical interaction (Bernal 1944).

Experimental evidence in support of Oparin’s proposal came first from Harold C. Urey’s laboratory, at the University of Chicago, who had considered the origin of life in the context of his proposal of a highly reducing terrestrial atmosphere (Urey 1952). The first successful prebiotic amino acid synthesis was carried out with an electric discharge and a strongly reducing model atmosphere of CH_4 , NH_3 , H_2O , and H_2 (Miller 1953). The result of this experiment was a significant yield of a racemic mixture of amino acids, together with hydroxy acids, short aliphatic acids, and urea. One of the surprising results of this experiment was that the products were not a random mixture of organic compounds; rather, a relatively small number of compounds, most of which were of biochemical significance, were produced in substantial yield. The Miller-Urey experiment marked not only a new epoch in the study of the origin of life but also led to surprisingly rapid acceptance by the public of both the heterotrophic theory and the idea of a primitive soup (Bada and Lazcano 2003).

Was There a Primitive Soup?

Although it is generally agreed that free oxygen was absent from the primitive Earth, there is no agreement on the composition of the primitive atmosphere; opinions vary from strongly reducing ($\text{CH}_4 + \text{NH}_3 + \text{H}_2\text{O}$, or $\text{CO}_2 + \text{H}_2 + \text{N}_2 + \text{H}_2\text{O}$) to neutral ($\text{CO}_2 + \text{N}_2 + \text{H}_2\text{O}$). In general, non-reducing atmospheric models were favored by planetary scientists, while prebiotic chemists leant toward more reducing conditions, under which the abiotic syntheses of amino acids, purines, pyrimidines, and other compounds are very efficient. Prior to the recognition that organic

compounds can be synthesized under the neutral conditions of a CO₂-rich atmosphere (Cleaves et al. 2008), the difficulties involved with the endogenous synthesis of amino acids and nucleobases have led to the development of alternatives.

In the early 1990s, Chyba and Sagan reanalyzed Oró's 1961 proposal on the role of cometary nuclei as sources of volatiles to the primitive Earth and, based on the chemical composition of carbonaceous meteorites, proposed that the exogenous delivery of organic matter by asteroids, comets, and interplanetary dust particles could have played a significant role in forming the primitive soup, by seeding the early Earth with the compounds necessary for the origin of life (Chyba and Sagan 1992). On the other hand, proponents of an autotrophic theory of the origin of life (Wächtershäuser 1988) have dismissed the role of prebiotic synthesis and accumulation of organic compounds. However, since the FeS/H₂S combination is a strong reducing agent that has been shown to reduce nitrate and acetylene, induce the formation of peptide bonds between amino acids activated with carbon monoxide and (Ni, Fe)S (Maden 1995; Huber and Wächtershäuser 1998), and catalyze the synthesis of acetic acid and pyruvic acid from CO under simulated hydrothermal conditions (Huber and Wächtershäuser 1997; Cody et al. 2000), the role of Fe/S minerals is also compatible with a more general, modified model of the primitive soup in which pyrite formation is recognized as an important source of electrons for the reduction of organic compounds (Bada and Lazcano 2002).

There has been no shortage of discussion about how the formation of the primitive soup took place. However, it is likely that no single mechanism can account for the wide range of organic compounds that may have accumulated on the primitive Earth and that the prebiotic soup was formed by contributions from endogenous syntheses in a reducing atmosphere, metal sulfide-mediated synthesis in deep-sea vents, and exogenous sources such as comets, meteorites, and interplanetary dust. This eclectic view does not beg the issue of the relative significance of the

different sources of organic compounds, but it simply recognizes the wide variety of potential sources of organic compounds, the raw material required for the emergence of life (Bada and Lazcano 2009; Lazcano 2010b).

The Prebiotic Broth: A Risky Metaphor?

Synonymous terms like "primitive soup," "primordial broth," or "Darwin's warm little pond" have led in some cases to major misunderstandings, including the simplistic image of a world-wide ocean, rich in self-replicating molecules and accompanied by all sorts of biochemical monomers. However, nowadays, it refers to parts of the prebiotic environment where the accumulation and interaction of the products of abiotic synthesis may have taken place, including oceanic sediments, intertidal zones, shallow ponds, membrane-bound systems, freshwater lakes, and lagoons undergoing wet-and-dry cycles. The soup may have been semifrozen, and glacial ponds where evaporation, eutectic separations, or other physicochemical mechanisms, such as the adherence of biochemical monomers to active surfaces, could have raised local concentrations and promoted polymerization (Bada and Lazcano 2009).

Given adequate expertise and experimental conditions, it is possible to synthesize almost any organic molecule. However, the fact that a number of molecular components of contemporary cells can be formed nonenzymatically in the laboratory does not necessarily mean that they were also essential for the origin of life or that they were available in the prebiotic environment. The primitive soup must have been a bewildering organic chemical wonderland, but it could not include all the compounds or molecular structures found today in even the seemingly most primitive prokaryotes. It is possible that some compounds, including perhaps RNA itself, may not have been synthesized prebiotically, so their occurrence in living systems may have been the result of early metabolic syntheses.

During the past few years, laboratory simulations of prebiotic synthesis have been developing models of specific detailed environments, including those that may have been provided by the

surface of clays, small volcanic ponds, and liposomes. Our ideas on the prebiotic synthesis of organic compounds are based largely on experiments in model system, and the evidence suggests that the remarkable coincidence between the molecular constituents of living organisms and those synthesized in prebiotic experiments is too striking to be fortuitous. The robustness of this type of chemistry is supported by the occurrence of many of these biochemical compounds in the 4.5-billion-year-old Murchison carbonaceous chondrite and other carbon-rich meteorites, suggesting that similar synthesis took place on the primitive Earth (Miller and Lazcano 2002).

Conclusions

How the first life evolved is not known, but analysis of carbonaceous chondrites and the laboratory simulations of the primitive Earth suggest that prior to the emergence of the first living systems, the prebiotic environment was endowed with (1) a large suite of organic compounds of biochemical significance; (2) many organic and inorganic catalysts (such as ► [cyanamide](#), metallic ions, sulfur-rich minerals and clays); (3) purines and pyrimidines, that is, the potential for template-dependent polymerization reactions; (4) membrane-forming compounds; and (5) the availability of many possible sources of carbon and nitrogen for primordial heterotrophs. Once life appeared and biosynthetic pathways developed, the reservoir of organic material present on the Earth then shifted from one initially characterized by compounds of abiotic origin to one made up entirely of biologically derived components (Lazcano 2010b).

The existence of different abiotic mechanisms by which biochemical monomers can be synthesized under plausible prebiotic conditions is well established. Of course, not all prebiotic pathways are equally efficient, but the wide range of experimental conditions under which organic compounds can be synthesized demonstrates that prebiotic syntheses of the building blocks of life are robust, that is, the abiotic reactions leading to

them do not take place under a narrow range defined by highly selective reaction conditions, but rather under a wide variety of experimental settings. Like other scientific metaphors, the term “primitive soup” is risky but useful and has become a part of popular lore. For all the uncertainties surrounding the emergence of life, it appears that the formation of the prebiotic soup is one of the most firmly established events that took place in the primitive Earth.

Cross-References

- [Aldehyde](#)
- [Amide](#)
- [Amine](#)
- [Amino Acid](#)
- [Ammonia](#)
- [Asteroid](#)
- [Clay](#)
- [Comet](#)
- [Cyanamide](#)
- [Haldane's Conception of Origins of Life](#)
- [Heterotrophic Hypothesis](#)
- [Hydrocarbons](#)
- [Meteorites](#)
- [Miller, Stanley](#)
- [Oparin's Conception of Origins of Life](#)
- [Pyrite](#)
- [RNA World](#)

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Principle of Plenitude

David Dunér

Lund University, Lund, Sweden

Keywords

Cosmology · History of Science · Philosophy of Science · Possibility

Synonyms

Fullness of being; *Plenum formarum*

Definition

The Principle of Plenitude suggests that every genuine possibility is realized or actualized. As an argument in astrobiology, this means that if an environment has the right conditions for life, one concludes that it also harbors life.

History

The Principle of Plenitude or “fullness of being” was coined by the historian of ideas, Arthur O. Lovejoy. In his classic volume *The Great Chain of Being* (1936) he explained the Principle of Plenitude as: “no genuine potentiality of being can remain unfulfilled, that the extent and abundance of the creation must be as great as the possibility of existence and commensurate with the productive capacity of a ‘perfect’ an inexhaustible Source, and that the world is the better, the more things it contains.” The universe is a *plenum formarum*, that is, all possible forms of existence have become realized. The principle has commonly been assumed in Western science and philosophy, from Plato, Aristotle, and Plotinus in the Antiquity, through medieval philosophers, to Spinoza, Leibniz, and the Enlightenment. In his dialogue, *Timaeus* from c. 360 BCE, Plato explained how the demiurge created a perfected world, and thus created all imaginable

possibilities (Plato 1989). The Principle of Plenitude was further more in line with a Christian worldview. God had, according to Christian theologians, made the creation of the world complete. All possibilities have actually been created.

The argument from the Principle of Plenitude, as Lovejoy claimed, lies behind much of the plurality of world debate up to the nineteenth century (Dick 1982; Crowe 1986, 2008; Crowe and Dowd 2013). In *De rerum natura* (On the Nature of Things) from the first century BCE, Lucretius proclaimed in an argument from plenitude: “when abundant matter is ready, when space is to hand, and no thing and no cause hinders, things must assuredly be done and completed” (Lucretius 2004). Giordano Bruno argued, in *De l’infinito, universo et mondi* (On the Infinite, Universe and Worlds, 1584), from the Principle of Plenitude when he supposed the idea of the plurality of worlds. Divine power cannot remain idle, and divine goodness must be infinitely diffused. Immanuel Kant wrote in *Allgemeine Naturgeschichte und Theorie des Himmels* (Universal Natural History and Theory of the Heavens, 1755): “Now, it would be senseless to set Godhead in motion with an infinitely small part of his creative ability and to imagine his infinite force, the wealth of a true inexhaustibility of nature and worlds to be inactive and locked up in an eternal absence of exercise.” Following the Principle of Plenitude, Kant says that creation rather ought to be a witness of this limitless power, an infinite manifestation of divine attributes. Johann Heinrich Lambert concluded in his *Cosmologische Briefe* (1761) from the Principle of Plenitude that other worlds must be inhabited. He asks: “Could the world be the effect of an infinitely active Creator, unless in every part of it life and activity, thoughts and desires, were found in the creatures? Could I conceive its perfection to consist in a continuous and inexhaustible diversification of similarities, and yet leave in it vacant places where there were no parts of a whole which should be infinitely complete? Such gaps I could not admit; and I had no hesitation in filling every solar system with habitable globes, so far as the admirable order which has been given to their course permits.”

Overview

The Principle of Plenitude was commonly used together with the Copernican Principle, stating that Earth has no privileged position in the universe. Implicit in the plenitude of the world was also the conception of continuity, a Chain of Being, from the simplest non-living matter to the most complex forms of life. Many proponents of the idea of a plurality of inhabited worlds explicitly started from the theological assumptions behind the Principle of Plenitude. If the universe was created by an omnipotent God, one concluded that this infinitely wise Creator also indeed created all possible things, because he was able to do it, and because one assumed that a richer and fuller creation is better than a poorer one. If life is something intrinsically good, a benevolent God must have filled the entire universe with life. This omnipotent and benevolent God would not have restricted himself and delimited life to just one minuscule place in the universe, our Earth. If other planets or stellar systems were devoid of life that would entail that God had wasted his creative power and had made desolate worlds to no use for any sentient being. The Principle of Plenitude, in other words, says that the universe ought to be as rich as possible. The Principle then implies that, because living things best demonstrate the richness of creation, life must be plentiful throughout the universe.

The Principle of Plenitude has historically been very influential in the debate concerning the existence of extraterrestrial life. But it is invoked implicitly or explicitly even today. Since the first confirmed discovery of exoplanets in 1995, the number of planets around normal Sun-like stars has turned out to be abundant. From an argument based on the Principle of Plenitude it seems tempting to conclude from this possible abundance of candidates for living planets that there must also exist life elsewhere in the universe. If the right conditions are in place, then the laws of nature would inevitably lead to the emergence of life. The Principle of Plenitude thus reminds of the principle of sufficient reason, which states that everything has a sufficient reason, cause, or explanation for being or not being. In this context,

plenitude means that if there is no sufficient reason for something not to be (or in other words, if it is indeed possible), then it exists. But a possibility is not a proof. What is possible is not always realized. Logically speaking, the Principle of Plenitude is not a valid argument. The right conditions for life do not entail that the actual environment also harbors life. It is a possibility, maybe a probability, and could in that respect function as a heuristic starting point for searching for extra-terrestrial life. But it is not a proof of life.

Cross-References

- [Bruno, Giordano](#)
- [Copernican Principle](#)
- [Cosmogony: Greece](#)
- [Great Chain of Being](#)
- [Life in the Solar System \(History\)](#)
- [Lucretius](#)
- [Plurality of Worlds](#)

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Prion

María Gasset

Consejo Superior de Investigaciones Científicas,
Instituto Química-Física Rocasolano, Madrid,
Spain

Keywords

Infectious agent · Protein aggregation · Protein conformation multiplicity · Protein-encoded infectivity · Protein-encoded inheritance · Strains

Definition

Prions are ► [protein](#)-based elements of infection and inheritance. Prions are made by alternate protein conformations that by acting as templates propagate their conformations to the precursor proteins. In general, this propagative state is an insoluble polymer, rich in tightly packed β -sheets and displaying amyloid staining features. This state is not structurally unique but polymorphic allowing strains. The protein undergoing prion conversion loses its normal function and acquires the ability to transform the precursor into its like. This protein conformational code provides physiological switches for fast environmental adaptation and underlies the spread of the mammalian neurodegenerative diseases known as transmissible spongiform encephalopathies.

History

The unique inactivation pattern displayed by the infectious agent causing scrapie reported by Alper et al. (1967) prompted Griffith (1967) to propose the “protein-only” hypothesis to explain a nucleic

acid-free information flow. This hypothesis considered mechanisms by which a protein could display replicative properties, as a catalyzed conformation and/or aggregation change. On the basis of the purification of the infectious agent causing scrapie, Prusiner (1982) coined the terms prion and PrP to refer to the proteinaceous infectious particle and the component protein, respectively. Since then, PrP prion properties have been ascribed to a conformational change from a normal cellular form (PrP^C) to a propagative form (PrP^{Sc}) that causes disease by converting the membrane-bound cellular form into its like. Whereas PrP^C is soluble and easily degraded by proteinase K, PrP^{Sc} is rich in β -sheets and aggregates into fibrils after proteinase K digestion (Prusiner 1998). While the essentiality of PrP^C for the prion infectivity, the propagative nature of PrP^{Sc} conformation, and its multiplicity have been demonstrated, the infectivity synthesized with pure protein polymers still provokes controversy by virtue of its low efficiency or by the requirement of effectors (Deleault et al. 2007; Aguzzi and Calella 2009; Colby et al. 2010; Makarava et al. 2010). Based on genetic observations, Wickner (1994) generalized the prion concept. Since then, an increasing number of yeast and fungi proteins exhibiting prion behaviors have been described. In fact, most of the compelling evidences for the prion concept have been established using these models. Of them, the direct demonstration of the infectious activity of a pure protein in its prion form was provided by [Het-s] prion (Maddelein et al. 2002). Establishment of the cell-to-cell transmissibility of some cytosolic self-aggregating proteins involved in distinct human disorders may allow soon their qualification as prions.

Overview

Despite being always viewed under the danger of their action and their heretical composition, prions are simply alternate structural states of proteins that, while perpetuating and transmitting, permit a fast and sustainable functional switch in response

to a trigger (Aguzzi and Calella 2009; Halfmann et al. 2010). In yeast, fungi, and mollusks, prions represent a beneficial biological tool for adaptation to environmental changes. For mammalian prions, the trigger remains unknown and is largely related to disease.

Proteins undergoing prion formation are structurally unrelated. However, according to the polypeptide chain, they can be classified into two groups. A first group is formed by those proteins containing a domain, generally featured by a high proportion of Q/N, which is indispensable for the function but hosts the prion formation capacity. The second group, exemplified by PrP, accounts for those chains in which the residues responsible for the prion function are scattered along the sequence.

Prion formation involves a conformational change in the precursor protein, which enables its polymerization. The resulting polymer is generally maintained by tightly packed intermolecular β -sheets that confer the assembly a peculiar resistance to degradation. Also, the feasibility of alternative packing arrangements makes possible a polymorphism in the assembly, which underlines the *strain* phenomena (Wiltzius et al. 2009).

Replication of prions occurs through the template-conversion of the precursor protein into its like. This reaction is a complex process involving steps of molecular recognition under the control of the protein sequence. Such recognition dependency sustains the *species-barrier* dependency of its transmissibility.

In addition to the previous traits, self-perpetuating protein aggregates become prions when they exhibit tractable cell-to-cell *transmission*. In prions from low organisms, transmission is linked to cell division and therefore follows an inheritable pattern, whereas in mammals, prions must travel from one cell to another (Aguzzi and Rajendran 2009).

Cross-References

- [Protein](#)
- [Proteins, Secondary Structure](#)
- [Proteins, Tertiary Structure](#)

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Priscoan

- [Hadean](#)

Privatization of Space

- [Commercial Use of Space](#)

Pro

- [Proline](#)

Probing Lensing Anomalies Network

David W. Latham¹, B. Scott Gaudi² and Nader Haghighipour³

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Department of Astronomy, Ohio State University, Columbus, OH, USA

³Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Synonyms

[PLANET](#)

Definition

The PLANET (Probing Lensing Anomalies Network) was a worldwide collaboration of astronomers that used telescopes spread throughout the Southern Hemisphere to follow up microlensing events discovered by other teams such as OGLE and MOA, in order to search for the short-lived signatures of exoplanets. In 2006, PLANET (along with the RoboNet, OGLE, and MOA collaborations) announced the discovery of the first cool ► [super-Earth](#) planet ► [OGLE-2005-BLG-390Lb](#). The PLANET collaboration ended in 2007. In 2009, a new collaboration, μ FUN-PLANET, was initiated.

Cross-References

- [Exoplanets, Discovery](#)
- [Microlensing Observations in Astrophysics](#)
- [OGLE-2005-BLG-390Lb](#)
- [Optical Gravitational Lensing Experiment](#)
- [Super-Earths](#)

Prokaryote

Ramon Rosselló-Móra
IMEDEA (CSIC-UIB), sporles, Mallorca,
Balearic Islands, Spain

Keywords

Archaea · Bacteria · Microorganism

Synonyms

[Bacteria](#)

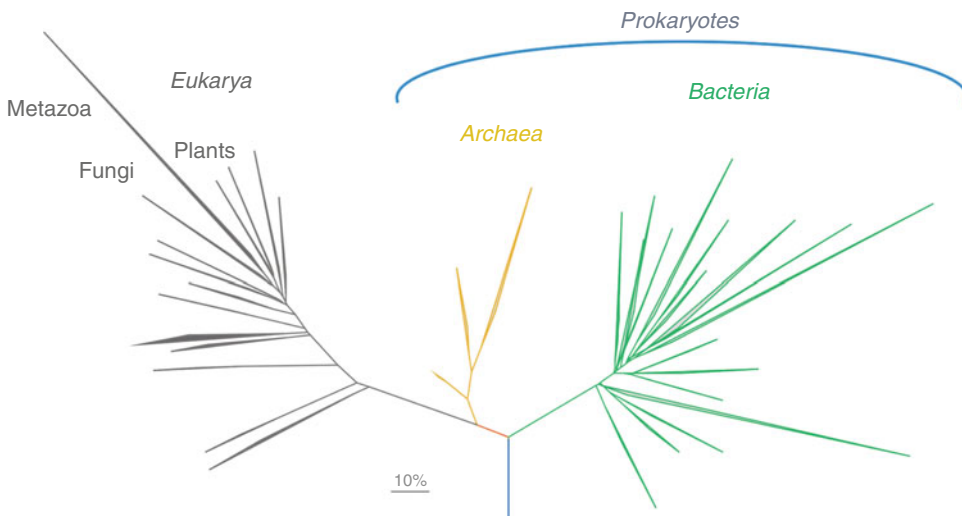
Definition

Prokaryote (from Greek *pro* [before] and *karyon* [nucleus]) denotes organisms that lack a membrane-enclosed nucleus, as well as other [organelles](#).

Overview

Cellular life is represented by three lines of descent: the domains [Bacteria](#), [Archaea](#),

and [Eukarya](#). Two of them (*Bacteria* and *Archaea*) are embraced by the term “prokaryote,” a term that has no standing in the taxonomic hierarchy. From the phylogenetic reconstructions based on the analysis of the ribosomal small subunit gene sequences, it seems that both domains differ dramatically in their evolutionary history (see Fig. 1). In this regard, *Archaea* and *Eukarya* seem to share a common ancestor, whereas *Bacteria* seem to be an independent line of descent. In contrast to eukaryotic cells, prokaryotes have a simpler internal structure, lacking membrane-enclosed organelles. Prokaryotes do not develop or differentiate into multicellular forms. Some grow in filaments, or masses of cells, but each cell in the colony is identical and capable of independent existence, they never form specialized tissues. It is generally accepted that the first living cells on the earth were prokaryotes that might have appeared about 3.5 billion years ago or before, and remained alone for about 1.5 billion years until the eukaryotes developed (2.0 billion years ago). Prokaryotes are considered to be the most abundant living cells in the biosphere, with numbers that range from 4×10^{30} to 6×10^{30} , and that produce a biomass equivalent to that of the vegetal material. They colonize almost every place on the earth where life is possible, and



Prokaryote, Fig. 1 Phylogenetic reconstruction based on 16S rRNA gene sequence analyzes of the three domains of life. The figure shows that the Prokaryotes appear to be a paraphyletic group embracing Archaea and Bacteria

show the widest range of extreme life habitats. They colonize any available surface and cavity, and their abundance depends on the habitat. For example, 1 cm³ may contain about 10⁶ cells in seawater, 10⁹ in sediments, 10¹² in soils, 10¹⁰ in animal gut. Their metabolism is very diverse and can obtain energy from light (phototrophy), inorganic chemicals (chemolithotrophy), or organic chemicals (chemoorganotrophy). Some can fix inorganic carbon (autotrophy), but others depend on the assimilation of organic carbon (heterotrophy). Respiratory metabolism can occur aerobically (by reducing oxygen as a terminal electron acceptor), or anaerobically (by reducing a wide range of molecules such as sulfate, nitrate, iron, manganese, among others). On the other hand, some organisms ferment (reducing organic products of their own metabolism), or generate methane as a product of their anaerobic oxidative metabolism. In the prokaryotic world all these combinations are possible, and many of them can switch their metabolism depending on environmental conditions and the availability of different carbon and energy sources. The endosymbiosis of prokaryotes with eukaryotic cells had been essential for the development of the latter in the biosphere. Mitochondria seem to have originated from the symbiosis of an alphaproteobacterium, and gave eukaryotes the ability to respire oxygen. Chloroplasts seem to have their origin from a symbiosis with a cyanobacterium that gave algae and plants their photoautotrophic metabolism. Some animals show additional symbiosis with chemolithotrophs that provided them with an autotrophic metabolism. Prokaryotes are essential for the development of the biogeochemical cycles in the biosphere, and finally are responsible for recycling the basic elements that maintain life.

Cross-References

- ▶ [Archaea](#)
- ▶ [Biogeochemical Cycles](#)
- ▶ [Cyanobacteria](#)
- ▶ [Electron Acceptor](#)
- ▶ [Endosymbiosis](#)

- ▶ [Eukarya](#)
- ▶ [Fermentation](#)
- ▶ [Microorganism](#)
- ▶ [Organelle](#)
- ▶ [Prokaryotes, Origin of](#)

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Prokaryotes, Origin of

Purificación López-García

Unité d'Ecologie, Systématique et Evolution,
CNRS UMR8079 Université Paris-Sud 11, Orsay
Cedex, France

Keywords

Archaea · Bacteria · Cenancestor · Early diversification of life domains · Last universal common ancestor

Definition

Prokaryotes are organisms constituted by cells lacking a nuclear membrane that separates the genetic material from the rest of the cytoplasm and, consequently, where transcription from

DNA to mRNA and translation from mRNA to proteins are coupled. As soon as mRNA begins to be synthesized, ribosomes begin to attach to it and translate it into protein on one end while transcription proceeds at the other end. There are two groups of organisms having a prokaryotic cell structure: ► [archaea](#) and ► [bacteria](#). The origin of prokaryotes refers to the origin and evolution of their shared common ancestor.

History

The terms *prokaryote* and *eukaryote* were introduced with their actual meaning in biology by microbiologists R. Stanier and C.B. van Niel in 1962. At that time, however, the third domain of ► [life](#), the archaea, had not yet been discovered, and prokaryotes were synonymous to bacteria. With the discovery of the archaea as a phylogenetically distinct domain of organisms, as distant from bacteria as from eukaryotes, it became clear that the term *prokaryote* should refer exclusively to a structural kind of cell but had no phylogenetic sense, since it grouped organisms from two far-distant groups.

Overview

The origin of prokaryotes can be viewed in two different ways, either as the origin of the ancestor from which archaea and bacteria diverged but also as the origin (specialization and/or diversification) of archaea and bacteria from that ancestor. The problem of the origin of prokaryotes is therefore intimately linked to that of the root of the tree of life and the evolution of the three phylogenetic domains of organisms. This is a highly debated and far-from-solved issue. Several theoretical possibilities have been proposed to explain the major splits in the three organismal domains, archaea, bacteria, and eukaryotes. One proposes that the last cenancestor (last universal common ancestor) was eukaryotic like and that prokaryotes derived from that ancestor by a reduction process, perhaps linked to the adaptation to high temperatures. This hypothesis is the least favored by

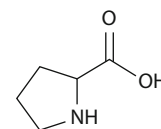
mainstream science, owing to the difficulties of explaining the origin of a rather complex eukaryotic cell early in evolutionary times from scratch. All the other hypotheses sustain the idea that prokaryotes emerged before eukaryotes and, hence, that the origin of prokaryotes is coincident with that of the last cenancestor. There are two major models for the evolution of the three domains of life from such a prokaryotic ancestor. The first proposes that the cenancestor splits in one branch leading to the bacteria and another branch that subdivided later into two branches corresponding to that of the archaea and to a third hypothetical protoeukaryotic branch in which the nucleus and several eukaryotic features such as phagocytosis evolved. This model, supported by C.R. Woese, is the most popular and the one explained in most textbooks. A related, though quite minority, model proposing the existence of a protoeukaryotic lineage sister to the archaea is that by T. Cavalier-Smith, who proposes that archaea and eukaryotes derive from within Gram-positive bacteria, sharing with them the possession of only one cell membrane. The second, increasingly expanding, set of models proposes that the last cenancestor simply split into two major branches leading to, respectively, archaea and bacteria. Eukaryotes would be the evolutionary outcome of one (or two) symbiotic event(s) between archaea and bacteria. The bifurcation between the archaeal and bacterial lineages would have been accompanied by a specialization of their membrane lipids and the replication machinery of DNA, which are very different in both lineages, as well as the fine-tuning of transcription and translation. The last cenancestor from which archaea and bacteria evolved was certainly a rather complex organism, but how and when it evolved from earlier life forms remain obscure at present.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Cyanobacteria](#)
- [Eukaryote](#)

- [Eukaryotes, Appearance and Early Evolution of](#)
- [Life](#)
- [LUCA](#)
- [Prokaryote](#)

Proline, Fig. 1 Structure of proline



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Proline

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Synonyms

[Pro](#); [Pyrrolidine-2-carboxylic acid](#)

Definition

Proline, C₅H₉NO₂, is one of the 20 protein amino acids. The amine in proline is a secondary amine (Fig. 1), whereas the other 19 coded amino acids

all contain primary(–NH₂) amino groups. Its three-letter symbol is Pro, and its one-letter symbol is P. It has a molecular weight of 115.13, and its isoelectric point is 6.30. Proline is a hydrophobic ► [amino acid](#). Since it contains a secondary amino group, its reactivity is different from that of the other amino acids, and special care is needed for its determination. For example, the reaction product of proline with ninhydrin is of a different color from that of the other coded amino acids.

Cross-References

- [Amino Acid](#)
- [Protein](#)

Propanal

- [Propionaldehyde](#)

Propanenitrile (IUPAC Name)

- [Ethyl Cyanide \(CH₃CH₂CN\)](#)

Propanone

- [Acetone \(CH₃COCH₃\)](#)

1, 2, 3-Propantriol

- [Glycerol](#)

Propene

► [Propylene](#) (CH_3CHCH_2)

2-Propenenitrile (IUPAC Name)

► [Vinyl Cyanide](#) (CH_2CHCN)

Proper Motion

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Apparent motion](#)

Definition

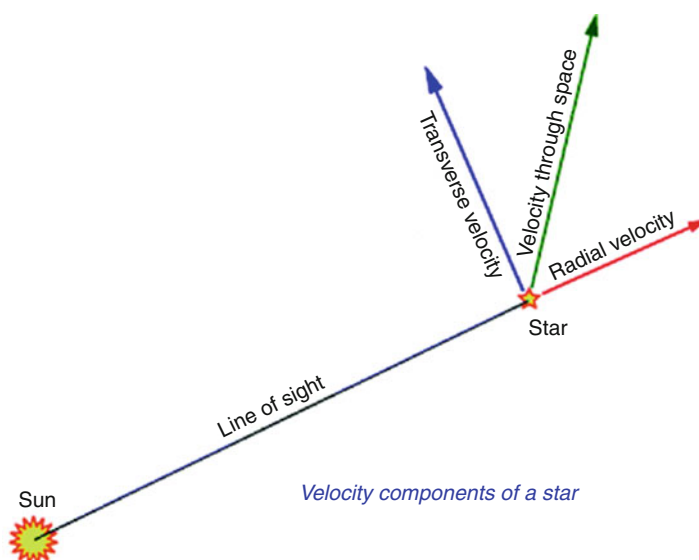
The proper motion is the apparent angular motion of a star or any celestial object on the

celestial sphere, as measured from the position of the Sun. Proper motion is given in arc seconds per year for each component of the equatorial coordinates (► [right ascension](#) and ► [declination](#)). Proper motion should not be confused with ► [parallax](#), which is the apparent motion of a star on the sky in 1 year, caused by the motion of the Earth as it travels along its orbit around the Sun.

Since the apparent motion is due to the star's velocity with respect to the Sun, the proper motion is proportional to the ratio of transverse velocity to distance; it is consequently larger when the star is nearby (Fig. 1). For instance, Barnard's star, one of the closest stars to the solar system (6 light-years), has the largest proper motion of all stars, moving at 10.3 s of arc per year (Fig. 2).

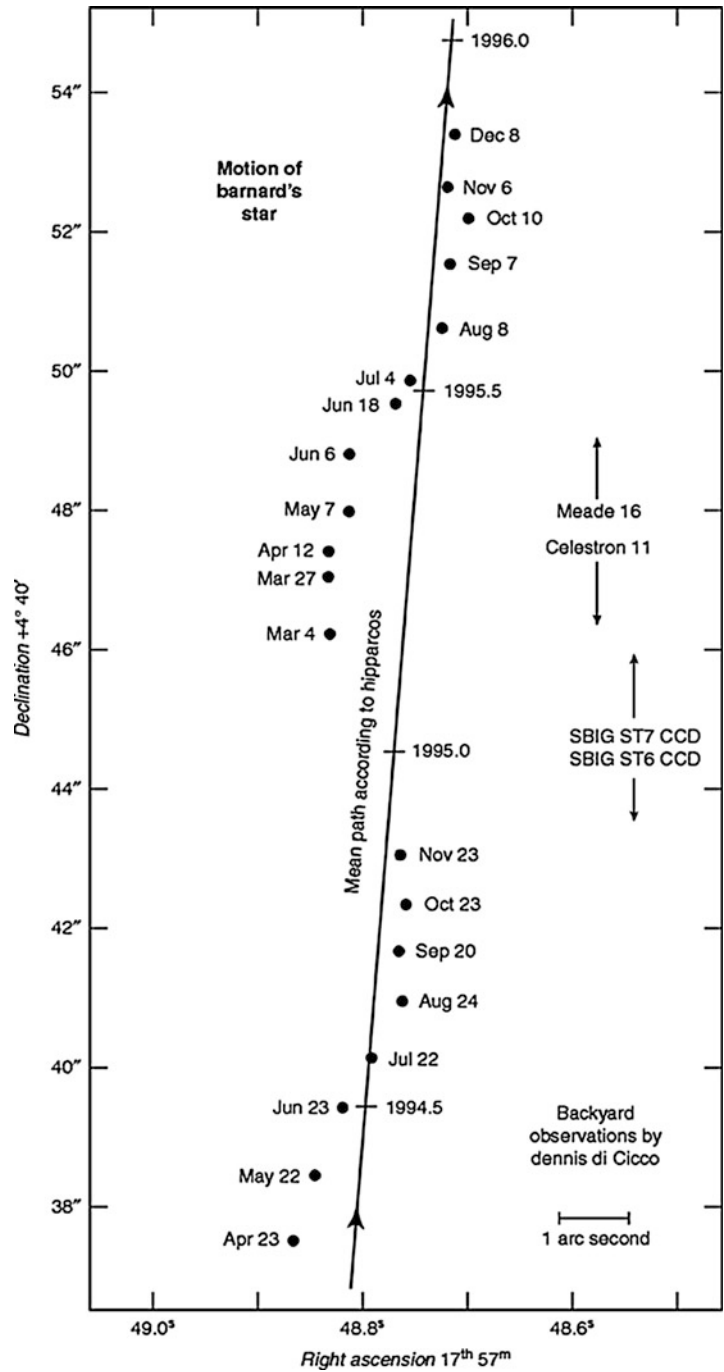
Until recently, proper motions of stars were obtained by comparing photographic sky survey images taken many years apart. The European ► [Hipparcos](#) satellite brought a revolution in the 1990s by providing much more accurate proper motion measurements for several millions of stars. The Gaia space mission launched in fall 2013 will extend the catalog to a billion stars with another very big step in accuracy.

Proper Motion, Fig. 1 A star has a certain velocity through space with respect to the Sun, and the transverse component of this velocity corresponds to the proper motion



Proper Motion,

Fig. 2 The nearby Barnard's star exhibits a very large proper motion, as illustrated by the measurements obtained by the European satellite Hipparcos



Since stars with large proper motions tend to be nearby, this is a way to select targets for exoplanet searches, either for direct detection or when the astrometric technique is used.

Cross-References

- [Coordinate Systems](#)
- [Parallax](#)

Propionaldehyde

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Synonyms

[CH₃CH₂CHO](#); [Propanal](#)

Definition

Propionaldehyde is an organic compound with the formula CH₃CH₂CHO. It is a colorless liquid at room temperature and pressure. Propionaldehyde has been discovered in the interstellar medium. Propionaldehyde is a Strecker synthesis precursor to α -amino-n-butyric acid, which has been detected in several carbonaceous chondrites.

Cross-References

- ▶ [Aminobutyric Acid](#)
- ▶ [Molecules in Space](#)

Propionitrile

- ▶ [Ethyl Cyanide \(CH₃CH₂CN\)](#)

Propyl

- ▶ [Protoplanetary Disk](#)

Propyl Cyanide (C₃H₇CN)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[C₃H₇CN](#)

Definition

The molecule propyl cyanide has two isomers, both of which have been detected in interstellar molecular clouds. The straight-chain isomer, *n*-propyl cyanide, is also called 1-cyanopropane, butyronitrile, or butanenitrile (the IUPAC name); while the branched form, *i*-propyl cyanide, is also known as 2-cyanopropane, *iso*-butyronitrile, and 2-methylpropanenitrile (IUPAC name). Moreover, *n*-propyl cyanide has two conformers, *anti*- or *a-n*-propyl cyanide and *gauche*- or *g-n*-propyl cyanide, where the former has a planar heavy atom frame and the latter has the CH₃-group or the CN-group rotated by 120°.

History

Propyl cyanide is among the largest organic molecules unambiguously detected by radio astronomers in the ▶ [interstellar medium](#). The lower energy, *anti*-conformer of *n*-propyl cyanide, was detected in the Galactic Center molecular cloud Sgr B2(N) by Belloche et al. (2009), who suggested that it may be produced by surface reactions on ▶ [interstellar dust](#) grains, perhaps by sequential addition of CH₂ or CH₃ radicals to known interstellar species such as CN and CH₂CN. It is the third member of the series that includes methyl cyanide (CH₃CN) and ▶ [ethyl cyanide](#) (CH₃CH₂CN).

Both the *gauche*-conformer of *n*-propyl cyanide and the isomer *i*-propyl cyanide were

subsequently detected in the same source by Belloche et al. (2014) using ALMA, and more recent observations have detected both isomers in the Orion molecular cloud. *I*-propyl cyanide is the first detected interstellar molecule that has a branched carbon backbone.

Cross-References

- [ALMA](#)
- [Ethyl Cyanide \(CH₃CH₂CN\)](#)
- [Interstellar Dust](#)
- [Molecules in Space](#)

References and Further Reading

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Propylene (CH₃CHCH₂)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[CH₃CHCH₂](#); [Methylethylene](#); [Propene](#)

Definition

Propylene (IUPAC name propene) is an unsaturated hydrocarbon with a double bond, the second alkene after ethylene. It is a gas at standard ambient temperature and pressure. It can polymerize

(polypropylene). It has been detected in the interstellar medium.

History

Propylene was not specifically searched for in the interstellar medium, as its rotational lines were expected to be weak, due to its low electric dipole moment. It has, however, been detected serendipitously in a spectral survey toward the dark cloud TMC-1 (Marcelino et al. 2007).

Cross-References

- [Molecules in Space](#)

References and Further Reading

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Propylene Oxide (CH₃CHCH₂O)

Brett A. McGuire¹ and P. Brandon Carroll²
¹Department of Chemistry, Massachusetts
Institute of Technology, Cambridge, MA, USA
²Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Methyl oxirane](#)

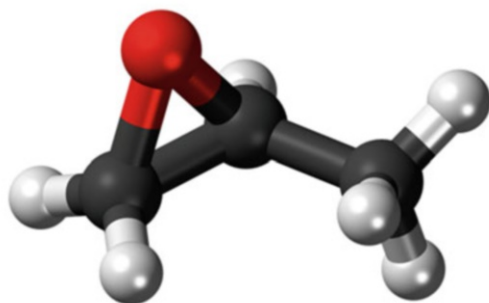
Chemical Formula

CH₃CHCH₂O

Definition

Propylene oxide (CH_3CHCH_2O) is a cyclic, chiral organic molecule detected in the interstellar medium toward the Sagittarius B2(N) high-mass star-forming region.

Structure



History

An unsuccessful attempt to detect propylene oxide in Sgr B2 and Orion was reported by Cunningham et al. (2007) using mm-wavelength observations. The successful detection of propylene oxide was later reported by McGuire et al. (2016) in the PRIMOS Molecular Line Survey of Sgr B2(N) using the Green Bank Telescope, and in confirming observations with the Parkes Radio Telescope, all at cm-wavelengths. It is the first chiral molecule to be detected outside the Solar System. The measurement was not able to discern whether an enantiomeric excess was present in the source. Theoretical work by Salzman (1998) has suggested that propylene oxide may be an excellent candidate molecule for observing microwave circular dichroism for the first time, providing a possible means by which an excess could be observed.

Cross-References

- [Chirality](#)
- [Homochirality](#)
- [Interstellar Medium](#)
- [Molecular Line Survey](#)

References and Further Reading

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Propynyl Radical

- [Propynylidyne \(\$C_3H\$ \)](#)

Propynylidyne (C_3H)

William M. Irvine
Department of Astronomy,
University of Massachusetts,
Amherst, MA, USA

Synonyms

[Propynyl radical](#)

Chemical Formula

C_3H

Definition

The radical C_3H can exist in either a linear form ($l-C_3H$) or as a tricarbon ring with the attached hydrogen atom ($c-C_3H$). Both isomers have been detected at millimeter wavelengths in the interstellar medium and in the envelopes of evolved

stars. C_3H is an important intermediary in the production of heavier species of the form C_nH ($n > 3$), which have been detected astronomically for $n = 4$ –8. The linear propynylidynium ion, C_3H^+ , has also been reported in the interstellar medium (Pety et al. 2012).

Cross-References

- [Interstellar Medium](#)
- [Molecules in Space](#)
- [Radical](#)

References and Further Reading

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Propynylidynium (C_3H^+)

William M. Irvine
Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Propynylidynium](#), $\text{l-C}_3\text{H}^+$

Definition

The cation C_3H^+ is thought to play an important role in gas phase reactions in the ► [interstellar medium](#) that lead to the formation of small

hydrocarbons. The neutral radical, C_3H (► [propynylidyne](#)) can exist in both a linear ($\text{l-C}_3\text{H}$) and a cyclic ($\text{c-C}_3\text{H}$) form, and both these neutral species have been detected in interstellar molecular clouds.

History

A detection of the linear cation C_3H^+ (denoted $\text{l-C}_3\text{H}^+$) in an interstellar ► [photodissociation region](#) was first reported by radio astronomers (Pety et al. 2012). Although in the absence of laboratory data on its rotational spectrum the identification was initially questioned, the carrier of the detected emission lines was subsequently detected in other molecular clouds (McGuire et al. 2013). Laboratory spectra and very accurate theoretical calculations have Brünken et al. (2014) and Botschwina et al. (2014) confirmed C_3H^+ as the carrier of the lines observed by radio astronomers. Recent observations confirm that this ion is ubiquitous in the diffuse interstellar medium (Gerin et al. 2019).

Cross-References

- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Photodissociation Region](#)
- [Propynylidyne \(\$\text{C}_3\text{H}\$ \)](#)

References

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Pety J, Gratier P, Guzmán V, Roueff E, Gerin M, Goicoechea JR, Bardeau S, Sievers A, Le Petit F, Le Boulrot J, Belloche A, Talbi D (2012) The IRAM-30 m line survey of the horsehead PDR. II. First detection of the $\text{I-C}_3\text{H}^+$ hydrocarbon cation. *Astron Astrophys* 548:A68

Propynylidyne, $\text{I-C}_3\text{H}^+$

► [Propynylidyne \(\$\text{C}_3\text{H}^+\$ \)](#)

Protein

Eric Gaucher¹ and Vanessa Cox²

¹School of Biology, Georgia Institute of Technology, Atlanta, GA, USA

²Georgia Institute of Technology, Atlanta, GA, USA

Keywords

Amino acid · Enzyme · Translation

Synonyms

[Peptide](#); [Polypeptide](#)

Definition

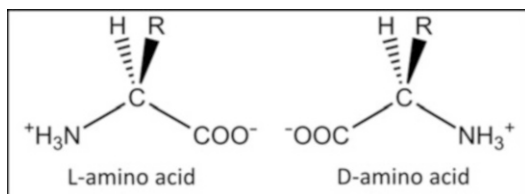
A protein is a biopolymer comprised of a linear chain of amino acids. Proteins not only act as the main catalytic molecules of life in the form of enzymes, they also serve structural, mechanical, and signaling roles, as well as other cellular functions. The chemical properties of amino acids and their sequential organization determine how a protein folds into a three-dimensional structure. This structure, in turn, dictates the function of the protein molecule. Instructions for the amino acid sequence of a protein are stored in the genetic material of a cell in the form of a gene.

History

According to the “RNA World” hypothesis, prior to the evolution of protein synthesis, RNA oligonucleotides acted as both the information carrier and the catalytic molecule of life. If true, proteins eventually replaced these oligonucleotides as superior catalytic molecules. Today, proteins are largely responsible for a cell’s metabolism and play a key role in most cellular processes. Although proteins are most noted for their catalytic capabilities, they also act as key structural components of cells, having important roles in the cytoskeleton and transport of small molecules through the cellular membrane. Researchers are able to study ancient life through a process termed ancestral sequence reconstruction to gain insight into ancient proteins, ancient organisms, and the environments in which ancient organisms may have lived. Across the domains of life, all proteins are made up of a canonical set of 20 different amino acids. However, evidence suggests that early proteins were likely synthesized from a reduced set of amino acids and that this set evolved over time to incorporate additional amino acids which have expanded chemical functionalities. Some interesting questions astrobiologists attempt to address include why nature selected these particular 20 amino acids, what was the function of early proteins, and how did the protein synthesis machinery evolve.

Overview

Proteins are linear biopolymers composed of a non-branching chain of amino acid monomers. All amino acids consist of a hydrogen atom, an amino group, a carboxyl group, and an R-group attached to a central alpha carbon. The R-group varies among amino acids and is the distinguishing feature between one amino acid and another. The various R-groups allow amino acids to exhibit a range of solubilities, hydrophobicities, and reactivities while maintaining a basic structure. Although dozens of different amino acid species can be observed in meteorites or as products in prebiotic synthesis experiments, all



Protein, Fig. 1 L and D amino acids. Biotically synthesized amino acids are found in the L configuration. However, abiotic amino acids, including those synthesized in labs or identified in meteors, can exhibit either chirality

known life uses the same set of 20 (or, in some cases, 22) amino acids for protein synthesis. This conservation of proteinogenic amino acid species, along with their uniform chirality (L) and central alpha carbon, led to one of the first hypotheses that all life on Earth evolved from a common ancestor (Fig. 1).

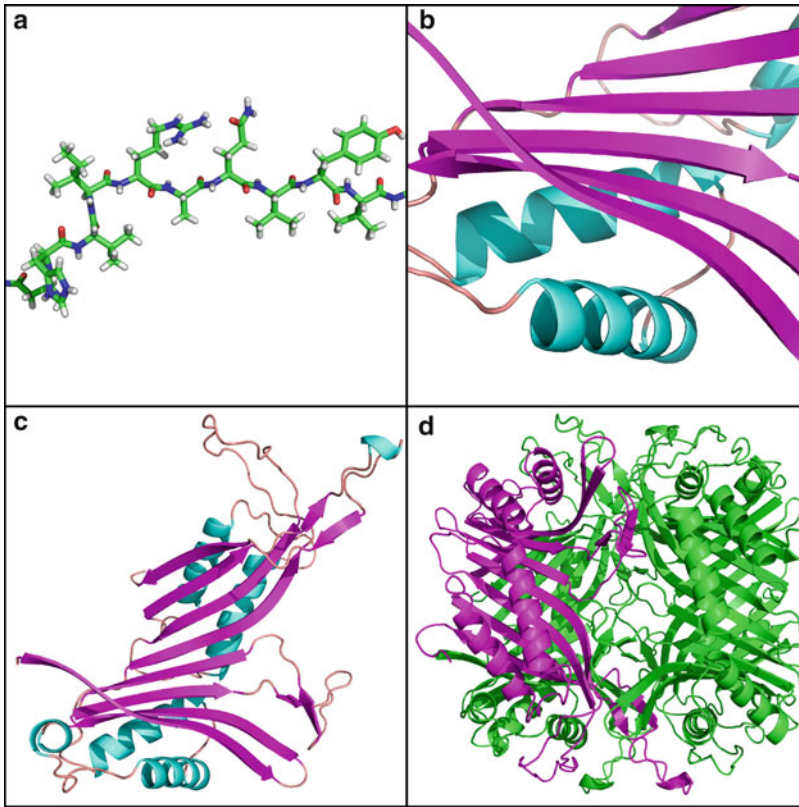
The sequence of amino acids comprising a protein is specified by its corresponding gene in the cell's genetic material and determines the structure and function of the protein. The sequence of amino acids is known as the primary structure of a protein. As a protein is synthesized (i.e., translated), the various chemical properties of the amino acid R-groups (such as size, charge and polarity) lead to chemical interactions that cause the growing chain of amino acids to adopt a three-dimensional structure. Local regions of a protein generally form alpha-helix or beta-sheet conformations, which can then fold to bring distal regions of the protein into close proximity. Alpha-helices and beta-sheets are classified as types of secondary structure. The three-dimensional arrangements of alpha-helices and beta-sheets in relation to each other create the protein's tertiary structure. Some proteins also have quaternary structure when multiple three-dimensional proteins associate as subunits to form a larger protein complex (Fig. 2). Chemical modifications of proteins (post-translational modifications) are often used to stabilize or modify protein structures (i.e., disulfide bonds) or to change their chemical and functional properties (i.e., methylation).

To assemble a protein's primary structure, individual amino acids are linked by a peptide bond between the carboxyl group of one amino acid and the amino group of the next amino acid via a condensation reaction. Due to resonance

structures, the peptide bond has some double-bond characteristics that make it much more rigid and slightly shorter than a true single-bond. Additionally, the six atoms comprising the peptide group are planar in spatial organization, which imparts rigidity to the peptide backbone (Fig. 3). These restrictions severely limit the number of conformations a protein's backbone can adopt. Such rigidity provides the peptide chain with a constrained shape and limited flexibility, and, thus, explains the prevalence of the secondary structural elements discussed above.

The alpha-helix and beta-sheet conformations allow hydrogen bonding between the positively charged amino groups and the negatively charged carboxylate groups along the backbone of a protein. Since the amino and carboxyl groups are charged at physiological pH, the result of these associations is the hydrophobicity of the protein is controlled by the amino acid R-groups, the side chains which differ among amino acids and lend them specific functionality, as opposed to the protein backbone, which is common to all proteins. Thus, not only can proteins demonstrate a wide range of hydrophobicities, but even within a single protein, different regions can have different hydrophobicities. A random coil (also called a beta-turn or a reverse turn) is another class of secondary structure identified by the absence of a regular secondary structure. These are amino acid sequences which are not part of an alpha-helix or beta-sheet but often connect these more common secondary structures.

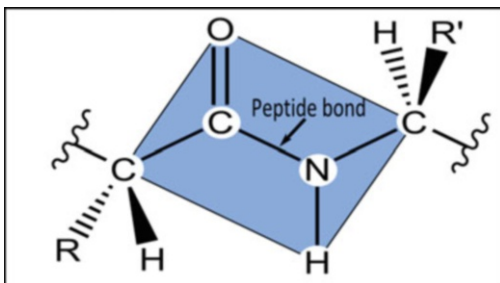
The design of the secondary structure participates in the formation of the tertiary and quaternary structure of the protein. Proteins must balance hydrophobic and hydrophilic properties in order to fold properly and fulfill their prescribed cellular function. For example, proteins active in the cytoplasm must be water-soluble. Additionally, the exterior of the protein and the interior of the protein may have different hydrophobicities. For example, a transport protein in a cell's membrane would have a hydrophobic exterior so it can span the lipid bilayer, while the interior core of the protein might be hydrophilic to allow water-soluble molecules passage between the interior and exterior of a cell, a passage not otherwise possible with a lipid bilayer.



Protein, Fig. 2 Ancient uricase structure. Above are cartoon depictions of the crystal structure of an ancient uricase. Frame (a) shows the primary structure of a beta-strand, part of a beta-sheet, whose sequence is histidine, valine, isoleucine, arginine, alanine, glutamine, valine, tyrosine, and valine *left to right*. Carbon atoms are *green*, nitrogen are *blue*, oxygen are *red*, hydrogen are *white*. The peptide backbone bisects the frame with the amino acids' R-groups protruding above and below the backbone. Frame (b) depicts alpha-helix (*blue*) and beta-sheet

(*magenta*) structures with the remaining portions colored salmon. Frame (c) illustrates the protein's tertiary structure. The *magenta* beta-sheets and *blue* alpha-helices make up the peptide strand's three-dimensional structure. In Frame (d), four monomers associate as a tetramer forming the proteins' quaternary structure. One monomer is highlighted in *magenta*; the other three are *green*. To make a functional uricase enzyme, 11 of these tetramers would associate to make the full protein complex

P



Protein, Fig. 3 Planar peptide group. The six planar atoms surrounding the peptide bond, highlighted by the *blue* polygon, impart rigidity to the peptide's primary structure, leading to the formation of the most common secondary structures, alpha-helices and beta-sheets

Cross-References

- [Alpha Helix](#)
- [Amino Acid](#)
- [Chirality](#)
- [Enzyme](#)
- [Genetic Code](#)
- [Hydrophobic Effect](#)
- [Meteorites](#)
- [Miller, Stanley](#)
- [Peptide](#)
- [Polypeptide](#)
- [Proteins, Primary Structure](#)

- [Proteins, Quaternary Structure](#)
- [Proteins, Secondary Structure](#)
- [Proteins, Tertiary Structure](#)
- [Ribosome](#)
- [Translation](#)

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Protein Synthesis

- [Translation](#)

Proteinoid Microsphere

Koichiro Matsuno
Nagaoka University of Technology, Nagaoka,
Japan

Keywords

Amino acids · Microspherules · Protocells

Synonyms

[Thermal copolymers of amino acids](#)

Definition

Proteinoid microspheres are spherical structures to be formed when a heated mixture of amino acid molecules in the dry conditions is dissolved in water. The diameter of a typical microsphere is about a few micrometers.

Overview

The first experimental observation of proteinoid microsphere was made by Sidney W. Fox, Kaoru Harada and their colleague in 1959 (Fox et al. 1959). The term proteinoid coined by Fox is for a thermal copolymer of amino acid molecules. Proteinoids maintain within themselves side-chain bonds in addition to peptide bonds.

Proteinoids readily form microspherules in water. This is due to the fact that they are amphiphilic, consisting of molecules having a polar water-soluble group attached to a water-insoluble group. The presence of a polar water-soluble group which can easily be ionized has indirectly been confirmed in a dynamic manner by observing the oscillation of electrical potential of the surface of proteinoid microspheres. In addition, when the proteinoids are rich in basic amino acids such as arginine and lysine, the surface of the resulting microsphere can have local areas where naked positive charges are exposed directly to the immediate surroundings. These naked positive charges can attract some types of molecule having negatively charged locales. A typical example of molecule having negatively charged locales includes both amino acids and nucleic acids. The surface of proteinoid microspheres may provide a reaction site for further chemical synthesis to follow. Furthermore, proteinoid microspheres can exhibit some forms of dynamic structural flexibility including an instance of giving birth to daughter microspheres through budding when the ionic strength or the pH of the aqueous milieu is changed.

Then, it would seem to follow that proteinoid microspheres may serve as a model of proto-cell in prebiotic evolution as championed by Fox. However, the subtle part in the claim of proteinoid microspheres as a model of protocell is in the difficulty of refuting the claim itself. A reliable model must be explicit in drawing the demarcation line beyond which it is not applicable. Although the model of proteinoid microspheres does not meet the requirement yet, this does not mean that it is irrelevant. The future fate of the proteinoid model remains to be seen.

Cross-References

► [Protocell](#)

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Protein-Protein Interaction Networks

► [Biological Networks](#)

Proteins, Primary Structure

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

The primary structure of a peptide or a ► [protein](#) describes the linear sequence of its amino acid units. By convention, the sequence of a protein

or peptide is reported starting from the amino-terminal (NH₂) end. Proteins also often contain disulfide cross-linkages, and the primary structure also specifies the cross-linking ► [cystine](#) residues. The primary structure also describes other post-translational and interstrand linkages.

Cross-References

► [Cysteine](#)
► [Cystine](#)
► [Disulfide Bond](#)
► [Protein](#)
► [Proteins, Secondary Structure](#)
► [Proteins, Tertiary Structure](#)

Proteins, Quaternary Structure

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Many proteins are composed of more than one folded polypeptide chain, which are known as ► [protein](#) subunits. Quaternary structure describes the organization of multiple subunits into a complex. Some examples of proteins with quaternary structure include hemoglobin and many ion channel proteins. Changes in quaternary structure can occur through conformational changes within individual subunits or through reorientation of the subunits relative to each other. These conformational changes, which may be cooperative or allosterically (induced by binding of other molecule) effected, often govern the mechanism by which proteins are regulated or perform their catalytic functions.

Cross-References

- [Protein](#)
- [Proteins, Primary Structure](#)
- [Proteins, Secondary Structure](#)
- [Proteins, Tertiary Structure](#)

Proteins, Secondary Structure

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In biochemistry, ► [protein](#) secondary structure describes common three-dimensional structural motifs found in proteins. Secondary structure is determined by inter-residue interactions mediated most often by hydrogen bonding occurring between backbone amide nitrogen and carbonyl groups of a polypeptide. The most common secondary structural motifs are ► [alpha helices](#) and beta sheets. Tight turns and flexible loops link the regular secondary structural elements.

Amino acids in a polypeptide vary in their tendency to form secondary structure elements. Proline and glycine are sometimes called “helix breakers” because they tend to disrupt the regularity of α -helical backbone conformations; however, both of these amino acids have unusual conformational abilities and are often found in turns. Amino acids that prefer to adopt helical conformations in proteins include methionine, alanine, leucine, glutamic acid, and lysine. In contrast, large aromatic amino acids such as tryptophan, tyrosine, and phenylalanine, and branched amino acids such as isoleucine, valine,

and threonine generally prefer to adopt β -strand conformations.

Cross-References

- [Alpha Helix](#)
- [Protein](#)
- [Proteins, Primary Structure](#)
- [Proteins, Tertiary Structure](#)

Proteins, Tertiary Structure

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In biochemistry, the tertiary structure of a ► [protein](#) is its three-dimensional structure, as defined by the atomic coordinates. Tertiary structure is largely determined by the protein’s primary and secondary structure. The environment in which a protein is synthesized and allowed to fold is a significant determinant of a polypeptide final folded conformation. In globular proteins, tertiary structure is often stabilized by the sequestration of hydrophobic amino acid residues in the protein’s interior, from which water is excluded, and by the exposure of charged or hydrophilic residues on the protein’s cytosol-exposed surface.

Cross-References

- [Disulfide Bond](#)
- [Protein](#)

- [Proteins, Primary Structure](#)
- [Proteins, Secondary Structure](#)

Proteobacteria

Irma Marín

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Ciudad
Universitaria de Cantoblanco, Madrid, Spain

Keywords

Alphaproteobacteria · Betaproteobacteria ·
Deltaproteobacteria · Epsilonproteobacteria ·
Gammaproteobacteria

Definition

Proteobacteria is the largest and most diverse phylum of the domain Bacteria.

Overview

Proteobacteria is an evolutionarily, geologically, and environmentally important group of microorganisms. All proteobacteria are ► [Gram-negative bacteria](#), with an outer membrane mainly composed of lipopolysaccharides. Members of this phylum show extreme ► [metabolic diversity](#), including chemoautotrophic, chemoorganotrophic, and phototrophic microorganisms, which represent most of the known bacteria of medical, industrial, and agricultural significance. Photosynthetic proteobacteria are called purple bacteria, referring to their reddish pigmentation. Most members of the phylum are facultative or obligate anaerobes, with gas vesicles, flagella, or the ability to move by gliding. Morphologically, they show a variety of cellular forms including rods, curved rods, ovoids, and spirals, and some have stalks or other appendages. There is evidence that eukaryotic mitochondria originated from an endosymbiotic relationship with a member

of this group of bacteria. Phylogenetically, the group is defined on the basis of sequence of the small ribosomal subunit RNA gene (16S rRNA) and is divided into five classes: *Alphaproteobacteria*, *Betaproteobacteria*, *Gammaproteobacteria*, *Deltaproteobacteria*, and *Epsilonproteobacteria*.

The *Alphaproteobacteria* comprise numerous phototrophs, chemolithotrophs, and chemoorganotrophs. Some members of this group are symbionts of plants and animals, and others have adopted intracellular life styles and constitute important human and animal pathogens.

Betaproteobacteria consist of several groups of aerobic or facultative bacteria, which are often highly versatile in their degradation capacities. Many of the species of this class play a role in ► [nitrogen fixation](#) in various types of plants or are able to use ammonium, hydrogen, or methane as a source of energy.

Gammaproteobacteria are the largest subgroup of proteobacteria. Many pathogens belong to this class. Many genera are chemoorganotrophs and facultative anaerobes, while others are chemolithotrophs. Some members of this group are photosynthetic using hydrogen sulfide as environmental reducing power.

Deltaproteobacteria is comprised of chemoorganotrophic microorganisms. This class can be divided into two branches. Aerobic predators and fruiting-body-forming bacteria have been found among one, while most of the known sulfate- and sulfur-reducing bacteria, an activity associated to the sulfur cycle, belong to the other.

Epsilonproteobacteria consist of few known genera with symbionts or pathogens species for humans or animals. Some environmental sequences have been recovered from cold and hydrothermal environments.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Anoxygenic Photosynthesis](#)

- [Bacteria](#)
- [Biogeochemical Cycles](#)
- [Chemolithotroph](#)
- [Chemoorganotroph](#)
- [Chemotroph](#)
- [Endosymbiosis](#)
- [Gram-Negative Bacteria](#)
- [Metabolic Diversity](#)
- [Nitrogen Fixation](#)
- [Photosynthesis](#)
- [Photosynthetic Pigments](#)
- [Phototroph](#)

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Proteome, Proteomics

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

A proteome is the complete set of ► [proteins](#) encoded by a ► [genome](#). It is also defined as the ► [protein](#) complement of the genome. Whereas the proteome of a species is the whole set of potentially expressed proteins, the proteome of

an individual organism displays variations according to the cell cycle, metabolic status, and environment-dependent variables. In multicellular organisms, the proteome is the subset of all encoded proteins which is expressed in a cell or tissue, also affected by the developmental stage and health of the organism. Proteomics is the field of molecular biology which studies the entire proteome for determining the structures and functions of the expressed proteins, as well as the relationships among them. Technologies widely used in proteomics include two-dimensional gel electrophoresis, mass spectrometry, techniques for structural characterization of proteins, and proteome-focused bioinformatic tools. In parallel to proteomics, other global and high-throughput “omic” fields have been developed including transcriptomics, interactomics, and metabolomics, where each of these fields involves the study of the entire set of transcribed mRNAs, protein-protein interaction networks, and metabolites within the cell, respectively. The basic and technological advances in the current “post-genomic era” have profound consequences in biology, medicine, and environmental sciences.

Cross-References

- [Bioinformatics](#)
- [Biological Networks](#)
- [Gene](#)
- [Genome](#)
- [Genomics](#)
- [Phenotype](#)
- [Protein](#)

Proterozoic Eon

Felix M. Gradstein

University of Oslo, Blindern, Norway

Keywords

Banded iron formation · Eukaryotes · Geological timescale · Great oxygenation event · Precambrian

Definition

The Precambrian includes the informal Hadean eon, as well as the formal Archean and Proterozoic eons. The latter is the youngest, which ranges from 2,500 to 538.8 Ma.

Overview

The Proterozoic Eon begins at 2.5 Ga, which approximately marks the time when oxygen from cyanobacteria began to dramatically change the composition of the Earth's atmosphere and oceans and when complex one-celled life (eukaryotes) evolved from simple cells (prokaryotes). The Proterozoic is subdivided into ten periods, generally of 200-Myr duration, grouped into three eras. The poetic names for these periods (see International Stratigraphic Chart: www.stratigraphy.org) are derived from the larger-scale tectonic or sedimentary features that occurred within each period. For example, the Siderian Period (2.5–2.3 Ga) is named from the banded iron deposits (σίδηρος = sideros = iron) that peaked within that interval. The lack of a diverse and well-preserved fossil record, the sparse volume of supracrustal rocks, a variable degree of metamorphism and tectonic disturbance, and the uncertainties in the configuration of the continents all contribute to making the establishment of a chronostratigraphic timescale beyond the Phanerozoic Eon problematical. Therefore, the main method for correlation of Precambrian strata requires radiometric ages of interbedded volcanic rocks. The Precambrian Subcommittee of the International Commission on Stratigraphy (www.stratigraphy.org; see also Gradstein et al. 2020) is striving to establish a more “natural” set of subdivisions that incorporates major tectonic, biologic, atmospheric, and geochemical events.

Cross-References

- Archaea
- Banded Iron Formation
- Cyanobacteria, Diversity and Evolution of

- Eukaryotes, Appearance and Early Evolution of
- Geological Timescale
- Great Oxidation Event
- Oxygenation of the Earth's Atmosphere

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Protists

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Protists are a diverse group of eukaryotic microorganisms that encompass mostly unicellular and some ► [multicellular organisms](#) that do not fit phylogenetically into the well-defined kingdoms: Animalia, Plantae, and Fungi. Historically, protists were treated as the kingdom Protista, but this group has been contested in modern taxonomy. Protists do not have much in common besides a relatively simple organization, either unicellular or multicellular, with no specialized tissues. The term protista was first used by Ernst Haeckel in 1866. Protists live in almost any environment that contains liquid water. Most protists, such as ► [algae](#), are photosynthetic and are fundamental primary producers in many ecosystems, making up a large part of the plankton of the oceans.

Cross-References

- Algae
- Eukarya
- Multicellular Organisms
- Photosynthesis
- Phylogeny
- Unicellular Organisms

Protists with Chloroplasts

► Algae

Protium

► Hydrogen Isotopes

Protobinary Star

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Binary star · young · Protostar

Definition

Binaries are pairs of stars locked into orbit around each other by their mutual gravitational attraction. When both stars are too young to undergo hydrogen fusion, the system is called a protobinary. In the very youngest protobinaries, neither star is optically visible, since both are still heavily embedded in the dust and gas that formed them. Several hundred protobinaries are known. In a few cases, the actual orbits of the component stars have been partially traced. Most protobinaries, however, are detected as close pairs of stars that share a common space motion within a young stellar cluster.

Overview

Most stars are not isolated objects, but have an orbiting companion. This fundamental fact was first established in the 1960s through surveys of main-sequence G-type stars, i.e., objects similar to the Sun. Over the last two decades, it has emerged

that pairing is also common among much younger stars. The term protobinary refers to a pair of stars in which the components are either ► [protostar](#) or ► [pre-main-sequence star](#). In the former case, each star is still accreting gas from its parent molecular cloud. A pre-main-sequence star, on the other hand, has reached its final mass, but is still too young to undergo hydrogen fusion at its center.

Both protostars and the youngest pre-main-sequence stars are still heavily obscured by surrounding dusty gas. Protobinaries are therefore only seen at infrared and longer wavelengths. The actual radiation detected comes from dust grains that are being heated by the stars within. Thus, the emitted spectrum depends more sensitively on properties of the dust than on properties of the star itself. It is therefore not surprising that the true evolutionary state of the many known protobinaries is uncertain.

In principle, one could identify a protobinary by seeing each star trace an orbit around the other. In practice, the spatial resolution at longer wavelengths makes such observations difficult, although they have been achieved using interferometers. Most of the known protobinaries were found, instead, as close pairs of infrared or millimeter point sources that share a common space motion within a young stellar cluster. Here, the physical separations range from several 100 to 1,000 AU. Assuming both stars to be of roughly solar mass, the corresponding periods are 1,000–30,000 years.

In some cases, optically visible, pre-main-sequence stars are accompanied by others that are still deeply embedded. The nature of these infrared companions is still unknown. It is doubtful that they are truly younger than the visible star for the following reason. When *both* stars in a binary are optically visible, pre-main-sequence stars, it is possible to measure their ages individually. These ages, typically a few million years, usually match fairly well. This finding also indicates that the components of protobinaries were born together, presumably out of a common molecular cloud core.

Cross-References

- [Binary Stars, Young](#)
- [Pre-main-sequence Star](#)
- [Protostars](#)
- [T Tauri Star](#)

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Protocell

Kepa Ruiz-Mirazo
Department of Logic and Philosophy of Science,
FICE, UPV-EHU, Biophysics Research Unit
(CSIC – UPV/EHU), San Sebastián, Spain

Keywords

Compartmented reaction systems · Lipid self-assembly · Prebiotic membranes · Protometabolism · Vesicles

Synonyms

[Artificial cells](#); [Cell models](#); [Synthetic cells](#)

Definition

A protocell is any experimental or theoretical model that involves a self-assembled compartment (typically a supramolecular structure, like a

lipid vesicle) linked to chemical processes taking place around or within it, aimed at explaining how more complex biological cells or alternative forms of cellular organization may come about.

Overview

Terrestrial biology is based on cells – systems that produce their own boundaries and carry out various transformation and replication processes within those boundaries. This includes processes leading to cell growth, cell division, and evolution of interacting cell populations. Furthermore, there are several good reasons to believe that the generation of any living entity, terrestrial or not, requires cellular compartmentalization (Morowitz 1992; Harold 1986). However, the level of molecular and organizational complexity shown by even the simplest known ► [prokaryotes](#) is so high that their origin remains a mystery. Different ideas to tackle this problem scientifically have been proposed. In some of them, compartmentalization through membranes is considered a late (or even the last) major event in the process, under the assumption that all the necessary prebiotic chemistry leading to biopolymer chemistry could have taken place in bulk (aqueous) solution, perhaps with the help of mineral surfaces. For approaches that, instead, consider that membrane compartments or colloidal organic interfaces must play an important role at an earlier prebiological stage, the idea of “protocell” becomes central. A protocell would be any chemically reacting system organized around or within a self-assembled, supramolecular boundary, which mimics – without fully reproducing – the behavior of biological cells. This is an important concept not only for the traditional research program in the origins of life, but also for related emerging fields of synthetic biology, artificial life, and astrobiology.

Early ideas on protocellularity involved quite diverse systems (Hanczyc 2009), which did not always resemble modern cells topologically nor in the molecular composition and structure of the boundary (e.g., Oparin’s “coacervates” or Fox’s “proteinoid microspheres”). Nevertheless, the

development of liposome technologies in the last few decades has made it possible to elaborate and implement model systems in the laboratory using lipid or amphiphilic bilayers, which contain – and are contained in – aqueous solutions, sharing many properties with biological membranes. Depending on the types of compounds making up the protocells (i.e., their boundary and their internal micro-environment), different models have been put forward over the years. For instance, due to their higher prebiotic plausibility, fatty acid vesicles have recently attracted attention of many researchers in the area, even if they are less stable and much more permeable, in general, than phospholipid membranes (Morigaki and Walde 2007; Deamer 2008). Regarding internal components and their dynamics, there is presently great interest in coupling vesicle growth and reproduction with polynucleotide replication taking place within the compartment (e.g., Mansy et al. 2008). Although the chemical logic of a minimum protocell would not necessarily involve complex macromolecules, like nucleic acid chains or other biopolymers (Morowitz et al. 1988), it seems that the search is currently focused on finding a protocell that can evolve – or be evolved – in a “Darwinian” way (i.e., with a mechanism for reliable heredity of molecular sequences), perhaps expecting that other relevant features of the system (robustness, internal lipid production, autonomous energetic viability, membrane functionalization, etc.) will derive from there. In the next years, it will become clearer whether this type of experimental shortcut proves successful, whether some other semisynthetic alternative (Luisi et al. 2006; Chen and Walde 2010) provides more solid results, or whether the bottom-up construction of functional protocells actually requires a longer, more winding pathway.

Cross-References

- [Cell Models](#)
- [Cell, Minimal](#)
- [Genome, Minimal](#)
- [Lipid Bilayer](#)
- [Permeability](#)
- [Self-Assembly](#)

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Protocell Division

- [Artificial Cell Division](#)

Proton Irradiation

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

Irradiation of a medium by high-energy protons (hydrogen ions) by using accelerators such as Van de Graaff accelerators and synchrotrons is called

proton irradiation. Cosmic rays are one of the possible energy sources for ► [prebiotic chemistry](#), and protons are predominant in cosmic rays. Thus, a number of proton irradiation experiments have been performed. The energy of the protons used in these experiments is usually a few MeV (mega electron volt; 10^6 eV) or higher. Not only the high-energy protons but also secondary electrons (electrons formed by the interaction of initial protons and target molecules) are effective for dissociation and ionization of molecules. Proton irradiation causes less specific chemical reactions than UV irradiation.

Proton irradiation of gas mixtures containing carbon species like methane or carbon monoxide and nitrogen species like nitrogen and ammonia produces a wide variety of organic compounds including precursors to amino acids (Koyabashi et al. 1998) and nucleic acid bases. In addition to irradiation of gas mixtures, proton irradiation of ice mixtures simulating ice mantles of ► [interstellar dust](#) particles has often been performed, to examine the possible role of cosmic rays in interstellar space (particularly in ► [molecular clouds](#)) (Kasamatsu et al. 1997). In these experiments, major targets have included carbon monoxide, methane, methanol, ammonia, and water ices. ► [Amino acids](#) were also detected after hydrolysis of the resulting irradiation products.

Proton irradiation is also used to determine the tolerance of organisms to cosmic radiation.

Cross-References

► [Amino Acid](#)

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Proton Motive Force

José Pascual Abad

Facultad de Ciencias, Departamento de Biología Molecular, Universidad Autónoma de Madrid, Madrid, Spain

Keywords

ATPase · ATP synthase · Electrochemical potential · LUCA · Proton gradient · Proton pump · Sodium motive force

Synonyms

[Chemiosmotic potential](#); [Electrochemical potential](#)

Definition

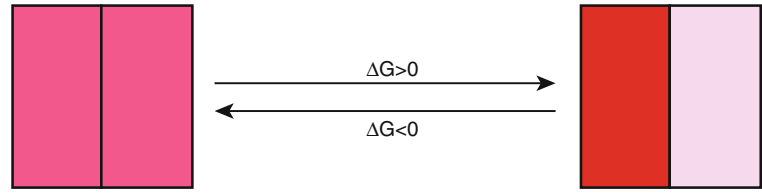
Proton motive force (PMF) is the force that promotes the movement of protons across membranes downhill the *electrochemical potential*.

Overview

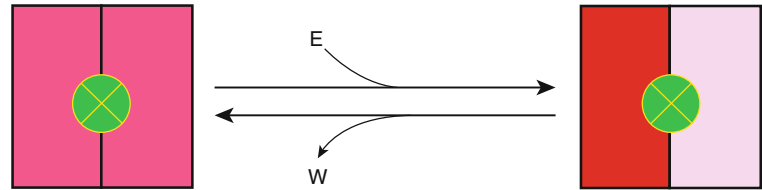
A difference of solute concentration between two compartments separated by a biological *membrane* generates a tendency to equilibrium, which, in the case of protons, is called proton motive force (PMF). This is measured in terms of the potential energy resulting from the difference in concentration between the two compartments. With a charged solute, the potential has two components: the chemical (concentration) and the electrical potentials (Fig. 1); thus, it is named *electrochemical potential*; thus proton motive force can be calculated as $\Delta p = \Delta \Psi - (2.3RT/F)(pH_{in} - pH_{out}) = \Delta \Psi - (2.3RT/F)\Delta pH$ ($\Delta \Psi$ is the transmembrane difference of electrical potential) (Harris 1995).

This energy can be used in different ways such as performing chemical work, particularly in the synthesis of *ATP* by *ATP synthases*, osmotic

Proton Motive Force, Fig. 1 Proton gradients and proton motive force



Proton gradients require energy to be formed ($G > 0$) and generate the proton-motive force, which favours re-establishing the equilibrium ($G < 0$)



Certain membrane-associated proteins can use energy to generate proton gradients (E) and/or use the generated proton-motive force to make different types of work (W)

Heat production	Decoupling of oxidative phosphorylation
Osmotic work	Ions or molecules transport coupled to proton translocation
Chemical work	Reactions of : H^+ -ATP-synthase H^+ -Pyrophosphate synthase H^+ -Transhydrogenase Reverse electron transport
Mechanical work	Prokaryotic flagellar movement Gliding movement of filamentous cyanobacteria

Proton Motive Force, Fig. 2 Proton motive force (PMF) can be used to perform different types of work

work, promoting different types of secondary transport, mechanical work, for example fueling flagellar or gliding movement of some bacteria, and, in some cases, generating heat (Fig. 2).

Proton gradients can originate in different ways and are an energy source for cells. In animal and plant cells, proton gradients are generated in mitochondria by means of the vectorial transport of protons driven by components of the respiratory chain. In plants, photosynthetic electronic transport also generates proton gradients in *chloroplasts* in which regulation of the two components of the PMF is essential for a correct response of photosynthetic light reactions to changing

environmental conditions (Armbruster et al. 2017; Li et al. 2021). In animal mitochondria PMF is not only used to synthesize ATP but for regulating proteostasis and linked to mitophagy and aging (Berry and Kaerberlein 2021). In some studies a relationship between PMF and certain characteristics of cancer cells has also been proposed (Brown and Ganapathy 2020).

In most *bacteria* and *archaea*, the electronic transport chain generates proton, and/or Na^+ , gradients, but fermenting bacteria use membrane-linked *ATPases* to hydrolyze ATP for uphill transport of protons. *Halobacteria*, a group of *Archaea* living at high salt concentrations, use

bacteriorhodopsin, a light-driven membrane protein to generate a proton gradient.

The wide use of PMF in several biological processes makes it a target for substances that may affect various processes. In bacteria PMF has been related to resistance (Crabbé et al. 2019; Feng et al. 2015; Le et al. 2021; Wu et al. 2019) or tolerance (Liu et al. 2018) to certain antibiotics, the capability to form *biofilms* (Ikonomidis et al. 2008), the natural competence involved in horizontal gene transfer (Domenech et al. 2020), and also may affect virulence of some bacteria (Iqbal et al. 2021).

Most extant organisms use PMF; however, the use of proton gradients might not have been the first gradient used by life systems. Some researchers suggest that this may be a mechanism that evolved from a more ancestral one based on Na^+ gradients, used by organisms when membranes were quite proton leaky (Dibrova et al. 2015; Mulikidjanian et al. 2008). The persistence of the use of a sodium motive force (SMF) by some obligate *anaerobes*, *thermophiles*, and *alkaliphiles* may be due to their low energy budgets that do not allow them to cope with the energy losses due to the proton leakiness of the modern membranes (10^5 – 10^7 times that of Na^+ ions). However, some authors claim that the last universal common ancestor (*LUCA*) used natural proton gradients (Lane 2017; Lane et al. 2010; Milshteyn et al. 2019). The evolutive origin of the use of ion gradients for *bioenergetics* purposes is still a very controversial issue. Extremophile organisms use different approaches for coping with environmental conditions that might affect the PMF (Baker-Austin and Dopson 2007; Matin 2009; Matsuno et al. 2018).

Cross-References

- ▶ ATPase
- ▶ ATP Synthase
- ▶ Concentration Gradients
- ▶ Last Universal Common Ancestor
- ▶ Membrane Potential
- ▶ Proton Pump
- ▶ Proton Transfer

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Proton Pump

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

The proton pump is a membrane-integrated enzymatic complex which is able to mobilize protons

to generate a proton gradient across the cell ► **membrane**. This proton gradient constitutes a fundamental energy reservoir. The proton pump plays an important role in cell ► **respiration** and ► **photosynthesis**. The ► **electron transport** chain in cell respiration generates an ► **electrochemical potential** which is coupled to the proton pumps located in the membrane. This proton gradient is an energy reservoir because it is the driver for the generation of chemical energy (ATP), or any secondary transport system associated to it, such as the transport of nutrients, the maintenance of the ionic homeostasis of cells, or the movement of bacterial flagellum.

Cross-References

- **ATP Synthase**
- **ATPase**
- **Bioenergetics**
- **Electrochemical Potential**
- **Electron Transport**
- **Energy Conservation**
- **Membrane**
- **Mitochondrion**
- **Photosynthesis**
- **Proton Motive Force**
- **Respiration**

Proton Transfer

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

In astrochemistry, proton transfer is a chemical process in which a positive ion reacts with a neutral molecule to add a proton to the neutral, e.g., $\text{XH}^+ + \text{Y} \rightarrow \text{X} + \text{YH}^+$.

For issues related to proton transfer in biology, see the entries on ► [Bioenergetics](#) and on ► [Proton Motive Force](#).

Protonated Cyanodiacetylene

► [HC₅NH⁺](#)

Protonated Tricarbon Monoxide

► [HC₃O⁺](#)

Proton-Induced X-ray Emission

► [PIXE](#)

Protoplanetary Disk

Jonathan P. Williams¹ and Michiel R. Hogerheijde²

¹Institute for Astronomy, University of Hawaii, Honolulu, HI, USA

²Leiden Observatory, Leiden University, Leiden, The Netherlands

Keywords

Accretion · Dust coagulation · Dust drift · Nebular hypothesis · Planet formation · Planetesimal · Pre-main sequence star · Protostar · Protoplanet · Solar nebula · Spectral energy distribution · Star formation

Synonyms

[Circumstellar disk](#); [Planet-forming disk](#); [Proplyd](#)

Definition

A protoplanetary disk is a flattened, rotating structure surrounding a young star, out of which planets form. They are composed of gas and dust, with temperatures ranging from over a thousand Kelvin close to the star to a few tens of Kelvin further away, and they emit from infrared to millimeter wavelengths. The largest disks have radii of several hundred astronomical units ($\sim 10^{13}$ m) and masses a few tenths of a solar mass ($\sim 10^{29}$ kg), though most are considerably smaller and less massive. Disks have diverse evolutionary pathways and lifetimes that range from less than 1 to greater than 10 Myr.

History

The concept of protoplanetary disks dates back to the eighteenth century, inspired by the motions of the planets in the solar system. Astronomers realized that the planets move in the same direction around the Sun, in approximately the same plane and in almost circular orbits. This led to the nebular hypothesis, initially outlined by Descartes and Swedenborg and developed by Kant in 1755 and Laplace in 1796, that the planets originated from a rotating disk of material that, at some point in the past, encircled the Sun. Modern science has revealed a compositional continuum and strikingly similar ages between the Sun, Earth, and meteorites, now extended to other planets, asteroids, and comets that demonstrate beyond refute a common origin for the solar system in a disk around the young Sun. Analogous disks around nearby young stars were indirectly inferred in the 1980s and then directly imaged in the 1990s. Most recently, newly formed planets have been detected in disks and ever more detailed observations test increasingly sophisticated theories.

Overview

Protoplanetary disks are a natural outcome of the ► [star formation](#) process by which a ► [molecular cloud](#) core collapses under its own gravity.

Conservation of angular momentum over this tremendous compression of size scales, from approximately light year to solar radii (10^{16} to 10^9 m), results in a rapidly spinning disk, flattened perpendicular to the rotational axis. The disk forms quickly while the ► [protostar](#) is enshrouded by the ► [dense core](#) and optically invisible. As the protostar grows, the core loses mass and is dispersed by radiation, winds, and outflows through stellar feedback. Within a few 10^5 year, the star becomes optically visible and, having reached its final mass, slowly contracts as gravitational potential energy is radiated away. Historically, the term protoplanetary disk referred only to the disks found around optically visible ► [pre-main sequence stars](#) (also known as ► [T Tauri stars](#)), but it is now recognized that the first steps of planet formation begin in the earlier, embedded phase of protostellar growth, and we use a more general definition here in considering any disk that has the potential to form planets independently of the precise stage of star formation.

Disks inherit their composition from the ► [interstellar medium](#) with a mass ratio of 74% molecular hydrogen, 25% helium, and only 1% heavier elements that reside predominantly in sub-micron-sized ► [dust grains](#). However, they vary widely in almost every other aspect, in particular size, with radii varying from ~ 1 to 100 au ($\sim 10^{11-13}$ m) and mass ranging from less than one to over one hundred times that of Jupiter ($\sim 10^{27-29}$ kg). This inherent diversity is likely due to the turbulent conditions in the collapsing core. Due to internal friction, or ► [viscosity](#), a rotating disk will spread out with time. The inner disk accretes onto the star, and gas in the outer disk is lost through photo-evaporation. The dust grains stick together and grow to millimeters and beyond, such that the solids decouple from the gas, settling to the midplane and concentrating in regions of high pressure. The accumulation of solids is the first step toward the formation of ► [planetesimals](#). Water and other compounds condense out of the gas at different distances from the star and affect planetesimal composition. After a few million years (and again with a large intrinsic diversity), protoplanetary disks dissipate through this combination of accretion, photo-

evaporation, and planet formation. The end-state is a ► [debris disk](#) composed of second-generation dust created by planetesimal collisions in a gas-poor system.

The next section, “[Basic Methodology](#),” introduces the main diagnostic tools used to study protoplanetary disks. The middle section, “[Key Research Findings](#),” discusses our current understanding of these objects. The final section, “[Future Directions](#),” lists the most important open questions that current and planned telescopes may address in the coming decade. This contribution focuses on disks around low-mass stars with masses ~ 0.1 – 2 Msun. Disks have been detected around more massive stars, with spectral types O and B, but less is known about them due to the rarity of these objects and their short formation times. Although OB stars are astrophysically important, their strong ultraviolet radiation field, many orders of magnitude greater than the Sun, and their brief lives, < 1 Gyr, imply that any accompanying disks have lower astrobiological significance.

Basic Methodology

The closest young star forming regions are about 150 parsecs away from the Earth. For typical radii of a few tens of astronomical units, disks extend over only a few tenths of an arcsecond on the sky which makes them extremely challenging objects to image in detail, especially since they are much lower mass and much colder than their host star. Nevertheless, a remarkable amount can be learned about disks by studying their unresolved emission over a range of wavelengths or spectral energy distribution. Moreover, in the last decade, developments in instrumentation have made high-sensitivity, sub-arcsecond imaging possible. This has provided detailed images of disks and revolutionized our understanding.

Observational Diagnostics

Although dust makes up only 1% of the (initial) mass of a protoplanetary disk, its ► [continuum](#) emission offers a powerful observational probe of the presence of disks and their structure. The

temperature of dust grains varies widely across a disk ranging from their sublimation point at 1000–1500 K in the inner regions at a few stellar radii to 10–20 K at tens of au in the midplane where radiation is almost fully attenuated. The peak of the thermal radiation therefore varies from about 2 to 300 μm from the hottest to the coolest regions, respectively. Ground-based telescopes can detect the near-infrared ($\sim 1\text{--}3\ \mu\text{m}$) emission from the inner disk and the tail of the modified [blackbody](#) at wavelengths longer than about 0.3 millimeters. At intermediate wavelengths, 3–300 μm (the mid- and far-infrared), the Earth’s atmosphere is bright, and space-based platforms are required. Small dust grains also scatter and absorb light, most efficiently at short wavelengths, and high contrast images reveal the disk surface.

The other 99% of the disk that consists of gas is, counter-intuitively, much more difficult to detect. Most of the disk is too cold for the main gas constituents, molecular hydrogen and helium, to emit (although the directly irradiated surface may produce detectable hydrogen lines in the near-infrared and ultraviolet). Instead, rarer molecules are used to trace the gas conditions, such as CO and its [isotope](#) counterparts, that are excited at the densities and temperatures in disks and which produce [spectral lines](#) at millimeter wavelengths.

Spectral Energy Distribution

One of the most basic tools for determining the structure of a protoplanetary disk is a plot of the amount of energy that it emits as a function of frequency, known as the spectral energy distribution (SED). This is typically plotted in logarithmic axes as $\log(\nu F_\nu)$ versus $\log(\nu)$, where F_ν is the observed specific flux in a narrow frequency band around the observing frequency ν . In such a plot, peaks of similar height provide similar contributions to the total radiated energy. Other common ways to plot the SED are $\log(\lambda F_\lambda)$ versus $\log(\lambda)$, which is the equivalent expression in terms of observing wavelength λ , or $\log(\nu L_\nu)$ versus $\log(\nu)$ where L_ν is the specific [luminosity](#) or flux corrected for the source distance. A schematic showing which part of a

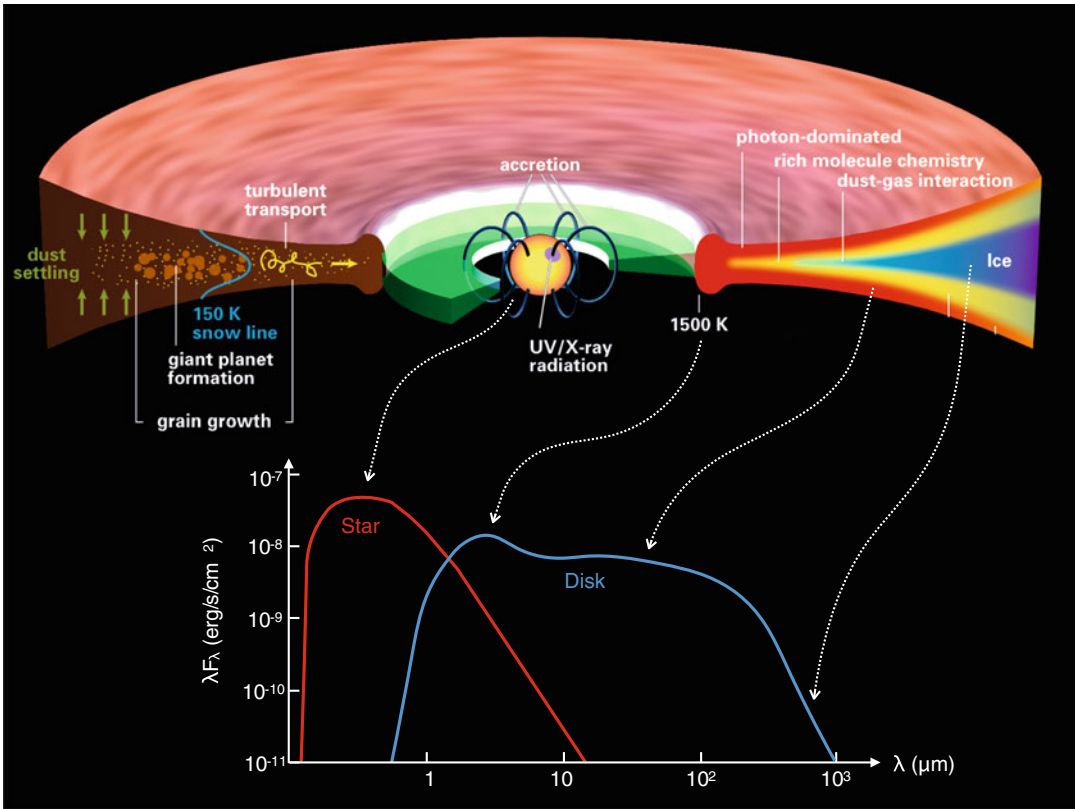
disk produces different parts of the SED is shown in Fig. 1.

The shape of the SED reflects the temperature distribution of the dust (since the emission from hotter material peaks at shorter wavelengths), which in turn depends on the location of the dust (Adams et al. 1987). Assuming vertical hydrostatic equilibrium, the location and the temperature of the gas and dust are closely linked. In this picture, the gas provides the pressure, while the small dust grains are largely responsible for the energy balance through the intercepted stellar radiation and their own continuum emission. To a lesser extent, other heating mechanisms (e.g., through the photoelectric effect or cosmic rays) and molecular or atomic line cooling may be relevant in some regions of the disk. With detailed measurements of the SED, a self-consistent model for the disk can be fit and the underlying disk structure obtained.

Imaging

Imaging has been crucial to advancing our understanding of protoplanetary disks in the last decade. The first images (and consequently the first direct detection) were made by the Hubble Space Telescope ([HST](#)) toward disks in the Orion star forming region which fortuitously lay in front of a bright background created by hot ionized gas. Dust absorbs this optical light and the disks therefore appear as silhouettes against the background. Analysis of the HST images provided disk sizes and a lower limit to their dust mass and revealed photoevaporation of gas from their surface. These objects were dubbed “proplyds” as a shorthand for protoplanetary disk (O’Dell et al. 1993), but this term is not generally used for disks that are not seen in silhouette.

Most disk images have since been made through high-resolution imaging of their emission at millimeter wavelengths. This has been achieved through [interferometry](#) whereby multiple radio telescopes are linked together over baselines ranging from hundreds of meters to many kilometers in length (ALMA Partnership et al. 2015). This technique does not require a particular arrangement of the disk and background and has opened up the investigation of hundreds of disks in



Protoplanetary Disk, Fig. 1 A schematic of a protoplanetary disk and its SED. The left-hand side of the disk shows dust processes that are discussed in Key Research Findings. The right-hand side shows the temperature and compositional profile. The hot dust in the inner disk produces near-infrared excess emission above that produced by the stellar photosphere shown in red. The flared

structure results in direct illumination of the disk surface at intermediate radii of a few to tens of au which produce strong mid- and far-infrared emission. The emission becomes optically thin at millimeter wavelengths and reveals large grains in the cold disk midplane. (Top image credit: Henning and Semenov (2013))

multiple star-forming regions with different ages and in different environments. Furthermore, the strength of the continuum and spectral line emission relate to the dust and gas mass respectively, and observations of different molecules can resolve chemical variations in the disk. Near-infrared interferometry reveals details of the hot dust at the star-disk interface, though the fidelity of such images is limited by the small number of baselines.

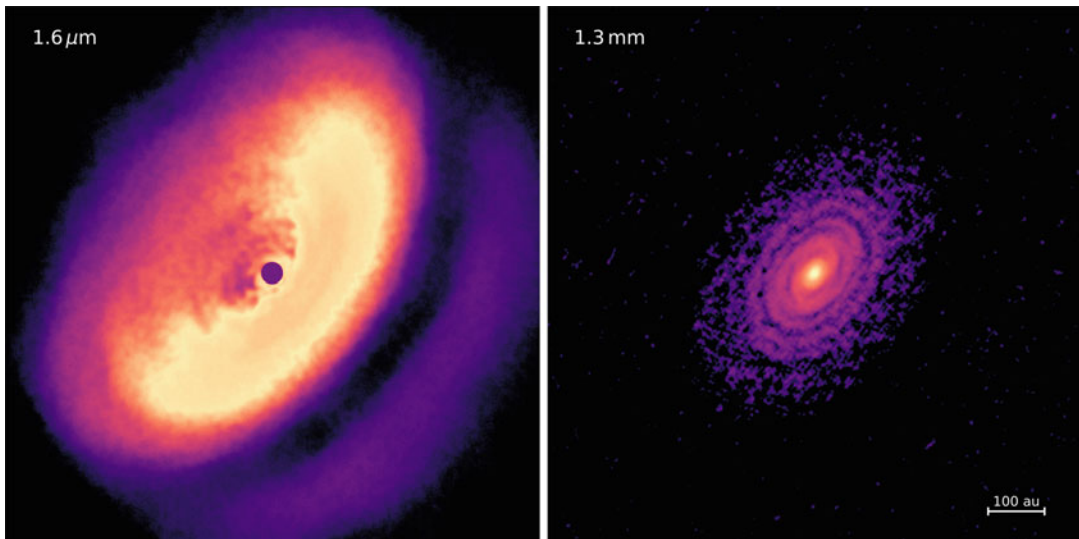
Driven by a broad astronomical need, high contrast adaptive optics imaging at near-infrared wavelengths on large ground-based telescopes has provided spectacular images of disks in recent years. In this case, the images map the light from the central star scattered by small dust grains in

the disk. This shows the disk surface and details therein and, in one clear case to date, newly forming planets. The combination of near-infrared scattered light and millimeter imaging, illustrated in Fig. 2, reveal different components of a disk and is a powerful technique to reveal internal processes.

Key Research Findings

Disk Incidence and Lifetime

The most sensitive way to determine whether a disk is present around a young star is to search for excess emission above the stellar photosphere at short wavelengths. Even very small amounts of



Protoplanetary Disk, Fig. 2 Two images of the IM Lup disk. The left panel shows scattered light at $1.6\ \mu\text{m}$ from small dust grains suspended in the gas. The bright emission comes from the upper layers of the flared surface. The central dot shows the location of the central, bright star that has been occulted in the optical path. (Image credit: ESO/H. Avenhaus et al./DARTT-S collaboration). The

right panel shows, on the same spatial scale, thermal dust emission at $1.3\ \text{mm}$ from much larger grains that lie in the disk midplane. Their extent is much smaller than that of the gas due to radial drift. The spiral structure may be due to disk self-gravity or torques from an unseen planet. These ALMA observations were published by Andrews et al. (2018)

dust close to a star, less than a lunar mass, will produce detectable emission in the near- or mid-infrared bands. This method works for individual stars but finds its true power when observing ► [stellar clusters](#) that can be observed together such as with infrared cameras on the ► [Spitzer space telescope](#). In color-color plots of the flux ratios at different wavelengths, equivalent to their difference in the ► [magnitude](#) system, the locus of stars with excess infrared emission is well separated from either field (► [“Main Sequence”](#)) stars or pre-main-sequence stars without excess. This way, the proportion of stars surrounded by disk material can be derived (Evans et al. 2009).

Since the age of a cluster can also be estimated more accurately than for individual stars, infrared surveys show how common disks are and their average lifetime. In the youngest clusters, with ages less than 1 Myr, the disk fraction (relative number of stars with excess emission) is over 80%. However, the stars without disks are close binary systems which are dynamically hostile places. Consequently, it appears that disks are essentially ubiquitous around young single stars.

Disk lifetimes vary from star to star, however, and the disk fraction decreases to less than 10% in old clusters with ages greater than 10 Myr, following an approximately exponential dependence with a half-life of 2 Myr.

Composition and Mass

Disks are composed of dust and gas from the interstellar medium. The dust originated in the winds from evolved (► [“Red Giant”](#)) stars and is mostly made of graphite and silicate minerals olivine, pyroxene, and forsterite in both crystalline and amorphous forms. In the cold interiors of the disk, these grains seed the freeze-out of volatiles from the gas and become surrounded by icy mantles. The various dust components produce broad spectral features in the mid- and far-infrared; they were observed by the ► [Infrared Space Observatory](#), ► [Spitzer space telescope](#), and ► [Herschel mission](#) and will be a major focus of study with the James Webb Space Telescope (► [“JWST”](#)).

Whereas infrared observations are very sensitive to the presence of dust, they cannot measure

how much there is since the emission saturates at the blackbody value. To measure the capacity of a disk to form planets necessitates measurements of its mass and requires observations at millimeter wavelengths where the emission has lower optical depth, generally less than one in all but the densest regions. In this regime, the continuum luminosity is directly proportional to the total dust mass with a temperature dependence through the blackbody function and an emissivity factor that converts the emitting surface area of a dust grain to its mass. The emissivity can be modeled using Mie theory or directly measured through laboratory experiments and depends on the composition, size, and shape of the grains. Because the grain properties are not precisely known and vary with location in the disk, dust mass measurements generally have a systematic uncertainty of about 3. The largest and most sensitive millimeter observatory, the Atacama Large Millimeter Array (ALMA), routinely achieves dust mass sensitivities of a Martian mass ($0.1 M_{\text{Earth}}$) in nearby star-forming regions. At this level, most (but not all) young stars with infrared excesses are detected. Those that are detected span a wide range in mass, with an approximately log-Normal distribution and dispersion of a factor of 10. The brightest, most massive disks have dust masses greater than $100 M_{\text{Earth}}$. The mean disk mass scales approximately linearly with the host stellar mass, but the large dispersion ensures that some low-mass stars have relatively high-mass disks and vice versa. The dust mass declines with time from a median $\sim 3 M_{\text{Earth}}$ in young regions < 3 Myr old to $\sim 0.3 M_{\text{Earth}}$ in relatively old regions with ages ~ 5 – 10 Myr. These values are all much lower than the amount of solid material in the solar system, $\sim 30 M_{\text{Earth}}$, likely because the observations are not sensitive to large particles that emit relatively weakly in proportion to their mass. The implication, discussed further below, is that most dust grains have grown by more than three orders of magnitude, from the sub-micron smoke-sized particles found in the interstellar medium to millimeter sizes of sand grains or hailstones, on Myr timescales.

The gas initially makes up 99% of the disk mass and is composed almost entirely of hydrogen

and helium. At the low temperatures and high densities of disks, the gas is predominantly molecular, although there are very small amounts of photodissociated and photoionized gas very close to the star and in a thin layer at the surface. The dominant species, H_2 , is very difficult to detect due to its symmetry and consequent lack of rotational dipole transitions. Warm H_2 emits weak quadrupole transitions in the mid-infrared, and energetic stellar radiation can excite vibrational and electronic transitions, but these are all limited to small and specific regions of the disk and do not relate to the total gas mass. Helium is effectively invisible but is well mixed with H_2 at its cosmic abundance and chemically inert.

The Herschel Space Observatory provided a unique opportunity, but with a limited lifetime that has now passed, to observe a far-infrared rotational line of deuterated molecular hydrogen, HD, which allowed the gas mass to be measured in a handful of disks. A complementary indirect method is to use estimates of the mass accretion rate from the disk onto the young star, measured through a variety of techniques from the ultraviolet to the infrared, multiplied by its age. The uncertainty in these methods is at least a factor of 3 but shows that many disks exceed the minimum mass solar nebula (MMSN) $\sim 0.01 M_{\text{Sun}}$.

Only trace amounts of C, N, O, and other elements are present in the gas and have been detected as simple molecular species such as CO, HCO^+ , H_2CO , CH_3OH , CN, HCN, and N_2H^+ through near-infrared and/or millimeter spectroscopy. The near-infrared lines originate in the inner disk and the millimeter lines from the outer disk but only in a relatively warm layer between an upper photodissociation layer and the cold midplane where ices form. Unlike the interstellar medium where CO and isotopic counterparts, ^{13}CO and C^{18}O , are a useful proxy for measuring gas masses, this does not appear to hold in protoplanetary disks. It is thought that mixing between the cold and warm disk layers in the outer disk may lock volatiles onto dust grains that settle, grow, and remain in the disk midplane. Consequently, disk CO abundances appear to be much lower than in molecular clouds and likely decrease with time.

The strong temperature gradient in disks leads to freeze-out of different molecules at different locations from the star. Water is almost completely absent in the gas phase beyond a few au where temperatures drop below 100 K, but CO remains in the gas phase over a much larger region of the disk where temperature is above 20 K. The interplay between the solid and gas components across these snowlines (and others such as CO₂) produces a rich chemistry that can be resolved in ALMA disk images and which may affect planetary composition in measurable ways through the C/O atmospheric ratios.

Dust Grain Growth

The low levels of dust emission, despite the abundance of planets, are an indirect indication that observations are missing the bulk of the solid mass in protoplanetary disks. Mie theory tells us that observations at wavelength λ are most sensitive to grains where $2\pi a \sim \lambda$. For a size distribution where the number of (spherical) grains with radius a scales as $n(a) \sim a^{-3.5}$, as expected in basic models of dust evolution through collisional aggregation and fragmentation, the cumulative mass is dominated by the largest particles which are relatively inefficient emitters per unit mass. Conversely, observations at longer λ can reveal the presence of larger grains. In practice, this is studied by measuring the power law index of the SED at millimeter wavelengths ($\nu = 300$ GHz), $F_\nu \propto \nu^{2+\beta}$, where $\beta = 0$ represents blackbody emission (in the Rayleigh-Jeans limit). Dust in the interstellar medium has $\beta \sim 1.7$, whereas protoplanetary dust has a significantly lower $\beta < 1$ which indicates more efficient emission at longer wavelengths due to larger grains. Thermal emission has been detected out to centimeter wavelengths indicating that grains have grown well beyond millimeter sizes. Such growth is promoted in disks by the high densities, low turbulence, and icy mantles that increase the sticking coefficient.

Although grain sizes of a millimeter are still many orders of magnitude smaller than a planetesimal, it is sufficient to have a profound physical effect. The grains are now massive enough that they have a significantly lower velocity dispersion than the gas and no longer feel its pressure. The

density and temperature in the disk decrease away from the star which creates a pressure gradient that opposes gravity and causes the gas to orbit slightly (less than a percent) slower than the Keplerian speed of the dust. Consequently, the larger dust grains feel a headwind, lose angular momentum, and drift radially inward (Weidenschilling 1977). They are similarly not hydrostatically supported and vertically settle to the midplane. These aerodynamic effects concentrate the solids in a critical first step toward planet formation. Dust grains that are large enough to decouple from the gas are known as “pebbles” although they might more closely resemble snowballs since the resolution of most observations is beyond the water snowline.

Structure

The structure of a protoplanetary disk refers to how its density, temperature, and composition vary with radius and scale height. Based on their SEDs and direct imaging, disk structures are generally well described by the theory of steady-state accretion disks, at least on scales greater than about 10 au. The theory is governed by a small number of conservation laws: conservation of mass dictates that, at every radius, the rate at which mass flows inward (or outward) is balanced by the amount of mass moving in from larger (or smaller) radii. Conservation of angular momentum dictates that the rate of change of the angular momentum at a given radius is balanced by the amount of angular momentum carried in (or out) of that radius by matter flow plus the amount of angular momentum that is transferred to material at adjacent radii by viscosity. The latter quantity relates the amount of torque that two adjacent radii exert on each other due to the gradient of angular velocity, or shear, between them. Viscosity causes fast-moving material close to the star to slow down while accelerating matter at larger radii, resulting in an outward transfer of angular momentum and an inward flow (accretion) of matter to smaller radii.

Ordinary molecular viscosity is far too small to match the observed disk accretion rates, and the source of viscosity remains unknown. Possibilities include turbulent mixing and

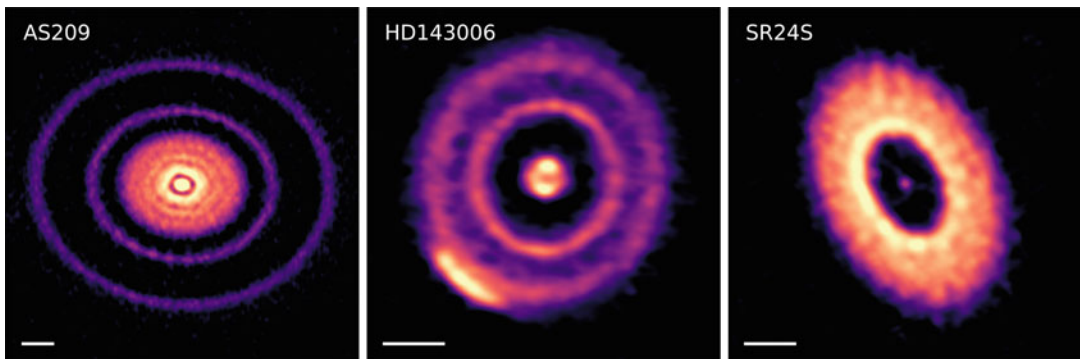
► **magnetohydrodynamic** instabilities. It is generally modeled as a free parameter following the Shakura and Sunyaev (1973) α prescription where viscosity, $\nu = \alpha H c_s$, for a disk hydrostatic scale height H and sound speed c_s . For a radial variation, $\nu \propto r^\gamma$, the surface density (mass per unit surface area) follows a power law form, $\Sigma(r) \propto r^{-\gamma}$, out to an exponentially truncated edge. Typical values between $\alpha(10\text{au}) = 10^{-4}$ – 10^{-2} and $\gamma = 0$ – 2 match the observed range of disk emission profiles and accretion rates. By 2020, about 200 disks had been resolved at millimeter wavelengths with radii ranging from 10 to 500 au where the radius is defined to include 90% of the total flux of the source. Most disks are at the small end of this range, near current resolution limits, but most detailed studies naturally focus on the rarer, largest objects. For these disks, the (millimeter sized) dust surface density at 100 au ranges from 10^{-2} to 10 kg m^{-2} .

The vertical disk structure follows from the radial density distribution and the assumption of vertical hydrostatic equilibrium, resulting in an exponential drop off of density with height above the midplane. For a geometrically thin disk, the temperature decreases with distance from the star as both the distance and the angle of incidence of the stellar radiation increase. However, the stellar gravity also decreases with distance, and the result is a scale height that increases with radius and a disk that is no longer perfectly thin. This raised surface intercepts more light,

causing the temperature to drop off less steeply with radius. This in turn causes the scale height to increase faster than the radius, and the disk starts to flare. Disk flaring naturally accounts for the bright mid- and far-infrared emission observed in disks. The scale height (of gas and small dust grains) increases with radius with typical values for the power law index ~ 1.3 – 1.5 and aspect ratio ~ 0.05 – 0.1 at 10 au, though there also exist some very cold disks that are much flatter.

One of the most exciting recent developments is the high-resolution imaging of protoplanetary disk substructures. These include rings, central holes, spirals, and arcs. Figure 3 shows a montage of ALMA 1.3 mm continuum maps at a resolution of 3 au. Even though only a few dozen disks have been imaged at this resolution so far, there is a remarkable diversity of structures. Rings are found at all radii and vary from narrow unresolved features to broad. Similarly, central holes range from the resolution limit to more than 50 au. Spirals are generally two-armed but range in tightness. Arcs extend from a few to over 180 degrees. The contrast of these features relative to the background varies substantially; sometimes they are seen in millimeter wavelength emission from large grains in the disk midplane, other times in scattered light from small grains in the upper atmosphere.

The basic physical explanations for these features is dust concentration in localized regions of high pressure. Just as the overall outward pressure



Protoplanetary Disk, Fig. 3 High-resolution ALMA images showing the variety of observed disk substructures: rings, arcs, central holes (and an inner disk). The horizontal line in the lower left of each panel is $0.1''$ across

corresponding to about 15 au at the distances of these sources. These data were originally published by Andrews et al. (2018) and Cieza et al. (2021)

gradient counteracts gravity to produce sub-Keplerian gas speeds and radially inward dust drift, a reversal at smaller radii would create super-Keplerian gas speeds and a tailwind on the solids that pushes them outward. Thus, millimeter- and larger-sized grains can be trapped in radial zones producing the observed rings. There are many (magneto-)hydrodynamical processes that can cause moderate ($\sim 20\%$) pressure variations in the gas that then lead a much stronger contrast in the density distribution of large dust grains. The concentration of solids can reduce local gas-to-dust ratios to unity whereupon the dust begins to dominate the dynamics and ultimately produce planetesimals (Chiang and Youdin 2010). Once formed, planets themselves produce pressure variations in the gas and can seed additional substructures, generally with an azimuthal dependence that would appear as spirals. Massive planets, several times that of Jupiter, or nearby stars, produce strong torques on the disk and can carve out gaps, central holes, and wide spirals.

Most high-resolution observations are of the dust components as they produce emission over a wide continuum which produces a much stronger signal than a narrow spectral gas line. Nevertheless, CO observations reveal the size of the gas disk and substructures within. The CO emission always extends beyond the millimeter dust, but this is partly due to its higher optical depth. In many cases, the difference is greater than a factor of two and confirms that the dust has radially drifted inward. Similarly, features such as rings and spirals in the gas generally have a lower contrast than those seen in the dust due to the stronger reaction of large grains to pressure perturbations. Different molecules can have different morphologies due to the chemistry, reflecting enhanced formation or destruction across snowlines and photodissociation (Öberg and Bergin 2020).

Kinematics

Millimeter-interferometric observations of the spectral lines from CO (and other molecular species) reveal the projected radial velocity at different locations in the disk. The motions are

dominated by Keplerian rotation with angular velocity, $\Omega \propto r^{-3/2}$, which allows the mass of the central pre-main sequence star to be accurately determined. The rotation is highly ordered with very low levels of ► [turbulence](#), generally below the thermal sound speed, $c_s \sim 0.1 \text{ km s}^{-1}$.

The high sensitivity and resolution of ALMA has led to more detailed studies of disk kinematics and investigations of radial and azimuthal flows related to accretion, substructures, and planet formation. A promising avenue is to search for localized deviations from Keplerian rotation that can detect sub-Jupiter mass planets and determine their mass and orbital radius.

Formation and Evolution

Disks are expected to form almost instantaneously as a molecular core gravitationally collapses. The envelope surrounding the growing protostar dominates the emission in the first ~ 0.1 Myr, limiting our knowledge of disk properties at these early times. Nevertheless, ALMA has mapped flattened rotating structures around the most deeply embedded, youngest protostars, and molecular lines from shocks where the infalling core hits the nascent disk have been identified in the mid-infrared. Ongoing work aims to study larger numbers of young disks in more detail and address questions about how fast they grow, whether instabilities produce massive accretions bursts known as FU Orionis events, and whether grain growth receives a head start during these early phases.

After about 0.5 Myr, the core has dissipated, and the disk, now around an optically visible star, is no longer growing and viscously evolves. The infrared excess decreases with time such that half the disks disappear within ~ 2 Myr, a half of the rest (i.e., one quarter of the initial) in the next 2 Myr, and so on. Based on exoplanet statistics, at least half the disks form planets. With a few exceptions, the disk emission decreases independently of wavelength indicating that the inner and outer disks disappear roughly simultaneously. Theoretical models show that the surface density of a viscously evolving disk will decrease gradually with time until the accretion rate decreases below the photoevaporation rate from the star. At

that point, the gas is lost from the inner disk faster than it can be replenished from the outer disk and an inner hole develops. The stellar radiation then directly impacts the hole rim accelerating the evaporation rate such that the disk rapidly clears from the inside-out on a timescale of ~ 0.1 Myr (Clarke et al. 2001).

A few disks are caught during the short transition time to complete dispersal. Their SEDs exhibit a mid-infrared decrement due to the lack of warm dust grains close to the star, and high-resolution imaging reveals the centrally cleared hole. However, the converse is not necessarily true, and there are many disks with central holes that cannot be explained by photoevaporative disk clearing. In some cases, low levels of gas or dust are detected in the gap, and in others, there is a small inner disk apparent either from direct imaging or near-infrared excess emission. In a subset of these, the plane of the inner disk is misaligned with that of the outer disk causing detectable shadows in scattered light or occultations (dips) in the optical light curve. The best explanation is dynamical clearing by a companion in the disk. Stellar binaries can completely clear out the central region leaving a circumbinary disk. The well-studied GG Tau and CoKu Tau/4 systems provide excellent natural laboratories to test theories. Planetary mass companions are less efficient at clearing the disk and allow some material to flow through the cavity. High enough flows can then replenish the inner disk which may also be dynamically perturbed from the plane of the outer disk. Direct detection of a faint planet close to the bright star is challenging, but the morphology is so suggestive that these disks are compelling targets for study.

The environment also plays a role in protoplanetary disk evolution. Stellar encounters truncate disks though this is unlikely to apply on solar system scales in all but the very most dense young clusters. However, stellar groups with more than a few hundred members are expected to include one or more OB stars. These produce copious amount of ultraviolet radiation which can significantly accelerate disk photoevaporation many parsecs away. This affects the outer regions

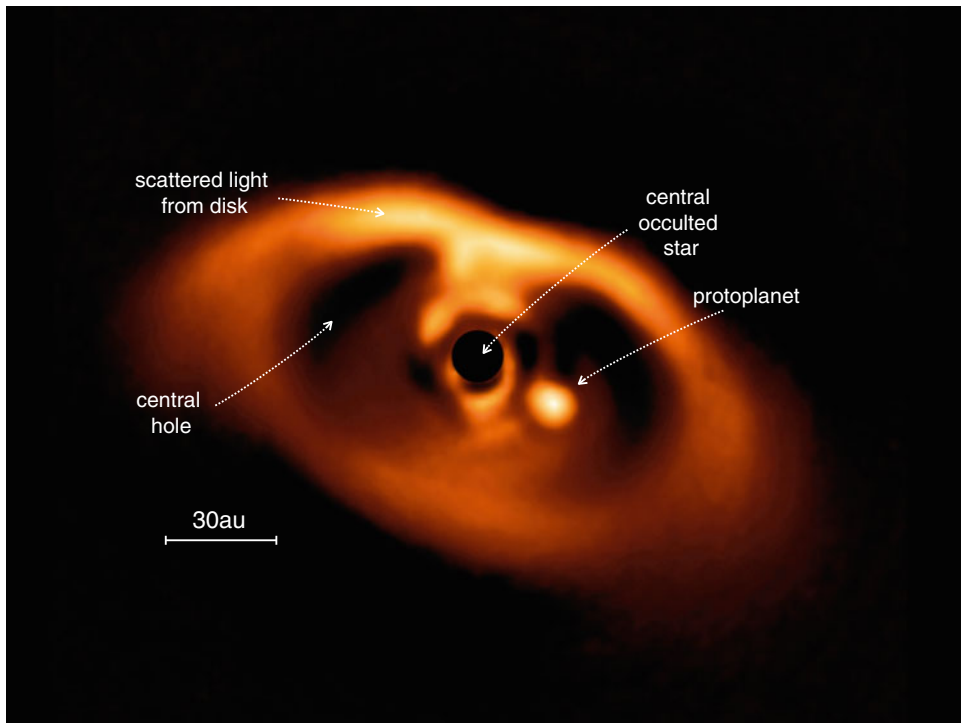
of the disk, however, and its impact on planet formation in the inner regions is unclear.

Planet Formation

Since the first resolved images, less than 30 years ago, disk research has revealed many important steps in the planet formation process. The gas mass is sufficient to form solar system scale planetary systems, and the dust grains have grown from microns to millimeters such that they aerodynamically decouple from the gas. Vertical settling, radial drift, and trapping in pressure bumps concentrate the solids. A leading theory for the next step is the streaming instability where pebble clumps provide a lower cross section per unit mass to the gas headwind and therefore catch up and accrete other pebbles, continuing to grow to a gravitationally cohesive planetesimal. Tests of planetesimal formation models are best made through observations of Kuiper belt objects, but there is tentative support for rapid pebble to planetesimal conversion in disks through an upper limit to the optical depth of dust rings which may indicate a surface density threshold.

Disk structures such as partially filled central holes, misaligned inner disks, and spirals are strong evidence for unseen planetary mass companions. Deviations from Keplerian rotation are also compelling signatures. Direct detections are challenging because they require contrasts of four or more orders of magnitude at sub-arcsecond scales in the optical or near-infrared. However, just as circumstellar disks are relatively easy to detect on account of their large emitting area, circumplanetary disks may be easier to detect than the planets themselves. So far, ALMA searches have only been able to provide upper limits showing that such disks are either very low mass or very small, but it is likely only a matter of time before the first detection.

A major advance was recently obtained through observations of the PDS70 star, shown in Fig. 4, which shows a Jupiter mass planet lying in the cleared central hole of a disk (Keppler et al. 2018). Follow-up observations found a second planet at the edge of the dust ring. This system will hopefully only be the first of many to come. Their characterization



Protoplanetary Disk, Fig. 4 The first incontrovertible image of a protoplanet within a disk around a young star. Taken at $2.2\ \mu\text{m}$ with the SPHERE instrument on the ► [VLT](#), the light from the central K5 star has been occulted to allow the much fainter emission from the planet and disk to be seen. The planet, PDS70b, is 23 au from the star and

is estimated to be a Jupiter mass. It lies within a large central hole in the disk, which is seen in scattered light. Though not obviously apparent in this image, a second planet, PDS70c, was subsequently found in the bridge of emission between the disk and star. (Image credit: ESO/A. Müller)

will provide the critical link between disk properties and their planetary outcomes.

Future Directions

The study of protoplanetary disks is an area of intense current research in both observations and theory and has a bright future. Progress has accelerated due to advances in high-resolution imaging at multiple wavelengths leading to significant advances in our understanding of planet formation, the origin of the solar system, and the transport of volatiles from the interstellar medium to the inner disk. As with all astronomical fields, the pace of discovery is generally driven by instrumentation, and we anticipate major new results from JWST due to its great sensitivity and spectroscopic capabilities at mid-infrared

wavelengths. Of particular astrobiological interest will be observations of the disk organic content in the (future location of the) habitable zone.

ALMA has revolutionized our view of disks in the last few years and it has only just got started. As high resolution, detailed imaging becomes routine, we anticipate a wealth of new studies. These include an unbiased census of disk substructures to learn whether there is any dependence on host star, age, or environment. In tandem with ever more sophisticated modeling, structural and kinematic features will provide new constraints on super-Earth to Jupiter mass planets at orbital radii of a few to many au. More insights into disk chemistry will strengthen the connection with planetary composition. Circumplanetary disks appear to be fainter than simple model predictions, but the first secure detections will happen soon. In the near-infrared, ongoing upgrades to

adaptive optics systems on ground-based telescopes will achieve smaller inner working angles and greater contrast, providing higher fidelity images closer to the star which will likely provide more “Rosetta stones” of direct planet detections in young disks such as those in Fig. 4.

The ► [Square Kilometer Array](#) (SKA) will start its first science operations in the mid-2020s. With its promise of high sensitivity at centimeter wavelengths and sub-arcsecond imaging, it will detect pebbles with centimeter and larger sizes and complex organics in the gas. Finally, plans for the next-generation Very Large Array (ngVLA) would achieve tens of micro-arcsecond resolution at 3 mm wavelength in the 2030s, sufficient to hunt for disk structures created by young planets in the terrestrial planet-forming region of the closest disks.

Cross-References

- [Accretion, Stellar](#)
- [Binary Stars, Young](#)
- [Blackbody](#)
- [Debris Disk](#)
- [Dense Core](#)
- [Dust Grain](#)
- [Flux, Radiative](#)
- [Herschel Mission](#)
- [Infrared Space Observatory](#)
- [Interferometry](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Isotope](#)
- [JWST](#)
- [Keplerian Orbits](#)
- [Luminosity](#)
- [Magnetohydrodynamics](#)
- [Magnitude](#)
- [Main Sequence, Star](#)
- [Molecular Cloud](#)
- [Photodissociation](#)
- [Photoionization](#)
- [Planetesimals](#)
- [Pre-main-sequence Star](#)
- [Protoplanetary Disk, Chemistry](#)
- [Protoplanetary Disk Instability](#)

- [Protosolar Nebula, Minimum Mass](#)
- [Protostars](#)
- [Red Giant](#)
- [Solar Nebula](#)
- [Spectral Line](#)
- [Spitzer Space Telescope](#)
- [Square Kilometre Array](#)
- [Star Formation, Feedback](#)
- [Stellar Cluster](#)
- [T Tauri Star](#)
- [Turbulence \(Planetary Disks\)](#)
- [VLT](#)

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Further Reading

There are two reviews of protoplanetary disk research in the Annual Reviews of Astronomy and Astrophysics series. The first, Williams and Cieza (2011), is a broad overview of disk evolution and, though many of the results have now been superseded by more recent ALMA data, still serves as a useful general introduction for beginning researchers. The second, Andrews (2020), discusses the emerging field of disk substructures with a focus on observations and modeling. A pedagogical reference for both students and researchers is the textbook on planet formation by Armitage (2020) that derives much of the physics of protoplanetary disks

Protoplanetary Disk Dead Zone

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

A dead zone is an annular region of a circumstellar disk where the local [viscosity](#) is essentially zero, leading to a negligible infall of disk material toward the central star. Viscosity is needed to remove the orbital energy and angular momentum from gas and dust in the disk, allowing material to spiral inward and accrete onto the central star (as observed in young stellar systems with known circumstellar material). The source of this disk viscosity is uncertain, but the most likely source is electromagnetic interactions between ionized species, known as the magnetorotational instability (MRI). Dead zones may be created when the local gas is insufficiently ionized to support the MRI. They can occur, for example, when the gas column density is large enough to protect the inner zones of the disk from ionization by cosmic rays.

Cross-References

- ▶ [Planetary Migration](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Turbulence \(Planetary Disks\)](#)
- ▶ [Viscosity](#)

Protoplanetary Disk Instability

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Gravitational instability](#)

Definition

Disk instability refers to a model for giant planet formation in which a region of a circumstellar disk becomes dense and cool enough to be unstable to gravitational collapse, resulting in the formation of a gaseous protoplanet. The disk instability mechanism for giant planet formation has been postulated as a mechanism for forming massive [giant planets](#) on short timescales (1 Ky–1 My), which may be required to form gas giant planets in short-lived disks and disks with a low metal abundance. However, it is unclear whether real circumstellar disks can cool sufficiently quickly to initiate gravitational disk instabilities before the gaseous disk dissipates. The quantitative measure of a disk's ability to become gravitationally unstable is the Toomre Q value.

Cross-References

- ▶ [Core Accretion, Model for Giant Planet Formation](#)
- ▶ [Giant Planets](#)
- ▶ [Gravitational Collapse, Planetary](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Q \(Toomre Parameter\)](#)

Protoplanetary Disk Midplane

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

The disk midplane corresponds to the region of a circumstellar disk where the vertical density distribution peaks. The midplane is thought to be the coldest region of the disk, due to the inability of stellar radiation to penetrate deeply. The low temperatures and high densities lead to the fastest growth timescales for ► [planetesimals](#) and result in planets with coplanar orbits (if no scattering or inclination pumping occurs).

Cross-References

- [Planetary Migration](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Turbulence \(Planetary Disks\)](#)

Protoplanetary Disk of Second Generation

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Synonyms

[Debris disk](#)

Definition

A second-generation ► [protoplanetary disk](#) is a disk of circumstellar material created by the

destruction of young planetary bodies during the late stages of planetary formation. Such disks are commonly called ► [“debris disks”](#). Debris disks have been detected around stars with ages from 10 My up to billions of years, and they usually contain approximately a lunar mass of material in small grains. The presence of planets is usually unknown, though several giant planets have now been directly imaged in debris disks.

Cross-References

- [Debris Disk](#)

Protoplanetary Disk, Chemistry

Dmitry Semenov

Max Planck Institute of Astronomy, Heidelberg,
Germany

Keywords

Accretion · Chemical reactions · Circumstellar disks · Depletion · Dissociation · Dust grains · Freeze out · High-energy radiation · Ices · Ionization · Isotopic fractionation · Molecular lines · Molecules · Photochemistry · Radio-interferometers · Solar nebula · (Sub) millimeter observations · Turbulence · Young stellar objects

Definition

► [Protoplanetary disks](#) (PPDs) surrounding young stars are short-lived ($\sim 1\text{--}10$ Myr), compact ($\sim 10\text{--}1,000$ AU) rotating reservoirs of gas and dust. Disks are believed to be the birthplaces of planetary systems, where tiny grains are assembled into pebbles, ► [planetesimals](#), and eventually planets, asteroids, and comets. The evolution of gas and grain growth in disks is related to the redistribution and transport of angular momentum, which is thought to be governed by

magnetohydrodynamical turbulence. The intense high-energy radiation from one or more young stars and strong spatial and temporal variations in the physical conditions (accretion rate, temperature, density, grain sizes) make a variety of chemical processes active in protoplanetary disks. In PPDs, simple molecules are rapidly produced in the gas phase via ► [ion-molecule](#) and ► [neutral-neutral reactions](#). The more complex (organic) species in disks are slowly synthesized on and in the icy mantles of dust grains and later are either released to the gas phase or become trapped inside growing dust aggregates.

Overview

It is particularly important to understand under what conditions prebiotic molecules and their simpler “building-block” precursor species could be produced and how they evolve during the star- and planet-formation process. Powerful ground-based and airborne observational facilities and robotic space missions have recently become available, which have permitted the chemical composition of nearby star-forming regions to be sensed remotely and pristine Solar System materials to be collected in situ. In addition, increasing computer power makes sophisticated simulations of the interstellar chemistry feasible. The progress is particularly rapid in understanding the physics and chemistry of protoplanetary disks around young stars – analogs of our Solar System at the age of several million years.

Many protoplanetary disks surrounding young Sun-like stars possess sufficient material, of order several Jupiter masses, to assemble planetary systems (e.g., Lin and Papaloizou 1980; Payne and Lodato 2007; Williams and Cieza 2011). According to the modern paradigm of star formation, the collapse of a cold ► [molecular cloud](#) of several solar masses leads to formation of (a) protostar(s) surrounded by a compact, rotating, flattened structure, the protoplanetary disk. The protostar is initially still enshrouded by an envelope of cloud material. During a few million years of dynamical evolution, much of the prenatal

cloud material accretes on to the protostar, with some material ejected as a ► [bipolar outflow](#). After that, the outflow ceases and the newly born central star becomes visible.

Photospheric activity of the star drives intense, variable ultraviolet (UV) and X-ray radiation, leading to steady photo-evaporation and, after taking account of ongoing accretion, to dispersal of remaining disk matter (e.g., Gorti et al. 2009). The dense disk interior conditions are favorable for rapid agglomeration of submicron-sized dust grains into larger cm-/m-sized pebbles and rocks. During formation, they sediment toward the disk equatorial plane (► [“Protoplanetary Disk Mid-plane”](#)), eventually forming ► [planetesimals](#) and planets as well as ► [comets](#), or move inward due to gas friction and are accreted onto the star. The forming planets interact gravitationally with the surrounding gas, inducing asymmetric spiral waves and other substructures, and may even open gaps or clear central holes in disks (e.g., Fukagawa et al. 2004; Grady et al. 2013).

Molecules are important diagnostics of physical conditions in disks. Also, molecules are key heating and cooling agents of the gas, especially in the disk atmospheres. Dust grains determine the opacity of the disk medium to the stellar radiation and so shape the disk thermal and density structure. Ionization chemistry induced by high-energy radiation from (a) central star(s) or interstellar space and cosmic ray particles (CRPs) determines the strength of the coupling between the gas and magnetic fields, thus controlling the global disk dynamics via ► [turbulence](#).

Consequently, a strong time-dependent variation of temperature, density, and dissociating radiation intensity across a disk induces pronounced spatial gradients and leads to a rich chemistry in the gas phase and on the surfaces of dust grains. In this entry, we summarize *the major modern observational methods and theoretical paradigms* used to investigate disk chemical composition and evolution and present the most important results. Future research directions that will become possible with the advent of the Atacama Large Millimeter Array (► [ALMA](#)) and other forthcoming observational facilities are also discussed.

Basic Methodology

In the table and in the text that follows, we use the standard spectroscopic notation that specifies the ionization state by Roman numerals: I for a neutral atom (e.g., NeI for Ne), II for singly ionized (e.g., NeII for Ne⁺), etc. So far, astronomers have discovered about 160 molecular species (230 including isotopomers) in space (► [Molecules in Space](#)). These vary from simple radicals (e.g., CH⁺) to complex molecules like cyanopolyynes (e.g., HC₁₁N), ► [polycyclic aromatic hydrocarbons](#) (PAHs; up to C₆₀ and C₇₀), and organic molecules (e.g., CH₃OH, HNC, HCOOCH₃, HOCH₂CHO) as well as positive (e.g., HCO⁺) and negative (e.g., C₈H[−]) ions. Among these interstellar species, only a handful of molecules have been identified in disks through infrared (IR) and (sub)millimeter spectroscopy: H₂, HD, CII, NeII, FeI, OH, H₂O, CO (and isotopologs), CN, HCN, DCN, HNC, HC₃N, C₂H, C₂H₂, c-C₃H₂, CS, HCO⁺, H₂CO, DCO⁺, NH₃, and N₂H⁺ (Dutrey et al. 1997, 2007b; Kastner et al. 1997; Aikawa et al. 2003; Qi et al. 2008, 2013; Chapillon et al. 2012).

Solid materials detected in nearby PPDs via infrared spectroscopy include aliphatic and aromatic carbon-based materials (in unknown form), polyaromatic hydrocarbons (PAHs), amorphous and crystalline silicates of olivine and pyroxene stoichiometry, and molecular ices (like CO, CO₂, H₂O). The presence of various other organic compounds has also been inferred (e.g., Terada et al. 2007; Acke et al. 2010; Min and Flynn 2010; Henning and Meeus 2011; Teske et al. 2011; Aikawa et al. 2012; Bergin et al. 2013).

Another vital source of information about the pristine composition of solids at the verge of planet formation in the young Solar System are the studies of meteoritic materials and cometary samples and remote observations of active comets passing near the Sun (Ehrenfreund and Charnley 2000). An isotopic analysis of various primitive refractory materials allows us to discern the time of their condensation (radiogenic dating). In addition, petrological, mineralogical, and texture analyses constrain the timescales of the cooling of the freshly formed minerals and the physical

conditions (temperature, density) at which they have condensed out.

Unfortunately, a vast majority of volatiles have either vaporized during the formation and evolution of solids or have been lost due to further thermal processing in the meteorite parent bodies or during the sample preparation in the laboratory. A direct access to the composition of pristine ices and organics in cometary dust is possible via robotic missions, like the *Stardust* mission that collected and delivered to Earth the first dust samples from the comet *Wild 2* (Elsila et al. 2009; Wozniakiewicz et al. 2012). The Rosetta mission of the European Space Agency will deposit by November 2014 a lander and an orbiter on the comet 67P/Churyumov-Gerasimenko for detailed in situ analysis of the comet surface (http://www.esa.int/Our_Activities/Space_Science/Rosetta/Europe_s_comet_chaser).

(Sub)millimeter Observations

Dusty PPDs are transparent only when observed at wavelengths longer than $\sim 100\ \mu\text{m}$ (far-infrared/(sub)millimeter wavelengths). Since the dominant molecular component of the gas, H₂, does not emit observable radiation at (sub)millimeter wavelengths apart from high-temperature regions around the star (e.g., Bitner et al. 2007), other trace species and dust are used to study physical conditions in disks (Table 1). A unique tracer of the total gas mass is deuterated molecular hydrogen, HD, whose fundamental rotational transition at 112 μm has been recently detected with the *Herschel* satellite toward the nearest protoplanetary disk around TW Hya (Bergin et al. 2013).

At (sub)millimeter wavelengths, there are no prominent solid-state features, but the observed continuum emission allows us to estimate dust disk mass and infer the presence of large, millimeter-sized grains. Since dust opacities at these wavelengths and the dust/gas mass ratio are poorly known, the constrained disk mass is subjected to large uncertainties.

By contrast, the (sub)millimeter spectral window is rich in molecular rotational lines. It is not fully accessible from the ground due to atmospheric absorption, primarily by water and

Protoplanetary Disk, Chemistry, Table 1 Diagnostic molecules used to study disk physics and chemistry and wavelength ranges of observations (e.g., millimeter, centimeter, and infrared (IR)). In the three columns giving the wavelength range of the observations for a particular

portion of the disk, 0 indicates that the molecule is not present and a dash(–) indicates that the molecule is either not excited or not present; in the Probe column, a dash indicates the same property as in the row above

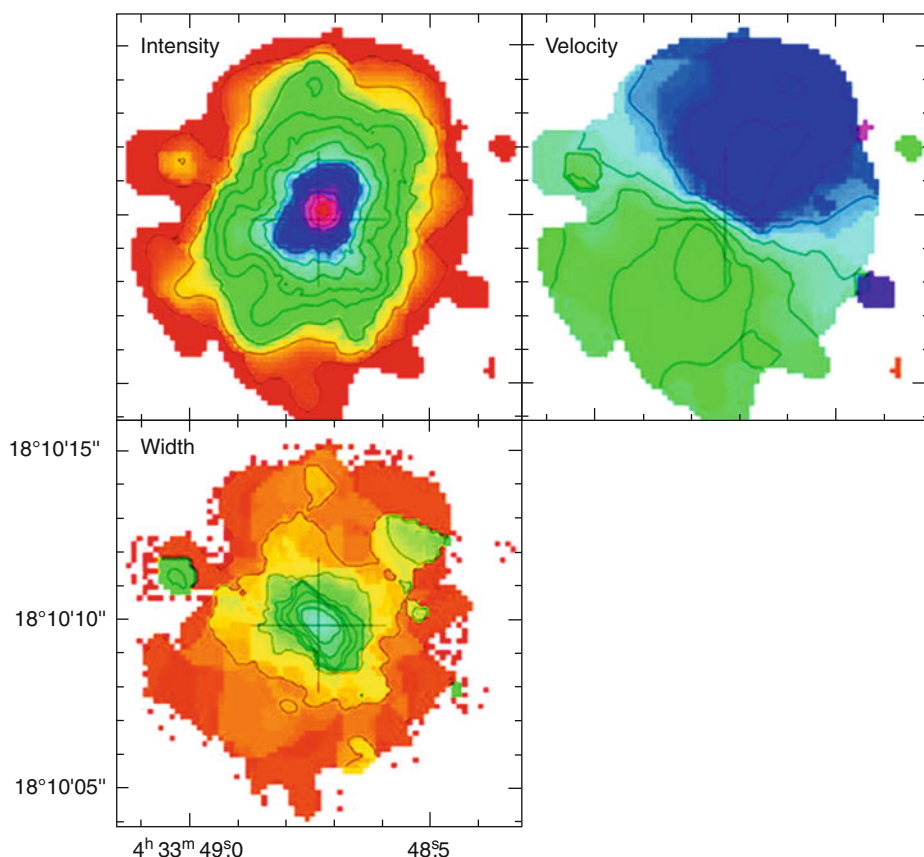
Species	Probe	Midplane	Molecular layer	Atmosphere	Inner zone
^{12}CO , ^{13}CO , C^{18}O	Temperature, density	mm	mm	sub-mm	IR
H_2	Temperature	–	–	–	IR
HD	Density	IR	IR	IR	–
NH_3	–	cm	cm	0	0
CS, H_2CO , HC_3N	Density	0	mm	0	IR
C_2H , HCN, CN, OH, H_2O , C_2H_2 , c- C_3H_2	Photoprocesses	0	mm	0	IR
HCO^+	Ionization	mm	mm	0	0
N_2H^+ , H_2D^+	–	mm	0	0	0
C^+	–	mm	0	IR	IR
Metal ions (e.g., NeII)	–	0	0	0	IR
Complex organics (e.g., H_2CO)	Surface chemistry	IR	IR, mm	0	IR, mm
DCO^+ , DCN, H_2D^+	Deuterium fractionation	mm	mm	0	0
CO, CS, HC_3N	► Turbulence	mm	mm	mm	0

hydroxyl (OH). Single-dish telescopes like the IRAM 30-m antenna (ESO, Spain), the APEX 12-m antenna (ESO, Chile), and the 15-m James Clerk Maxwell Telescope (UK, Hawaii) are used to survey PPDs in lines of potentially detectable species. Although lacking the spatial resolution to resolve the disks, single-dish molecular spectra allow astronomers to constrain disk-averaged amounts of emitting molecules (column densities) and roughly estimate disk orientation and temperature.

The sub-arc-second imaging required to resolve PPDs is provided by antenna arrays such as the Plateau de Bure Interferometer (France), the Submillimeter Array (USA), and the Combined Array for Research in Millimeter-wave Astronomy (USA). Since 2013, observations have begun with the much more powerful Atacama Large Millimeter Array (► [ALMA](#), Chile), a joint project of Europe (ESA), the USA, and Japan. Until the advent of ALMA, such studies were scarce and restricted to outer disk regions ($r > 30$ AU). The objects best studied thus far included DM Tau, LkCa 15, AB Aur, TW Hya,

MWC 480, HD 163296, and HD 100546. In PPDs, most molecular lines are optically thin and so their observed spectral line shapes result from a combination of molecular spatial distribution, excitation conditions, and transport of the line radiation through the disk. The molecular spectra yield unique information on disk kinematics and geometry, temperature and density structure, and the intensity of dissociating and ionizing radiation.

The disk size and orientation can be constrained directly by the geometry of dust emission and integrated line intensity maps (e.g., ^{13}CO 1–0); see Fig. 1. Next, the PPD kinematics can be recovered by analyzing the velocity at various points in the disk from the Doppler shift of molecular lines. By high-resolution observations of heavy molecules like CS and HC_3N , which have narrow intrinsic and thermal broadening of the line profiles, one can constrain the levels of gas turbulence in outer disk regions (Guilloteau et al. 2012, see also Hughes et al. 2011). For molecules with high dipole moments and regular energy-level structure (e.g., CS, H_2CO , HC_3N , HCO^+),



Protoplanetary Disk, Chemistry, Fig. 1 The DM Tau disk imaged with the Plateau de Bure Interferometer in the HCO^+ 1–0 line with $1.5''$ resolution. Shown are the integrated line intensity (*top left*) that increases toward the central star (indicated by cross), the velocity map (*right*

top) that reveals a “butterfly”-like symmetric pattern typical of rotating disks (*bluer* side approaching, *greener* side receding), and the line width distribution (*bottom left*), where velocity increases toward the disk center due to Keplerian rotation ($V(r) \propto r^{-1/2}$)

multi-transition observations constrain the gas density distribution, since higher energy transitions require higher densities for excitation. The thermal disk structure is derived from the strength of optically thick CO lines (e.g., ^{12}CO 1-0, ^{12}CO 2-1, etc.), which trace different disk heights. The line shapes of CO [isotopologs](#) carry information about both temperature and molecular density distribution, and these can be used to derive the disk surface density profile. Ratios of line intensities for a parent molecule and its photodissociation product (like HCN and CN) reflect the strength of the disk irradiation by high-energy UV photons. However, for larger molecules, the population is divided over many energy levels, leading to lower line intensities and making it

harder to detect and resolve the spectra of such species. Furthermore, the spectra of molecules with a complex level structure, like water, are particularly difficult to analyze. Therefore, to fully interpret interferometric spectra of a given molecule, one has to construct computational models which take into account many disk properties, kinematics and geometry, density and thermal structure, and radial and vertical molecular distributions, and employ a line radiation transport model to fit the observed data iteratively.

Infrared Observations

At IR wavelengths, spectral features associated with various components of solid dust particles are evident, as are the rotational-vibrational and

vibrational bands of gas-phase species (e.g., due to stretching and bending of molecular bonds). Atmospheric transparency windows permit limited observations from the ground, and so spaceborne telescopes are essential for full spectral coverage. From analysis of these data, we can constrain the local temperature and amount of absorbing/emitting material on the line of sight. The ratio between near-IR and far-IR dust emission is used to indicate an evolutionary phase of a disk, because in an old system, dust grains may grow so big in the dense inner region that the near-IR flux disappears, while the far-IR excess emission is still characteristic of cold, submicron-sized grains (Bouwman et al. 2008).

The inner, $\sim 1\text{--}20$ AU planet-forming disk regions only recently became accessible, with the advent of near- and mid-IR ground-based interferometers (such as those at the Palomar Observatory, W.M. Keck Observatory, and Very Large Telescope Observatory) and the launch of space observatories (the ► [Infrared Space Observatory](#), ► [Spitzer Space Telescope](#), and ► [Herschel Mission](#)). IR interferometers do not retain the phase information of the detected signal and thus require sophisticated analysis of the acquired data based on template disk models to constrain the geometry and mass of the hot dust region. The (ro-)vibrational emission/absorption molecular lines and solid-state emission bands of ices as well as a variety of silicates and polyaromatic hydrocarbons (► [PAHs](#)) and simple organics have been detected in disks (van Dishoeck 2004; Pontoppidan et al. 2005; Lahuis et al. 2006; Pascucci et al. 2007; Bouwman et al. 2008; Zasowski et al. 2009; Acke et al. 2010; Salyk et al. 2011; Teske et al. 2011; Fedele et al. 2012). Identified species include H_2O , C_2H_2 , HCN, OH, NeII, and some others; from their spectra local temperature, FUV intensity and molecular concentrations can be derived.

The major components of dust grains in disks are amorphous and crystalline silicates (e.g., MgSiO_3 and Mg_2SiO_4), troilite (FeS), metals and oxides, quartz, C-containing compounds, and water/CO ices (Pollack et al. 1994). Metals do not have any distinct spectroscopic signatures, while only certain carbon-bearing compounds

show generic aliphatic and aromatic features, making it difficult to identify their exact composition (which is likely a mixture of ► [hydrogenated amorphous carbon](#), diamonds, ► [PAHs](#), and polymerized organic materials). Studies of chemical and petrological compositions of meteorites and samples of cometary materials seem to be the only possibility to try to understand the properties and composition of the pristine organics that can be present at the planet-formation stage of the disk evolution (Ehrenfreund and Charnley 2000).

Key Research Findings

Outer Disk: (Sub)millimeter and Far-Infrared Observations

High-resolution interferometric observations at submillimeter and millimeter wavelengths have allowed the chemical composition and physics of the outer regions (beyond 30–50 AU) to be examined in several nearby PPDs. Observations at the Plateau de Bure Interferometer (PdBI; France), the Very Large Array (USA), and the Australia Telescope Compact Array (ATCA) at millimeter and centimeter wavelengths show evidence for significant grain growth up to cm sizes in disks (e.g., Rodmann et al. 2006; Cortes et al. 2009; Guilloteau et al. 2011). The IR spectroscopic surveys of young stars in stellar clusters of various ages have placed tight constraints on typical dispersal times of dense ► [protoplanetary disks](#) of ~ 5 Myr, while their inner, planet-forming zones ($< 10\text{--}100$ AU) are cleared of submicron-sized dust grains within only ~ 1 Myr (Fedele et al. 2010).

Prominent low- and high-energy CO rotational lines are readily excited by collisions at densities of $\sim 10^3\text{--}10^5\text{ cm}^{-3}$. The ^{12}CO lines are optically thick, and their intensities measure kinetic temperature in the disk upper layer. The lines of less abundant ^{13}CO and C^{18}O are typically optically thin or partially optically thick and are sensitive to both temperature and the CO column densities through the disk. Strong CO lines are suitable for accurate determination of disk kinematics, orientation and geometry, and hence the mass of

the central star. From interferometric observations, it has been found that measured disks radii appear the smallest for the dust continuum and progressively larger in the C^{18}O , ^{13}CO , and ^{12}CO lines, with typical values of ~ 100 – $1,000$ AU. Multi-line CO studies have revealed a clear sign of vertical temperature gradients in several disks, increasing from ~ 10 K at the midplane to ~ 50 K in the atmosphere region (e.g., Dartois et al. 2003; Qi et al. 2006; Piétu et al. 2007). The high surface temperature of the TW Hya disk as measured by the ^{12}CO ($J = 6-5$) line cannot be solely caused by the black body stellar radiation and requires an additional heating source, likely stellar X-rays (Qi et al. 2006). A number of protoplanetary disks with large inner “dust” holes, such as LkCa15, do not show temperature variation in the vertical direction and thus must have a peculiar structure. Dartois et al. (2003) and Piétu et al. (2007) have reported that a large amount of CO and other gas-phase molecules exist at ~ 10 – 15 K in the DM Tau disk, which contradicts the expectation that most of these molecules should reside on grains at such low temperatures. The recent interferometric observations of water vapor in the closest disk around TW Hya by (Zhang et al. 2013) determined the location of the “snow line” (the location where water ices is thermally evaporated, $T \sim 120$ – 160 K) and thus constrain the disk’s radial temperature distribution. In a similar study, (Qi et al. 2013) have observed the TW Hya and HD 163296 disks in lines of N_2H^+ and H_2CO and inferred the location of the “snow line” for CO, which is located far away from the central stars, where dust temperatures are below 20 K.

Molecules with larger electric dipole moments than CO require higher gas densities to excite emission, since collisional excitation must overcome radiative de-excitation in order for higher energy levels to be populated. An easily observable molecular species in disks is HCO^+ , which does have a larger dipole moment (3.92 D = Debye). The lower energy $J = 1-0$, $2-1$, and $3-2$ transitions of this ion (J is the rotational quantum number) are excited at densities of $\gtrsim 10^5 \text{ cm}^{-3}$ and are (partially) optically thin. This is one of the most abundant charged species in PPDs, the other being C^+ , which is not observable at

millimeter wavelengths. Due to its large dipole moment, HCO^+ is a good density probe, in addition to being a tracer of ionization degree (see Table 1). Another, less abundant observable ion in disks is N_2H^+ (3.37 D). The $1-0$ N_2H^+ line exhibits hyperfine splitting, and so from relative intensities of its individual components, one can reliably determine the **optical depth** of the line and constrain the N_2H^+ column density. Using these ions as probes, it has been found that the degree of ionization in disk interiors is $\sim 10^{-9}$ (one charged species per billion), in agreement with the derived cosmic ray ionization rate and predictions from disk chemical models (Qi et al. 2003).

The distribution and total amount of HCN and its dissociation product, CN, depend on the intensity and spectral shape of the high-energy UV radiation impinging into the disk (Bergin et al. 2003). The stronger the FUV flux, the higher the CN-to-HCN line ratio due to higher concentrations of CN and lower abundances of HCN. The observationally inferred elevated ratio of CN to HCN abundances indicates that the chemistry in PPDs is indeed affected by the stellar FUV radiation. Another radical observed in disks, C_2H , is sensitive to the X-ray luminosity of the central star, as higher flux of X-ray photons replenishes more of the elemental carbon locked in CO back into the gas phase, where it is quickly converted to light hydrocarbons (Henning et al. 2010). The recently detected cyclopropenylidene ($\text{c-C}_3\text{H}_2$) in the disk of TW Hya with the ALMA interferometer by Qi et al. (2013) seems to be another excellent tracer of the UV radiation intensity penetrating through disk upper layers.

Rotational lines of the less abundant CS and H_2CO are difficult to observe even in bright disks. The CS lines, excited at densities $n \sim 10^5$ – 10^7 cm^{-3} , have very narrow intrinsic widths and as such can be utilized to measure turbulent gas velocities in disks through the Doppler effect, as well as to discern disk density structure. The measured turbulent broadening is subsonic, with a typical microturbulent velocity of ~ 0.05 – 0.2 km s^{-1} (Hughes et al. 2011; Guilloteau et al. 2012). The simplest organic molecule, H_2CO , has a slightly asymmetric top

structure and serves as both a densitometer and a thermometer. It is partly produced on surfaces of dust grains and can also be used as a probe of the efficiency of surface chemical processes. Recently detected DCO^+ and DCN in TW Hya have abundances comparable to the abundances of their main isotopologs, HCO^+ and HCN (Qi et al. 2008), while the cosmic abundance ratio of D/H is only 10^{-5} . Their radial distributions in the TW Hya disk have been derived by Oberg et al. (2012) using the Science Verification ALMA data. While DCO^+ column density increases with radius in the disk, the DCN emission is more centrally peaked, indicating different pathways to deuterium fractionation in disks. It remains to be verified though whether such a large degree of deuterium fractionation is a heritage of pre-disk cold evolutionary phases in the parent [molecular cloud](#) or if these large D/H ratios can be produced in situ in PPDs.

A remarkably consistent finding is that gas-phase molecular abundances relative to molecular hydrogen are lower by factors of 5–100 compared to the values in the cold interstellar Taurus Molecular Cloud (Dutrey et al. 2007). This has been interpreted as a combination of intense UV and X-ray dissociation of molecules at elevated disk heights by the young central stars and proficient sticking of gas-phase molecules to dust grains in cold disk interiors, forming thick icy mantles.

The observations at far-infrared wavelengths with the *Herschel* space telescope probe molecular emission lines and solid-state bands of ices and silicates arising at distances of ~ 1 –100 AU in disks. The data are still being reduced and analyzed; here we report on major recent discoveries that have been published.

In a number of protoplanetary disk orbiting around Sun-like and more massive, hotter intermediate-mass Herbig stars, emission from hydroxyl (OH) has been detected. Combined with *Spitzer* observations of warm water, there is an apparent lack of water in the more heavily irradiated disks around Herbig stars, suggesting that H_2O in their upper inner disk regions can be severely dissociated (Fedele et al. 2013).

The non-detection of cold H_2O in DM Tau provided stringent upper limits to the amount of water vapor in the outer disk region. The low

amount of water vapor cannot be explained by modern astrochemical models. A plausible scenario is that a substantial fraction of water ice (the major reservoir of water) can be already locked in big grains that settled toward the mid-plane, unable to be photo-evaporated (Bergin et al. 2010). A higher amount of water vapor in the disk around another star, DG Tau, was inferred by Podio et al. (2013). Using an advanced disk physical and chemical model, they derived that the water emission stems from a hot region of ~ 600 K in the upper disk region, with a total amount of water vapor of $\sim 10^2$ – 10^3 Earth oceans (and 100 times more in the solid form).

(Hogerheijde et al. 2011) have successfully detected emission lines from both the ortho- and para-spin isomers of water in the disk around TW Hya. This ratio cannot be changed by radiative or collisionally induced transitions and can only be modified by chemical processes involving proton exchange. The ortho-para ratio (OPR) of water is thought to be determined by the temperature at which water ice formed on dust grains via hydrogenation of surface O and OH. Hogerheijde et al. have found that the ortho-para ratio for H_2O in TW Hya is 0.77, indicating low temperatures of the H_2O ice formation, ~ 15 – 20 K. Interestingly, this temperature seems to be lower than the temperatures derived from various OPR ratios measured in Solar System comets (~ 30 – 50 K; see Woodward et al. 2007; Bockelee-Morvan et al. 2009; Bonev et al. 2013).

A detection of pure HD rotational lines in the TW Hya disk allowed probing for the first time the total gas disk mass, as the HD/ H_2 ratio should not change much even in warm protoplanetary disks (Bergin et al. 2013). The inferred disk mass was larger than previously suggested, 0.05 solar masses, which is somewhat surprising for a ~ 5 million-year-old system.

Inner Disk: Infrared Spectroscopy

Results from the [Infrared Space Observatory](#) and the [Spitzer Space Observatory](#) have revealed the presence of a large amount of ice, [polycyclic aromatic hydrocarbons \(PAHs\)](#), and both amorphous and crystalline silicates in disks (e.g., Bouwman et al. 2008; van Dishoeck 2004;

Pontoppidan et al. 2005; Lahuis et al. 2006; Pascucci et al. 2007). The PAH features at $\sim 3\text{--}12\text{-}\mu\text{m}$ probe the intensity and shape of the incident radiation field and the density distribution in the disk. Only $\sim 10\%$ of PPDs around young Sun-like stars show aliphatic (C-H) and aromatic (C-C) PAH bands, and often these bands appear only in the outer disk zone (beyond $\sim 30\text{--}100$ AU). The small PAHs with unbound geometry (< 50 C atoms) are destroyed by the intense FUV and, in particular, X-ray stellar radiation, while bigger and compact PAHs do survive in PPDs. The PAHs remain in the gas phase only in dilute, ice-free upper disk regions and are frozen out in disk interiors. It is interesting to note that the $3\text{-}\mu\text{m}$ diamond emission tends to be centrally peaked in PPDs, which may indicate a high-temperature conversion of H-poor large PAHs into nano-diamonds.

A multitude of amorphous and crystalline silicates with varying Fe/Mg ratios and grain topology/sizes have also been detected (Bouwman et al. 2008). A striking result is that both the crystallinity fraction and the abundance ratio of forsterite/enstatite ($\text{Mg}_2\text{SiO}_4/\text{MgSiO}_3$) change across a disk. The fact that mid-IR features are characteristic of mostly iron-poor silicates implies their rapid condensation from the gas phase during transformation of a [molecular cloud](#) into a disk. Other metals like Fe and Ca are found as a component (often as sulfides) of glassy inclusions inside a silicate matrix in meteorites (see [GEMS](#)). The variety of observed silicate band profiles is due to various average sizes of emitting grains, implying that small submicron-sized particles and bigger, several micron-sized grains exist in PPDs.

Ices are present in the cold, outer disk region beyond the “snow line,” at temperatures below ~ 120 K ($r \gtrsim 20$ AU). These features are easier to detect in highly inclined systems. The major mantle component is water ice, with an abundance of about 10^{-4} (relative to the total particle density). Water ice is intermixed with other, more volatile ices of, e.g., CO, CO₂, NH₃, CH₄, H₂CO, and HCOOH (Zasowski et al. 2009). Typical abundances of these minor constituents are about 0.5–10% with respect to water. As it has

been revealed from the complex shape of icy features with substructures, a substantial part of these volatile ices can be chemically bound to grain surface sites (“chemisorbed”) and thus will remain frozen even at elevated grain temperatures and UV irradiation.

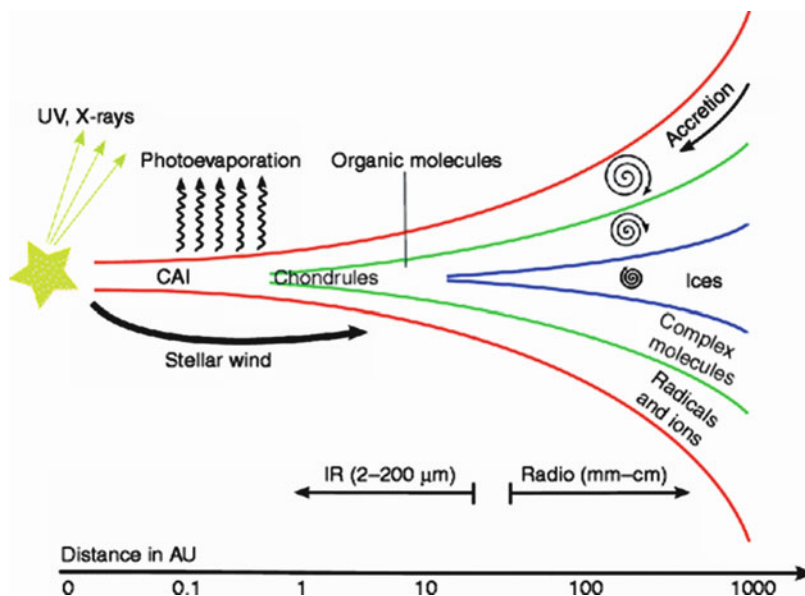
The detection of NeII line emission from several disks, as well lines from iron, sulfur, and argon, has confirmed theoretical predictions that the disk atmosphere is heavily ionized and superheated by the energetic photons. Detected rotational H₂ and (ro-)vibrational CO, CO₂, C₂H₂, and HCN as well as H₂O and OH lines trace a hot gas in the inner, planet-forming disk zone with $T \sim 300$ K (Lahuis et al. 2006; Salyk et al. 2008). The HCN-to-C₂H₂ ratio is a sensitive tracer of the UV/X-ray intensity or accretion rate inside an inner disk, while the easily populated CO lines allow us to constrain kinetic temperature. The rich chemical composition inside planet-forming disk zones suggests that many endothermic reactions with barriers become active there.

Theoretical Picture of Chemical Structure of a Disk

We present a general scheme of a PPD structure based on observational results and theoretical predictions in Fig. 2 (see, e.g., Aikawa and Herbst (1999), Willacy and Langer (2000), Bergin et al. (2003), van Zadelhoff et al. (2003), and Semenov et al. (2004); for a discussion of [CAIs](#) and [chondrules](#), see the links). The viscous evolution of the disk gas is driven by the angular momentum transport due to turbulent torques. This leads to inward transport of the bulk of the disk matter ($\sim 80\%$), while a minor fraction of the disk gas carries the angular momentum outward (mostly along the midplane). This leads to a steady-state power-law surface density profile that has a radial dependence that is roughly proportional to $r^{-3/2}$ (surface density $\sim 1,700$ g cm⁻² at 1 AU for the model [solar nebula](#)). In the vertical direction, the gas density drops exponentially away from the midplane. The average temperature in disks decreases radially outward and, for a given distance, increases from the disk midplane to disk atmosphere. The stellar radiation

Protoplanetary Disk, Chemistry, Fig. 2

A sketch of the vertical structure of a protoplanetary disk



heats the upper layers such that the disk develops a flared structure. The upper disk atmosphere has a low density, resulting in higher gas temperatures compared to those of the dust. Closer to the star, the gas temperature in the disk atmosphere rises so high ($T \sim 1,000\text{--}5,000\text{ K}$) that the matter starts to evaporate. As one moves below the upper atmosphere, the disk density increases and the gas and dust temperatures reach an equilibrium value. In the very inner part, the disk midplane is again warmed up by the viscous accretion heating.

The intensity of ionizing and dissociating UV radiation is determined by the dust opacities, while penetration of the stellar X-ray radiation into the disk is controlled by the gas density structure. The larger the energy of a photon or a particle, the deeper disk regions it can reach. The stellar X-ray emitting source is often located high above the star's photosphere, at distances of several stellar radii ($\sim 0.01\text{ AU}$), and thus X-ray photons reach the disk atmosphere at an oblique angle and are able to penetrate deeper into the disk interior compared to the UV photons. The stellar UV intensity drops in the disk with radius as r^{-2} , while the X-ray intensity decreases even faster, and the interstellar UV radiation starts to prevail in the outer disk region ($r \gtrsim 100\text{ AU}$). The FUV continuum radiation is blocked by a gas column of

$< 0.01\text{ g cm}^{-2}$, hard X-ray photons ($\sim 1\text{--}5\text{ keV}$) are stopped at a gas column of $0.1\text{--}1\text{ g cm}^{-2}$, and $\sim\text{GeV}$ cosmic ray particles penetrate gas columns as large as $\sim 100\text{ g cm}^{-2}$.

Consequently, the disk structure can be divided into four chemically distinct regions: the warm “inner zone” where a planetary system is built (observable currently only at IR and optical wavelengths) and the differing layers in the outer disk region observed by modern radio-interferometric facilities. The inner region is at thermodynamical equilibrium, and chemical abundances there can be calculated as a function of temperature, pressure, and elemental abundances by ► [condensation sequence](#) modeling. The major problem here is to obtain reliable equilibrium coefficients for all species of interest. Chemical kinetics controls the evolution of the outer disk region ($r > 20\text{--}50\text{ AU}$). It is divided into a cold, dense disk midplane where dust grains are coated with ices, a slightly UV/X-ray-irradiated warm layer above the midplane with a rich chemical composition, and a heavily ionized, hot, and dilute disk atmosphere.

The key reactions for disk chemistry are summarized in Table 2. Modern astrochemical databases include up to 600 species involved in 6,000 gas-phase, gas-grain, and surface reactions. Only

Protoplanetary Disk, Chemistry, Table 2 Key chemical processes in protoplanetary disks

Name	Representation	Example	Rate ^a
Radiative association	$A + B \rightarrow AB + h\nu$	$C^+ + H_2 \rightarrow CH_2^+$	$\sim 10^{-10} - 10^{-17} \text{ cm}^3 \text{ s}^{-1}$
Ion-molecule	$A^+ + B \rightarrow C^+ + D$	$CO + H_3^+ \rightarrow HCO^+ + H_2$	$\sim 10^{-7} - 10^{-10} \text{ cm}^3 \text{ s}^{-1}$
Neutral-neutral	$A + B \rightarrow C + D$	$O + CH_3 \rightarrow H_2CO + H$	$\sim 10^{-10} - 10^{-16} \text{ cm}^3 \text{ s}^{-1}$
Charge transfer	$A^+ + B \rightarrow B^+ + C$	$C^+ + Mg \rightarrow C + Mg^+$	$\sim 10^{-9} \text{ cm}^3 \text{ s}^{-1}$
Radiative recombination	$A^+ + e^- \rightarrow A + h\nu$	$Mg^+ + e^- \rightarrow Mg + h\nu$	$\sim 10^{-12} \text{ cm}^3 \text{ s}^{-1}$
Dissociative recombination	$AB^+ + e^- \rightarrow A + B$	$HCO^+ + e^- \rightarrow CO + H$	$\sim 10^{-7} \text{ cm}^3 \text{ s}^{-1}$
Ionization	$A + h\nu \rightarrow A^+ + e^-$	$C + h\nu \rightarrow C^+ + e^-$	$\sim 10^{-10} \times RF^b \text{ cm}^3 \text{ s}^{-1}$
Dissociation	$AB + h\nu \rightarrow A + B$	$CO + h\nu \rightarrow C + O$	$\sim 10^{-10} \times RF \text{ cm}^3 \text{ s}^{-1}$
Accretion	$A + g \rightarrow A(g)$	$H_2O + g \rightarrow H_2O(g)$	$\geq 4 \cdot 10^{-6} \text{ cm}^3 \text{ s}^{-1}$
Surface reaction	$A(g) + B(g) \rightarrow AB(g)$	$H + H \rightarrow H_2$	$\geq 10^{-9} \text{ cm}^3 \text{ s}^{-1}$
Desorption	$A(g) \rightarrow A (h\nu \text{ or } T)$	$H_2CO(g) \rightarrow H_2CO$	$\sim 0 - 10^5 \text{ s}^{-1}$

^aChemical reaction rates vary widely in disks due to strong gradients of physical conditions

^bRF designates the local UV radiation field in the disk; $h\nu$ represents a photon

$\sim 10\%$ of the reaction rates have been accurately measured in the laboratory or calculated theoretically, making calculated molecular concentrations uncertain by factor of $\sim 3-5$ (see, e.g., Wakelam et al. 2006; Vasyunin et al. 2008). The most widely utilized astrochemical networks are those of the University of Manchester (UMIST) (Woodall et al. 2007), the Ohio State University (OSU) (Smith et al. 2004), Kinetic Database for Astrochemistry (KIDA; Wakelam et al. 2011), and a network incorporated in the Meudon code (Le Petit et al. 2006). Several datasets of surface reactions have also been compiled (e.g., Tielens and Hagen 1982; Hasegawa et al. 1992; Garrod and Herbst 2006).

The formation and destruction of polyatomic molecules in a **protoplanetary disk** continue from preceding dense core phase and are controlled by various chemical processes (Table 2). In the dense inner zone, three-body gas-phase processes become competitive at densities above $\sim 10^{10} - 10^{13} \text{ cm}^{-3}$ (Aikawa et al. 1999); otherwise all gas-phase reactions in PPDs are one- and two-body processes. As majority of key species such as H_2 , H_2O , and CO have been formed in cold prestellar cores or even at earlier evolutionary stages, radiative association reactions like $C^+ + H_2 \rightarrow CH_2^+$ (Herbst 1985) creating new molecular bonds are of less significance.

The reactions between neutral and charged molecules in the gas phase and on the surfaces

of dust grains dominate the synthesis of new species in disks. The ion-molecule reactions dominate the gas-phase chemistry, especially at low temperature in the outer disk region. Most of these reactions are exothermic, with high rate coefficients, $\sim 10^{-7} \text{ cm}^3 \text{ s}^{-1}$ that often increase toward low temperatures, and low (if any) reaction barriers (e.g., Dalgarno and Black 1976). The long-distance Coulomb attraction of an ion and a molecule with a high dipole moment is what makes the ion-molecule rates increase when temperature decreases. **Ion-neutral reactions** lead to the restructuring of molecular bonds. One of the most important classes of reactions in disks is proton transfer reactions involving a key H_3^+ ion, such as $H_3^+ + CO \rightarrow HCO^+ + H_2$. A number of **neutral-neutral reactions** between radicals and radicals, radicals and open-shell atoms, and radicals and unsaturated molecules are competitive in disks even at low temperatures (van Dishoeck 1988), with a typical rate coefficient that is only about an order of magnitude lower than for the ion-molecule processes (e.g., Smith et al. 2004). These reactions usually have barriers and as such become more active within the warm inner zone of a disk. One of the most interesting reactions of this type is the formation of formaldehyde: $CH_3 + O \rightarrow H_2CO + H$ (Woodall et al. 2007). The reaction rates of ion-molecule reactions are usually accurate within 50%, while

those for neutral-neutral reactions are harder to constrain due to reaction barriers.

The rapid neutralization of polyatomic molecular ions by dissociative recombination with electrons and negative ions leads to the production of smaller neutral molecules in disks. These processes are fast at low temperatures, with typical rates of about $10^{-7} \text{ cm}^3 \text{ s}^{-1}$ (Woodall et al. 2007). For nearly all observed molecules, dissociative recombination is an important formation pathway. Often, at late evolutionary phase, $\sim 0.1 \text{ Myr}$, dissociative recombination balances protonation reactions, e.g., $\text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2$ followed by $\text{HCO}^+ + \text{e}^- \rightarrow \text{CO} + \text{H}$.

Additional energy is brought to reacting gas species by cosmic ray particles (CRPs), X-rays, and UV photons, which dissociate and ionize species, destroying molecular bonds. The cosmic rays dominate ionization at disk interiors (unless surface density does not exceed $\sim 100 \text{ g cm}^{-2}$), whereas X-rays and FUV photons are important at upper disk regions (surface density $\lesssim 1 \text{ g cm}^{-2}$). The cosmic ray- and X-ray-driven ionization is mainly caused by secondary energetic electrons upon primal ionization of H_2 . The respective reaction rates are uncertain, since the CRP and X-ray spectra cannot be directly derived from disk observations (e.g., due to local absorption of low-energy CRPs and X-rays). The key ionization reactions in PPDs are CRP/X-ray ionizations of H_2 and He.

The ionization and dissociation of some chemical species proceed by absorption of the UV continuum radiation, while other molecules are destroyed by absorbing UV photons of particular energies. For example, H_2 and CO dissociate via absorptions of FUV photons in discrete lines, whereas other molecules are dissociated either by the continuum (e.g., CH_4) or by the continuum and lines (e.g., C_2 ; see van Dishoeck et al. 2006). Atmospheres of young Sun-like stars generate nonthermal UV radiation, with an intensity at 100 AU from the star that can be as high as 1,000 (in units of the interstellar UV field, see Bergin et al. 2003). In some stars like TW Hya, a significant fraction of the total UV luminosity of the star is emitted in the $\blacktriangleright$ Ly alpha line. Stellar and interstellar UV photons are able to penetrate

deep into flaring disks by scattering on dust grains (van Zadelhoff et al. 2003). By dissociating and ionizing molecules, mild UV radiation drives active chemistry involving these ions and radicals, increasing the chemical complexity of the disk. For example, the high ratio of CN to HCN abundance observed in some disks (Dutrey et al. 1997) is attributed to the intense photodissociation of HCN when part of the stellar UV flux comes as Ly alpha photons (121.6 nm; Bergin et al. 2003).

The key photodissociation reaction in disks is that for CO – a molecule that otherwise locks up almost all the elemental carbon see (Table 2). Since the dissociation of the H_2 and CO molecules involves absorption of FUV at discrete wavelengths shortward of $\sim 115 \text{ nm}$, $\blacktriangleright$ self-shielding and isotope-selective photodissociation effects are possible. In the disks, H_2 and CO are so abundant that dissociating FUV lines saturate, shielding the rest of molecules from being destroyed (Draine and Bertoldi 1996; Lee et al. 1996). In contrast, rare, less abundant $\blacktriangleright$ isotopologs of CO absorb FUV photons at shifted wavelengths compared to $^{12}\text{C}^{16}\text{O}$, making self-shielding unimportant and enriching the gas with rare O and C isotopes (Thiemens and Heidenreich 1983).

The observed overabundance of deuterated species in disks compared to the measured interstellar D/H ratio of $\sim 10^{-5}$ is well established. Deuterium enrichment operates at low temperatures of 10–20 K via a key fractionation reaction: $\text{H}_3^+ + \text{HD} \leftrightarrow \text{H}_2\text{D}^+ + \text{H}_2 + 232 \text{ K}$ (Gerlich et al. 2002). A reactive H_2D^+ ion acts similar to H_3^+ , donating D to neutral radicals via a “protonation” reaction. For example, a predominant reaction pathway to produce DCO^+ is via the ion-molecule reaction of CO with H_2D^+ . Two other key fractionation reactions are active till higher temperatures (up to 70 K): $\text{CH}_3^+ + \text{HD} \leftrightarrow \text{CH}_2\text{D}^+ + \text{H}_2 + 390 \text{ K}$ (Asvany et al. 2004) and $\text{C}_2\text{H}_2^+ + \text{HD} \leftrightarrow \text{C}_2\text{HD}^+ + \text{H}_2 + 550 \text{ K}$. Both reactions lead to, e.g., DCN by the ion-molecule reaction, $\text{N} + \text{CH}_2\text{D}^+ \rightarrow \text{DCN}^+ + \text{H}_2$, followed by protonation reaction and then dissociative recombination. The mass-dependent fractionation for heavier elements like C and O is not that effective, due to the much lower mass difference between isotopologs, and other mechanisms, like mass-

independent isotope-selective dissociation and surface processes, have to be considered.

In cold disk regions, where $T \sim 10\text{--}120$ K, volatile species can condense out on dust grains. The rate of this freeze-out process depends on grain sizes and concentration and is effective in the outer disk midplane where grains do not grow significantly beyond $\sim 1\text{ }\mu\text{m}$. At $\sim 10\text{--}20$ K, many gas-phase molecules stick to a grain with a nearly 100% probability by [▶ weak van der Waals](#) forces, while some may form a much stronger chemical bond with the surface. Consequently, desorption of chemisorbed species requires higher temperatures/UV irradiation than that of physisorbed molecules and thus allows limited surface chemistry to occur even under harsh conditions.

Frozen species are released back to the gas by thermal evaporation, CRP heating, and UV desorption. A molecule evaporates thermally when it has energy to overcome binding to the surface (e.g., Leger et al. [1985](#)). Typical binding energies are about 1,000 K for light molecules such as CO and N₂ (Bisschop et al. [2006](#)) and larger for heavier [▶ cyanopolyynes](#) and carbon chains ($\sim 5,000$ K). CRP-induced desorption is a transient heating event when a relativistic Fe atom hits a grain and raises T to 70 K (e.g., Leger et al. [1985](#)). Also, UV photons can kick off surface molecules with a probability which has been roughly measured to be $\sim 10^{-6}\text{--}10^{-3}$ (e.g., Öberg et al. [2007](#)).

The dust grain surfaces serve as a catalyst for many reactions with slow gas-phase rates (such as endothermic reactions with barriers). The most notable example is the formation of molecular hydrogen that proceeds entirely on dust at $T < 15\text{--}20$ K (e.g., Hollenbach and Salpeter [1971](#)). A reaction may occur when an accreted atom or light radical, if it is not chemisorbed or desorbed back to the gas, hops over the surface sites and finds a radical. At low temperatures, surface hydrogenation of radicals is a key mechanism, leading to the formation of saturated products like water, methane, ammonia, and methanol (e.g., Tielens and Hagen [1982](#)). At higher temperatures of ~ 50 K, heavier reactants become mobile (such as O, C, OH, HCO, etc.), and complex

molecules are produced. So far, this is the only viable route to form complex organic matter in protoplanetary disks.

Applications

Nonexistent for this topic apart from similar fields of astronomy such as chemistry in (exo)planetary atmospheres, chemistry of primordial prebiotic molecules (in astrobiology), and isotopic fractionation in the early solar nebula.

Future Directions

The [▶ ALMA](#) interferometer in northern Chile is becoming fully operational in 2014. It will revolutionize our understanding of protoplanetary disks by providing high spatial resolution (up to $0.01''$), large collecting area ($5,000\text{ m}^2$) and thus high sensitivity, and a broad frequency coverage ($86\text{--}950$ GHz or $\sim 0.2\text{--}3$ mm). This is a gain by a factor of 50 in resolving power and orders of magnitude in sensitivity in comparison with earlier observational facilities. First, this will allow us to observe high-lying rotational transitions of simple abundant species like CO, CN, HCN, and HCO⁺ and to discover more complex molecules with weaker lines at low frequencies. With this information, we can better constrain disk chemical composition and physical conditions. Second, with much higher spatial resolution, we will be able to image planet-forming regions around nearby PPDs in detail and thus determine the distribution of and properties of dust there. Third, molecular layers in protoplanetary disks may become directly observable for the first time, allowing us to better tune theoretical disk chemical models and laboratory measurements of photodissociation and freeze-out processes. Fourth, data acquisition will be rapid with ALMA, and many protoplanetary disks around various young stars will be surveyed, enabling their proper statistical analysis. Other future instruments, like the Square Kilometer Array (SKA) at cm wavelengths, may allow the detection of low-energy lines from highly complex

(organic) species in cold disk regions. Future progress in our understanding of disk physics and chemistry will not be achieved without development of more advanced chemical disk models, in particular, including disk dynamics, grain evolution, and transport of UV and X-ray radiation. The chemical models will strongly benefit from ongoing activities of laboratory/theoretical chemists to derive the rates and products of astrophysically relevant processes, binding energies and photodesorption yields of surface species, and high-precision IR/microwave spectra of potentially detectable, chemically interesting species.

Cross-References

- ▶ [ALMA](#)
- ▶ [Bipolar Flow](#)
- ▶ [Chemisorption](#)
- ▶ [Chondrite](#)
- ▶ [Electron Dissociative Recombination](#)
- ▶ [Infrared Space Observatory](#)
- ▶ [Interstellar Chemical Processes](#)
- ▶ [Ion-Neutral Reaction](#)
- ▶ [Isotopic Fractionation \(Interstellar Medium\)](#)
- ▶ [JWST](#)
- ▶ [Molecular Cloud](#)
- ▶ [Molecules in Space](#)
- ▶ [Neutral-Neutral Reaction](#)
- ▶ [Optical Depth](#)
- ▶ [Physisorption](#)
- ▶ [Polycyclic Aromatic Hydrocarbon](#)
- ▶ [Protoplanetary Disk](#)
- ▶ [Protostars](#)
- ▶ [Solar Nebula](#)
- ▶ [Spitzer Space Telescope](#)

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Protoplanetary Nebula

Sun Kwok

Faculty of Science, The University of Hong Kong, Hong Kong, China

Keywords

Planetary nebulae · Reflection nebulae · Stellar evolution

Synonyms

Pre-planetary nebulae

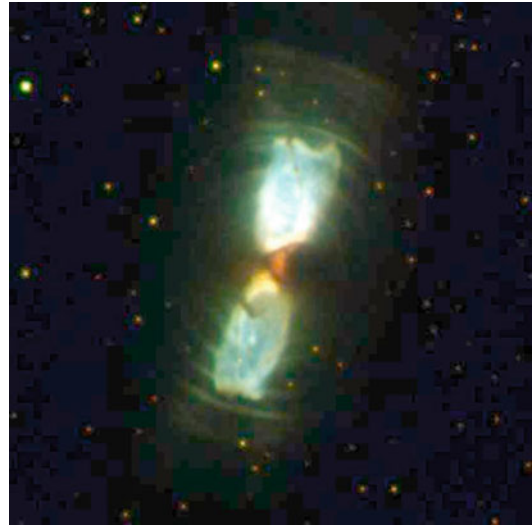
Definition

Protoplanetary nebulae (PPN) are objects in transition between the ► [asymptotic giant branch](#) (AGB) and the ► [planetary nebulae](#) (PN) phases of stellar evolution. The optical nebulosity of PPN is due to scattered light from the central star, not emission lines as in the case of PN. Observationally, PPN are defined as gaseous nebulae surrounding stars in a post-AGB phase of evolution showing no emission lines in their optical spectra.

History

Since the 1970s, PN have been known to be descendants of AGB stars, and the nebulae represent remnants of ejecta from AGB stars. The visual brightness of PN is the result of ► [line emission](#) from gas photoionized by a hot central star. From models of stellar evolution, it was known that the central stars of PN need a few thousand years to evolve from the end of the AGB to a temperature hot enough to emit a significant amount of ultraviolet radiation capable of photoionizing the circumstellar gas (Schönberner 1983). However, for a long time, no such transition object was known and the phase linking AGB stars and PN represented a missing link in the late stages of stellar evolution.

The emission mechanisms responsible for the brightness of PN are primarily recombination lines and collisionally excited lines. Both are extremely efficient, making PN bright optical objects (Kwok 2000). Without ionized gas, PPN have to rely on scattered light from the central stars, making the nebulosity very faint in the visible. However, since AGB stars are known to be strong infrared sources due to dust emission, it was suspected some infrared sources discovered in the Air Force Infrared Sky Survey



Protoplanetary Nebula, Fig. 1 Hubble Space Telescope Wide-Field Planetary Camera 2 image of the protoplanetary nebula IRAS 17150-3224 (the Cotton Candy Nebula). The visual brightness of the object is entirely due to scattered light. In addition to its bipolar morphology, multiple concentric arcs can also be seen

could be PPN (e.g., AFGL 618, Westbrook et al. 1975; AFGL 2688, Ney et al. 1975). After the Infrared Astronomical Satellite (IRAS) sky survey observed a large number of AGB stars and planetary nebulae, it was realized that PPN could be identified as objects having infrared colors intermediate between those of AGB stars and planetary nebulae (Volk and Kwok 1989). A systematic search of IRAS sources matching such color criteria has resulted in the discovery of ~30 PPN (Kwok 1993), one of which is shown in Fig. 1.

Overview

PPN have the following observational characteristics: (i) their central stars have spectral types intermediate between those of AGB stars and PN, usually of spectral types F, G, and K; (ii) their central stars have low surface gravity, often classified as luminosity class I or Ia; (iii) their infrared spectra are dominated by thermal continuum emission from warm dust; (iv) molecular emission lines can be seen in their

mm/submm spectra; (v) their spectral energy distributions show evidence of detached dust envelopes; and (vi) their optical nebulosity is due to scattered light.

Imaging observations by the *Hubble Space Telescope* have shown that many PPN show bipolar morphology, suggesting that the transformation from spherical to bipolar morphology has already taken place during the post-AGB phase of evolution (Balick and Frank 2002). Some PPN have binary central stars (Van Winckel 2003), which may play a role in the creation of the nebular bipolar morphology.

Most interestingly, spectral signatures of aromatic and aliphatic organics first appear during the PPN stage, suggesting that the synthesis of complex organics can occur in the circumstellar environment (Kwok et al. 1999).

Cross-References

- [Asymptotic Giant Branch Star](#)
- [Stellar Evolution](#)
- [Unidentified Infrared Emission Bands](#)

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Protoplasmic Theory of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Definition

During the second part of the nineteenth century, the British biologist, Thomas Huxley (1825–1895), claimed that, inside the cell, the protoplasm was essentially composed of albuminoidal bodies and would be the place of the physical basis of life. This theory led some biologists, as the German Ernst Haeckel (1834–1919), to assume that origin of life could correspond to the formation of free protoplasm.

Cross-References

- [Abiogenesis](#)
- [Cellular Theory, History of](#)
- [Huxley's Conception on Origins of Life](#)

Protoplast

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Spheroplast](#)

Definition

A protoplast is a bacterial, fungal, or plant cell that has had its cell wall completely or partially removed using either enzymatic or mechanical means. ► [Cell walls](#) are made of a variety of polysaccharides (► [peptidoglycan](#), chitin, cellulose). Protoplasts

are generally prepared by degrading cell walls with a mixture of appropriate polysaccharide-degrading enzymes. In the case of gram-positive ► [bacteria](#), lysozyme, an enzyme that breaks the bonds that maintain the structure of the peptidoglycan, is used. To prepare plant cell protoplasts, a mixture of hydrolyzing enzymes (cellulose, proteinase, and xylanase) is required. In the case of fungal protoplast, chitinase is the enzyme of choice. During and subsequent to digestion of the cell wall, the protoplast becomes very sensitive to osmotic stress. This means that cell wall digestion and protoplast storage must be carried out in an isotonic solution to prevent the disruption of the plasma membrane. Protoplasts are useful for genetic recombination experiments, because the absence of a cell wall facilitates the transport of DNA molecules to the cytoplasm. Protoplasts are normal cells, their growth allows the generation of cells with cell walls. Although most prokaryotes cannot survive in nature without a cell wall, some are able to do so. These include the mycoplasma, gram-positive bacteria, and *Thermoplasma*, an acidophilic and thermophilic *Euryarchaea*.

Cross-References

- [Acidophile](#)
- [Bacteria](#)
- [Cell Wall](#)
- [Euryarchaeota](#)
- [Fungi](#)
- [Gram-Positive Bacteria](#)
- [Peptidoglycan](#)
- [Thermophile](#)

Protosolar Nebula, Minimum Mass

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Synonyms

[Solar nebula](#)

Definition

The minimum-mass ► [solar nebula](#) is the theoretical minimum amount of mass required to have formed the Solar System. The amount is calculated based on the known quantity of refractory elements in the planets and adjusting for the original composition of the pre-solar nebula (i.e., adjusting for the failure of most of the planets to completely incorporate the more volatile elements from the nebula). The minimum-mass solar nebula model typically assumes a surface density that decreases with orbital distance r as $r^{(-3/2)}$, with a total mass between 0.01 and 0.1 solar masses. This is comparable to the masses of some disks observed around young stars. More recent observations of disks suggest that the radial distribution of mass is flatter than the $-3/2$ power law, probably much closer to a -1 slope.

Cross-References

- [Protoplanetary Disk](#)
- [System Solar Formation, Chronology of](#)

Protostars

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Accretion · T Tauri star

Definition

Stellar evolution begins when a diffuse interstellar cloud undergoes gravitational collapse. Toward the cloud's center, a primitive star forms and continues to build up its mass from the surrounding gas. This object, called a protostar, is unique in that most of its luminosity stems from the kinetic

energy of infalling matter crashing onto its surface and surrounding disk. The infalling envelope of gas contains dust grains, which absorb and reemit stellar photons into the infrared. The fusion of deuterium inside protostars determines the location of the stellar [▶ birthline](#) in the [▶ Hertzsprung-Russell diagram](#). In the most massive protostars, ordinary hydrogen ignites while cloud infall is still occurring.

Overview

Stellar Life Cycle

All stars are born through the gravitational collapse of diffuse, interstellar clouds. During its initial, protostar phase, the star is optically invisible, as it is completely embedded in its parent cloud. Indeed, it is still gathering mass from that body. The protostar phase is unique in that the star's luminosity arises mostly from the kinetic energy of infalling gas. Following infall, the star then contracts slowly. During this longer, pre-main-sequence phase, energy is released by the increasing gravitational binding of the star.

Stars achieve maturity once they begin to fuse hydrogen into helium at their centers. This main-sequence phase comprises the longest period, by far, in the star's life. As hydrogen is consumed, the central regions of the star contract and heat up, so that successively heavier elements (helium, carbon, oxygen, etc.) begin to fuse. The process is an accelerating one. During this relatively brief post-main-sequence phase, the outer layers of the star swell, and the object brightens enormously, as a consequence of both the increased fusion and the further gravitational contraction of its central region.

The final fate of a star depends on its initial mass. Our Sun, after shedding a large amount of gas during the post-main-sequence epoch, will become a white dwarf, an object with the diameter of the Earth. Lacking nuclear reserves, the white dwarf will gradually cool over billions of years. In more massive stars, the remnant, condensed object at the center is a [▶ neutron star](#), with a diameter of a few kilometers or a [▶ black hole](#), an object so dense that not even light can escape it.

Taking a larger, galactic perspective, star formation represents the conversion of interstellar gas into the much more condensed objects we call stars. But the process does not just operate in one direction. Stars themselves spew back matter into space, in the form of winds, novae, and supernovae. This matter, enriched in heavy elements by previous fusion, cools and eventually becomes new interstellar clouds which in turn produce more stars. White dwarfs, neutron stars, and black holes constitute a sink that slowly drains mass away from this cyclical process.

Parent Clouds

The interstellar medium consists of both ionized and neutral gas. The specific interstellar clouds that form stars are those composed of molecular hydrogen and are thus known as molecular clouds. Of all the clouds in interstellar space, only these are dense and cold enough so that self-gravity plays an important role in their overall force balance. Since stars form through gravitational collapse, molecular clouds are strongly implicated in the process.

Molecular clouds have a range of sizes and masses. At the top end of the spectrum are the giant complexes. With typical sizes of 50 parsecs, these are the largest coherent entities in the Galaxy. We can also see giant molecular complexes in other, nearby spiral galaxies. All complexes are highly clumpy. A single clump can have a mass of hundreds to thousands of solar masses. The clumps are also found individually, outside of a giant complex, where they are more commonly known as dark clouds. The term refers to the fact that these objects obscure background starlight, giving the sky a patchy appearance.

Stars do not form uniformly throughout a giant complex, but only in its interior clumps. They also form within the more isolated dark clouds. But again, it is only the very densest gas that can produce stars. Both the clumps within complexes and dark clouds contain numerous patches of especially dense gas. These regions, typically 0.1 parsecs in size, are known as dense cores. They are the objects which collapse to form stars. We know this critical fact because a large fraction of dense cores contain embedded stars. The latter

appear as point sources of infrared or submillimeter radiation.

Dense cores, like their surrounding molecular gas in the clump or dark cloud, have temperatures of 10–20 K. Even this very low temperature provides some thermal pressure. Prior to its collapse, a dense core is supported against self-gravity by this outward force. The parent clump has a similarly low temperature. However, its higher mass also implies a stronger force of self-gravity. Support of the larger object comes from the pressure associated with internal, turbulent motion. Dense cores are special locations within the clump where the turbulent motion has, for some reason, died down.

Not all dense cores are currently forming stars. Barren objects called starless cores appear rather similar to those containing infrared point sources. However, the densest of the starless cores appear to be undergoing a slow, inward contraction. This motion may be the prelude to the full-scale collapse that gives rise to a star.

We know all of these facts because of the emission of radio and millimeter waves by the dense cores. The chief constituent of these objects is molecular hydrogen, which unfortunately is a very poor emitter at the extremely cold, ambient temperatures. We must therefore turn to other molecules which, despite their rarity, emit more strongly. Carbon monoxide is a convenient choice, especially for the larger clumps and dark clouds. In dense cores, the millimeter radiation from carbon monoxide becomes trapped, and other molecules must be used. Ammonia is one such species, emitting a strong spectral line at 1.3 cm.

Careful analysis of the spectral line emission, often from a variety of molecules, has yielded the densities and temperatures of all types of molecular clouds, including dense cores. Furthermore, the detailed shape of the line gives information about the gas motions. We know, for example, that larger clouds are turbulent because their carbon monoxide lines are much too broad to arise solely from thermal motion of the molecule. Conversely, it is the relative narrowness of the ammonia lines in dense cores that indicates their quiescence.

Inside-Out Collapse

It is still unclear whether we have observed dense cores in the act of collapse. As mentioned previously, a large fraction of starless cores do show signs of inward motion. The signature is an asymmetric line profile in an optically thick, i.e., relatively opaque, molecular line. The blueward component of the line is stronger than the red, and there is often a strong absorption dip near line center. Such a profile is also seen in YY Orionis stars, older, pre-main-sequence objects that are surrounded by infalling gas. In the case of dense cores, the asymmetric line is observed over a broad area and indicates slow, subsonic infall velocities. Lacking a detailed explanation for these observations, we must rely on theory to tell us how collapse proceeds.

A clear advance in our understanding of cloud collapse came in the 1960s, through computer simulations and accompanying analytical models. Prior to that time, the assumption was that clouds collapse as a whole. Moreover, collapse could lead to fragmentation and further collapse of the fragments. Theorists came to realize that this picture does not hold when the original cloud is close to a state of force balance. In that case, the density rises sharply toward the center of the object. The local [free-fall time](#) is correspondingly brief in that region. As a result, the center of the cloud collapses first, while the outer regions lag behind.

This inside-out mode of collapse undoubtedly applies to dense cores. Observations show that their internal temperatures are sufficiently high that the objects as a whole are indeed in force balance between thermal pressure and self-gravity. Moreover, the spatial rise in density toward the cloud center can be seen directly in molecular line observations. Since the strongest, highly supersonic collapse is concentrated in the central region, that motion is more difficult to observe.

Both analytic theory and numerical simulations predict that the boundary of infall spreads outward through the cloud. In effect, the collapse and infall to the central protostar has lowered the gas pressure. A rarefaction wave of collapse propagates at the local speed of sound. Given typical dense core sizes and temperatures, the wave

reaches the cloud edge in a time of 100,000 to a million years. This time span measures the lifetime of protostars.

The most detailed models assume a perfectly spherical cloud. Observations show, however, that real cores are aspherical, with aspect ratios of about 2–1. This fact alone demonstrates that there are more supporting forces than simply thermal pressure, which is intrinsically isotropic. One obvious candidate is the interstellar magnetic field, which exerts a force that is comparable to that from thermal pressure. The direction of the magnetic force depends on that of the field lines. Observers have recently begun to obtain images of bent magnetic field lines penetrating dense cores. These images were achieved by mapping the polarization direction of light emitted by dust grains. Clearly, detailing the collapse in a magnetized cloud is a more daunting proposition, and no complete models exist. Nevertheless, the general picture of inside-out collapse should hold.

What precedes collapse? To first approximation, starless cores are in a state of hydrostatic (or, more correctly, magnetostatic) equilibrium. However, the object is actually evolving. Most theorists agree that this evolution occurs through the slippage of neutral matter past the internal magnetic field, the process known as ► [ambipolar diffusion](#). This slippage is possible because it is only the charged species in the cloud (ions and electrons) that directly feel the magnetic force. These species then transfer their momentum to the neutral gas via collisions. In a dense core, however, the level of ionization is so low that such collisions are rare. Hence, gravity can pull the neutral gas inward, past the magnetic field.

While there is a good theoretical understanding of ambipolar diffusion, the applicability of the concept to dense cores is not yet secure. The difficulty is that ambipolar diffusion is relatively slow. For typical conditions, a dense core will not begin collapse for about ten million years. However, we see young clusters in which stars were born over an interval of just a few million years. Some other process, operating on a larger scale, must be synchronizing dense core contraction and collapse. One possibility is that the larger, parent body (clump or dark cloud) is also slowly

contracting and somehow stimulating the growth and collapse of its internal dense cores.

A second difficulty is that most models of collapsing, magnetized clouds find that the object flattens in a plane perpendicular to the main field direction. This finding runs counter to observations. Both starless cores and those containing central stars exhibit similar aspect ratios. One must de-project this shape to obtain the object's true, three-dimensional configuration. It appears that dense cores of both types are prolate. That is, they are elongated, rather than flattened. Clearly, there is some important ingredient missing in our understanding of the role magnetic fields play in dense core formation and collapse.

Main Accretion Phase

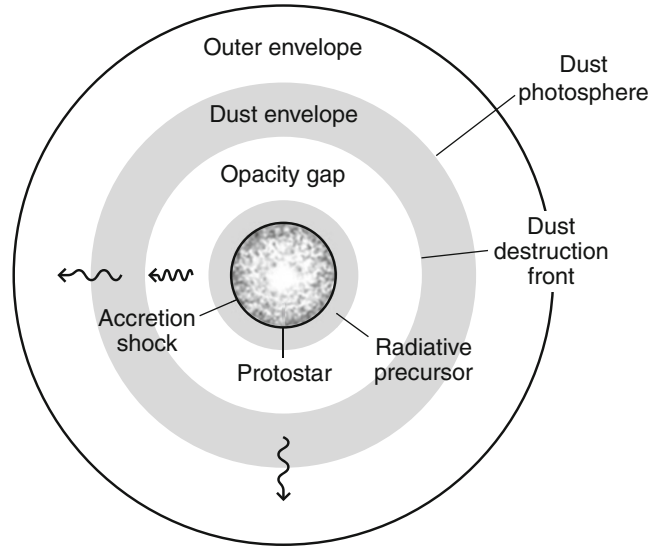
As the dense core collapses, the first stable object to form at its center is not a star, but a more compact cloud composed of molecular hydrogen. This short-lived entity is traditionally (and rather confusingly) known as the first core. It reaches a mass of less than 0.1 times the solar value and a radius of about 5 AU before it too collapses on itself. This second collapse is triggered by dissociation of the hydrogen molecules. Such dissociation effectively absorbs energy. Since the internal pressure is not rising appreciably during the process, gravity overwhelms it, and the first core collapses.

Following the demise of the first core, a much smaller and denser object arises at the center of infalling gas. This is a protostar. Its internal gas is ionized, and so the object will not suffer the destabilization that doomed the first core. The protostar is a genuine star, although one that is deeply buried in the infalling gas of the surrounding dense core. The period during which the dense core gas falls onto the protostar is known as the main accretion phase. As previously estimated, this phase lasts from 100,000 to a million years for a solar-type star. Figure 1 depicts schematically a protostar during its main accretion phase.

The outer boundary of an ordinary star is a photosphere, a thin surface layer through which radiation can escape. In contrast, the outer boundary of a protostar is a shock front, where infalling gas impacts the star itself. This gas is moving at

Protostars,

Fig. 1 Structure of a spherical protostar and its infalling envelope. The relative dimensions of the outer regions are greatly reduced for clarity. Note the convection induced by deuterium burning in the central protostar. Note also the conversion of optical (short-wavelength) to infrared (long-wavelength) photons in the dust envelope



hypersonic speed. Consequently, post-shock gas has a very high temperature, of order one million Kelvin. This heated gas radiates X-rays, both into the outside flow and back into the body of the protostar.

Remember that a protostar, by definition, derives most of its luminosity from infall. This luminosity is that generated just behind the accretion shock front. However, the X-ray photons themselves never leave the dense core. They are quickly absorbed by infalling gas just outside the star. This gas reradiates the energy into optical wavelengths. Thus, while the total energy output in radiation is conserved outward, the character of that radiation changes markedly.

Indeed, even the optical radiation does not escape. Infalling dust grains, present in the original dense core, absorb these photons. Heated dust grains radiate in the infrared region of the spectrum. As this infrared flux travels outward through the dust, it is continually degraded through multiple absorption and reemission to yet longer wavelengths. Eventually, the photons have such long wavelengths that they break free of the infalling, dusty gas. The dust photosphere, located some 10 AU from the central protostar, is the surface which emits the bulk of the luminosity.

The radius of the dust photosphere is still tiny compared to that of the dense core itself, which is larger by a factor of 1000. It makes sense,

therefore, that protostars are observed as unresolved point sources of infrared and submillimeter radiation inside dense cores. The energy emitted by these sources is relatively high. For a protostar of solar mass, the luminosity is about ten times the solar value, and the radiation peaks in the mid- to far-infrared regime.

The dust grains responsible for degrading the protostar's radiation into the infrared do not survive close to the central object. As they fall inward, they are heated by the outgoing flux of energy. At a distance of about 1 AU from the star, the grains reach a temperature of 1500 K and sublimate. There is thus a zone surrounding the protostar through which the shock-generated radiation can propagate freely. This region is known as the opacity gap. The inner boundary of the opacity gap is the layer of infalling gas that is absorbing the shock-generated X-rays and converting them into optical photons. The outer boundary of the gap is known as the dust destruction front.

Deuterium Fusion

Protostars, as we have emphasized, are too young and cold to fuse hydrogen into helium. Indeed, they are younger than pre-main-sequence stars, which derive their luminosity from gravitational contraction rather than fusion. Nevertheless, both protostars and pre-main-sequence stars do ignite

deuterium. This hydrogen isotope, whose nucleus consists of a proton and neutron, fuses with protons at a temperature of only 1000,000 K, an order of magnitude lower than the ignition temperature of ordinary hydrogen.

The luminosity generated by deuterium fusion represents a minor fraction of the protostar's total energy budget. Furthermore, this luminosity does not escape the star, but is absorbed in gas overlying the central region of active fusion. However, this very heating does aid in swelling the protostar as it continues gathering mass from its infalling cloud envelope. The net result is that protostars of a given mass all have nearly the same radius while burning deuterium, regardless of their detailed accretion history. This fact, in turn, means that the youngest pre-main-sequence stars have a nearly unique mass-radius relationship. These are the optically visible objects that lie along the birthline in the Hertzsprung-Russell diagram. In summary, the location of the birthline is largely determined by the phenomenon of deuterium fusion in protostars.

Deuterium fusion has another interesting consequence. The intense heat generated near the protostar's center creates thermal convection. This motion of buoyant, heated fluid elements, rather than the diffusion of photons, carries outward the protostar's luminosity. In protostars more massive than a few tenths of the solar mass, the region of convective instability extends to the surface, just below the accretion shock. This property, too, is bequeathed to the youngest pre-main-sequence stars, which are fully convective. In the present-day Sun, the convection zone extends inward from the photosphere for about the outer third of the solar radius.

Disk Formation

Our description of the main accretion phase has omitted two key ingredients – magnetic fields and rotation. We know that dense cores are penetrated by the interstellar magnetic field. If the ionization fraction in the gas is sufficiently high, this field is dragged down toward the protostar during collapse. Two circumstances prevent the buildup of very strong fields. First, field lines of opposite direction reconnect, releasing energy and

lowering the field strength. Second, in regions of very low ionization, such as those found deep inside the ► [protostellar envelope](#), the neutral matter slips past the field, in the process known as ambipolar diffusion. Since this slippage already occurred in the parent dense core prior to collapse, it must be amplified here. In any case, detailed calculations of protostellar collapse incorporating both magnetic reconnection and ambipolar diffusion are not yet available.

Rotation, the second missing ingredient, is key to the formation of circumstellar disks. Many pre-main-sequence stars are believed to have such disks. In a few cases, they have been imaged directly. In many other objects, the classical T Tauri stars, the presence of a disk is inferred from the excess emission at infrared wavelengths. It is these disk structures that ultimately form planets. Their presence in even the youngest pre-main-sequence stars implies that they were created earlier, during the protostar phase. If the collapse were spherically symmetric, no disk would arise. However, dense cores are observed to rotate, so a purely spherical picture of infall cannot be correct.

The rotation of dense cores is too slow to affect their gross structure. For example, the observed departure of these clouds from spherical symmetry cannot be attributed to rotational distortion. On the other hand, angular momentum is conserved during collapse. As each fluid element carries inward its initial angular momentum, the associated centrifugal force rises. If this force reaches or exceeds the gravity of the central protostar, the fluid element is effectively repelled. Rather than falling onto the star, it goes into orbit within the equatorial plane perpendicular to the cloud rotation axis. Thus are born circumstellar disks.

While the birth of disks is thus understood generally, our description is again a simplification. As the collapse proceeds, an increasing amount of gas is diverted to the disk, at the expense of the central star. Eventually, the mass of the disk would rival or exceed that of the protostar. But such massive disks are unstable to fragmentation. We observe intact disks, and these contain typically a few percent of the stellar mass. Some process must limit their growth. The consensus is that

matter within the disk spirals inward toward the star, a process known generically as disk accretion. The spiraling process must occur even as more matter is impacting the disk from the protostellar envelope. For many stars, the bulk of their mass may be acquired by this route, rather than by direct infall from the protostellar envelope.

What causes the spiraling? There is no generally accepted answer to this question. One widely discussed possibility is that magnetic fields become trapped in the disk and are tangled up by its rotation. In effect, the disk material becomes turbulent. As is well known in fluid dynamics, turbulence can create an effective viscosity. In principle, such internal friction causes the more rapidly orbiting disk material to transfer its angular momentum outward and to drift inward. Another possibility is that spiral arms develop in the disk, analogous to those in galaxies. Such a perturbation of the density also creates internal torques that might result in the desired effect. Yet a third possibility is that the disk sheds angular momentum in the form of a rotating, magnetized wind.

Whatever its cause, the outcome of the process is clear enough. At least half of known pre-main-sequence stars of solar-type mass, the classical T Tauri stars, are born with disks. Another portion, dubbed weak-lined stars, have little or no disk material surrounding them. Apparently, the spiraling process operated more efficiently in the latter group.

Massive Protostars

We have described how the fusion of deuterium near the center of a protostar drives convection throughout the interior. Parcels of gas, heated by the nuclear reactions, rise upward toward the surface. There, in the layers behind the accretion shock, they mix with infalling gas containing fresh deuterium. After radiating their energy, these cooler, denser parcels drift back down, to start the cycle anew. In this manner, the concentration of deuterium throughout the protostar is kept spatially uniform.

The situation changes for protostars that achieve a mass of from two to three times the

solar value. The opacity of stellar gas to radiation is a decreasing function of temperature. Since more massive protostars tend to be hotter on the inside, they are in effect more transparent to radiation. Convection ceases, first in the deep interior and then further out.

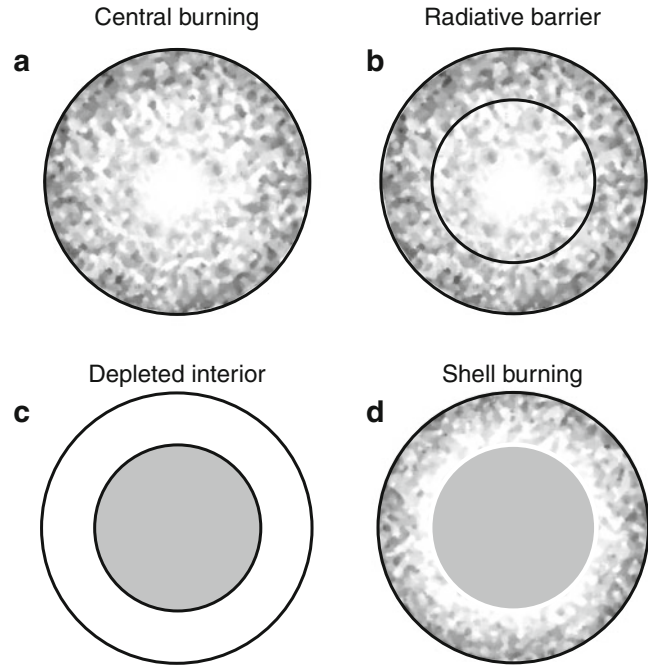
In these radiatively stable protostars, deuterium cannot be resupplied continually from the outside. Once the isotope fuses, it vanishes from the star's interior (see Fig. 2). The fuel only remains in a thin layer below the accretion shock. The fusion reactions now occur, not at the star's center, but at the bottom of this mantle. Although this mantle contains little mass and is geometrically thin, its heating has a dramatic effect. Protostars undergoing deuterium shell burning quickly swell.

These swollen protostars are the ancestors not of T Tauri stars, but of the more massive Herbig Ae and Be stars. The very youngest stars in this class indeed have observed radii that are larger than one would expect by extrapolation from their lower-mass counterparts. The theory of protostar evolution has successfully explained this fact.

Another puzzling fact is also neatly explained. Some close binary stars seem to be *twins*. That is, the masses of the two stars orbiting each other are essentially identical, to within the errors of measurement. However binary stars form in detail, it is unreasonable to expect that two dense cores (or two regions within a single dense core) would happen to produce the same stellar masses. Clearly, the two young stars must have been in contact, trading mass as they evolved. Just such a picture applies if one of the stars is swollen because of deuterium shell burning. Gas can overflow this swollen envelope and fall onto the close, companion star.

As we consider protostars with masses exceeding about ten times the solar mass, there is a new development. Interior temperatures are now so high that ordinary hydrogen, and not just the deuterium isotope, begins to fuse. The subsequent release of energy quickly overwhelms that from infall. The star essentially joins the main sequence while it is still acquiring gas from its parent dense core. Such nuclear burning protostars are the precursors to all the most massive and luminous stars

Protostars, Fig. 2 The four stages of deuterium burning in protostars. Active burning begins at the center and continues until a radiative barrier appears. The entire protostar is then stable against convection, and its interior depleted of deuterium. The fuel later ignites in a thick shell, driving convection in the outermost region



we see in our Galaxy and others, those of spectral type O and B.

In summary, O and B stars have no pre-main-sequence phase, but go directly from the protostar to the main-sequence stage of evolution. Moreover, it is not at all clear that the main accretion phase, as we have described it, applies here. The harsh ultraviolet radiation from O stars, together with their vigorous winds, tends to drive back the cloud envelope. Some researchers believe that the formation of an O star can only proceed through the coalescence of lower-mass objects. Others think that the traditional ideas concerning protostar formation continue to apply in this regime.

End of Infall

The far more common stars of solar-type mass and below do not have copious ultraviolet emission. The single biggest shortcoming in the current theory of protostars is that it gives no indication how the main accretion phase ends in general. Since the mass of the star is built up during this period, theorists cannot account for the fact that these masses have a well-documented distribution, known as the initial mass function.

Explaining the initial mass function has been a goal for many years, as yet unrealized.

In general, there are two processes that might end cloud infall. First, all of the dense core may collapse onto the star, either directly or through the circumstellar disk. This possibility was implicitly assumed in the early computer calculations of cloud collapse and protostar formation. It faces the obvious objection that there is no rigid wall separating the dense core from its surroundings. Indeed, we know little about the real transition region, beyond the fact that gas outside the dense core seems to be more turbulent than gas inside.

The second broad possibility is that the dense core is dispersed by the star itself during the infall phase. This picture gains credence from the observation that most, if not all, embedded young stars drive jets and molecular outflows. The jets are fast-moving winds expelled by the star and channeled into narrow, bipolar flows. Molecular outflows trace cloud gas that has been entrained by the jet and also driven outward in a bipolar pattern. There is no question that stellar winds do disperse molecular clouds.

A question that arises is the scale over which cloud dispersion occurs. Stellar jets extend several parsecs from their driving stars, well beyond the size of their parent dense cores. It is plausible that the larger clouds spawning entire clusters of stars are dispersed by these flows, but what of dense cores themselves? There are several images of jets erupting from seemingly intact cores. If future observations show that these clouds are more turbulent than those without internal stars, then the case for wind dispersal will be stronger.

In the last decade, several groups have documented the mass distribution of dense cores within larger molecular clouds. Dense core masses were obtained either by the observed thermal emission from heated dust grains or else by these objects' extinction of near-infrared light from background field stars. An intriguing result has emerged. The mass distribution of dense cores is very similar in shape to the initial mass function for stars. Specifically, it appears that each dense core produces, on average, a star containing about one third of the core mass.

This result, if upheld by future work, has at least two implications. First, the idea that all of dense cores collapse onto its protostar will have been disproved definitively. We are left with the wind dispersal picture. Within this context, the new results imply that each star successfully disperses its parent dense core once it reaches a fixed fraction of the core mass. Our present, admittedly limited, understanding of protostellar winds gives no clue as to why such a universal relationship should hold.

Observational Prospects

Infrared point sources are commonly seen in T associations, loose groups containing primarily T Tauri stars. The latter are optically visible objects that often have excess infrared radiation, indicating the presence of circumstellar disks. However, the very fact that they are visible means that T Tauri stars are *not* surrounded by infalling dense cores. Hence, they are in the pre-main-sequence, rather than the protostar, phase of evolution. Some of the nearby objects

that are only seen at infrared and longer wavelengths must be true protostars. Others could be pre-main-sequence stars that still possess a residual envelope of dusty gas, perhaps trapped in the star's strong magnetic field.

In principle, there is a clear distinction between these two kinds of objects. Protostars, we recall, derive most of their energy from the accretion of an infalling gaseous envelope. Pre-main-sequence stars are releasing internal energy through slow gravitational contraction, with only minor residual disk accretion. As already indicated, it has proved difficult to verify the presence of infalling motion directly. Moreover, stars of both types appear similar when cloaked in a sufficient quantity of dusty gas. Under these circumstances, the emergent spectrum largely reflects the absorption and emission properties of the dust grains and is rather insensitive to characteristics of the underlying star other than its total luminosity.

Nevertheless, there is an intriguing pattern to the spectra. For visible T Tauri stars that have an infrared excess, the observed flux declines between 2 and 10 μm . In the so-called Class I infrared sources, the flux rises in this range. Finally, there exists an even more embedded set of objects designated as Class 0. Here, there is no flux at near- or mid-infrared wavelengths. The observed emission peaks in the far infrared and continues to be strong into the submillimeter regime.

Class I sources are often loosely called "protostars." However, there is serious doubt as to whether the term applies. Relative to the pre-main-sequence phase of slow contraction, the phase of true infall is quite brief. Hence, the fraction of protostars in any T association should be correspondingly small. Class I sources, on the other hand, comprise a large fraction of the stars in the best-studied, nearby groups, typically 30% of the total membership. Moreover, a protostar should be brighter on average than a pre-main-sequence star, since it is deriving extra energy from infall. Class I sources are observed to have the same luminosities as T Tauri stars. This fact constitutes the "luminosity problem" of star formation theory.

The problem goes away if Class I sources are actually older, pre-main-sequence stars that are

still embedded in surrounding dust. Indeed, both Class I and Class 0 sources are always associated with dense cores of molecular gas. It seems that the main infall phase has ended for the former, but still might be ongoing for the latter. This supposition is supported by the lower ratio of submillimeter luminosity (tracing the envelope mass) to total luminosity in Class I sources. It is also true that Class 0 sources are brighter on average than T Tauri stars, and there are relatively few of them. This scarcity, however, hampers any attempt to draw quantitative conclusions.

It is encouraging that the dense cores surrounding both types of sources often show asymmetric profiles in molecular line emission. Such emission, we have noted, is thought to arise from inward motion of the molecular gas. The associated velocities are subsonic, far below those of gas elements entering the accretion shock of a protostar. A primary goal for the future is to obtain more direct evidence for both supersonically infalling gas and for the emission expected from the accretion shock itself.

Cross-References

- [Ambipolar Diffusion](#)
- [Bipolar Flow](#)
- [Birthline](#)
- [Convection, Stellar](#)
- [Dense Core](#)
- [Fragmentation of Interstellar Clouds](#)
- [Free-Fall Time](#)
- [Gravitational Collapse, Stellar](#)
- [Hertzsprung-Russell Diagram](#)
- [Molecular Cloud](#)
- [Pre-Main-Sequence Star](#)
- [Protoplanetary Disk](#)
- [Protostellar Envelope](#)

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Protostellar Envelope

Steven W. Stahler

Department of Astronomy, University of California, Berkeley, CA, USA

Definition

The mantle of gas surrounding a protostar is called the protostellar envelope. This material is freely collapsing onto the central star and its surrounding disk. The envelope is the densest portion of a ► [molecular cloud](#) core that went into gravitational collapse. Infalling, envelope material impacts the ► [protostar](#) and disk, creating a radiating shock front. The envelope gas contains solid dust grains, which absorb all optical and ultraviolet radiation from the star and accretion shock, reradiating it at infrared and longer wavelengths. Within about 1 AU from the star, the dust grains are thermally destroyed by sublimation. The dust photosphere (10 AU) is the radius at which the grains are so sparse that radiation streams passed them unimpeded. The emergent spectrum resembles a cold blackbody.

Cross-References

- [Birthline](#)
- [Free-Fall Time](#)
- [Gravitational Collapse, Planetary](#)
- [Molecular Cloud](#)
- [Protostars](#)

Protosun Composition

Yann Alibert¹ and Ravit Helled²

¹Space Research and Planetary Sciences,
Physics Institute, University of Bern, Bern,
Switzerland

²Geophysical, Atmospheric and Planetary
Sciences, Raymond and Beverly Sackler Faculty
of Exact Sciences, Tel Aviv University, Tel Aviv,
Israel

Keywords

Solar Nebula

Definition

The protosun composition is the initial composition of the giant ► [molecular cloud](#), from which the solar system has formed (sun and protoplanetary disk). This composition consists of about 70.5% hydrogen, 27.5% helium, and 2% of heavier elements.

Cross-References

- [Molecular Cloud](#)
- [Protoplanetary Disk](#)
- [Solar Nebula](#)

Proxima-b

Guillem Anglada-Escudé
Institut de Ciències de l'Espai – CSIC, Barcelona,
Spain
Institut d'Estudis Espacials de Catalunya (IEEC),
Barcelona, Spain

Keywords

Radial velocity · Exoplanet

Overview

Proxima b (or Proxima Centauri b) is an exoplanet orbiting the nearest star to the Sun, the star Proxima Centauri. Its discovery was reported in 2016 as the result of a specifically designed observational campaign –called Pale Red Dot – following the trail and tentative evidence accumulated over 20 years of observations with various instruments, most prominently ground-based high-precision spectrometers (Anglada-Escudé et al. 2016).

The planet was detected using the Doppler technique, which consists of measuring the radial velocity wobble caused by the counter-motion of the star with respect to the center of mass of the system. High precision instruments such as UVES, but more crucially, HARPS (both operated by the European Southern Observatory, Pepe et al. 2002) played a central role in the detection.

Proxima Centauri is a red dwarf with about 12–14% mass of the Sun. It has luminosity 500 times lower. As for red dwarfs in general, this provides several advantages towards the detection of small rocky planets in temperate orbits. The low stellar mass combined with temperate orbits close to the star which imply correspondingly larger signals. Because of the short orbital periods, the signal repeats much more often than on sun-like stars (a few weeks compared to the orbital period of one year of Earth). Thanks to these factors and with a suitable observing cadence, a detection and confirmation of Proxima b could be achieved with campaigns of a few months only (independent confirmation using ESPRESSO spectrometer by Suárez Mascareño et al. 2020).

Given that some of its characteristics are like Earth's (about 1.3–1.5 times the mass of the Earth, similar equilibrium temperature), and given this is the nearest star to us, Proxima b is considered a prime target for characterization of temperate terrestrial exoplanets, and hence for the search of evidence of life beyond the Solar System. Unfortunately, no transits have been detected, which have been searched using both space and ground-based observations (see, e.g., Jenkins et al. 2019, using the SPITZER/NASA space

telescope). Its potential for supporting Earth-like life remains unclear as for the rest of terrestrial planets around red dwarfs. The most critical unknown being the interaction and possible fate of their atmospheres as surface water reservoirs given their proximity to the star and the longer and stronger magnetic activity displayed by small stars, including recurrent megafares, and higher UV and X-ray fluxes received at the planet orbit (e.g., MacGregor et al. 2021 detection of a megafare of Proxima in multiple wavelengths). However, there is evidence that red-dwarf planets might be very volatile rich (more than a few percent of water content from start, like those of the Jovian moons, see Agol et al. 2021 for the TRAPPIST-1 System), so their evolution and suitability to support a biosphere over cosmic timescales remains unclear. The discovery of Proxima b along with other very remarkable multi-planet systems around nearby red-dwarfs (aka TRAPPIST-1, Gillon et al. 2016), combined with the imminent deployment of new major observatories (NASA's James Webb Space Telescope and the ground-based Extremely Large Telescopes) anticipates significant advancement in the search for life beyond Earth in the decades to come (2020–2030s).

Cross-References

- [ESPRESSO](#)
- [Radial Velocity](#)
- [Radial-Velocity Planets](#)
- [Transit](#)
- [TRAPPIST-1 System](#)

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Pseudofossil

Emmanuelle J. Javaux
Early Life Traces & Evolution-Astrobiology,
University of Liège, Liège, Belgium

Definition

A pseudofossil is a non-biological structure, impression, or trace resembling a biological structure. Several natural physical and chemical processes produce mineral, organic, or organo-mineral objects, traces, or patterns mimicking biological structures. Minerals or mineral-organic mixtures may auto-assemble to form complex shapes, such as spheroids aggregates, hollow tubes, or twisted, spiraling, branching tubes similar to biological shapes. Mineral precipitation or folded rocks form convex-upward layered structures resembling microbial constructions. Weathering of mineral concretions can also produce complex objects that could be mistaken as fossils. Abiotic or biological organics can migrate within rocks carried by fluids to form carbonaceous droplets or mineral casts. These structures can then be preserved three-dimensionally in chert by silicification and form

pseudofossils. Such abiotic structures differ from organic-walled microfossils that are hollow and preserved as carbonaceous compressions parallel to shale laminations. However, sub-circular grains of fossil oil (pyrobitumen) or vesicles formed by auto-assembling amphiphile lipids could be incorporated in fine-grained rocks and be mistaken for simple spheroidal fossils. Also, pebbles rolling on a soft bedding surface may leave imprints resembling biological tracks. Pseudofossils (sometimes also called “biomorphs”) can also be made artificially in the laboratory in simulated early Earth or extraterrestrial conditions.

Pseudofossils are unambiguously abiotic, in contrast to ► [dubiofossils](#). Only a multi-scale and multi-proxy combination of analyses, together with a good understanding of the physicochemical conditions of formation and of preservation of these structures (the geological context and taphonomy), and a falsification of possible abiotic hypotheses, make it possible to distinguish unambiguous fossils from pseudofossils and dubiofossils. Knowledge of non-biological processes and characterization of structures mimicking life are crucial when looking for early traces of life on Earth or for extraterrestrial life.

Cross-References

- [Archaean Traces of Life](#)
- [Biogenicity](#)
- [Biomarkers](#)
- [Biosignature](#)
- [Dubiofossil](#)
- [Fossil](#)
- [Microfossils](#)

16 Psyche

- [Psyche](#)

Psyche

Line Drube

DLR Institute of Planetary Research,
German Aerospace Center (DLR), Berlin,
Germany

Synonyms

[16 Psyche](#)

Definition

Psyche is considered the tenth most massive main-belt asteroid and contains about 1% of all the mass in the main-belt. Its mass has been estimated based on its gravitational effect on asteroids 94 Aurora and 13,206 Baer during close flybys. Over the last 10 years, the diameter has been estimated to range from 186 to 288 km, which makes the bulk density difficult to estimate, and everything from 1.8 to 7 g/cm³ has been published.

Psyche has a featureless spectrum and a surface reflecting 12% in the visual light and an exceptionally 42% in radar, making it a metallic-rich M-type and an Xk-type. If the density turns out to be close to the 7 g/cm³, then it points toward the composition of Psyche being almost pure iron-nickel. In that case Psyche would once have been part of the metallic core of a differentiated body, which experienced a catastrophic collision, leaving the core exposed. The high metallicity makes Psyche a promising site for planetary mining companies.

Psyche orbits the Sun about three times farther out than Earth with a Psyche year being equal to 5 Earth years and a day just 4.196 h long. From radar and light-curve measurements, the shape seems to be ellipsoidal. Some postulate that Psyche might have a strong remnant magnetic field.

History

Italian astronomer Annibale de Gasparis discovered Psyche in 1852 as his fifth asteroid discovery and as the sixteenth asteroid discovered in all of history.

Cross-References

► [Main Asteroid Belt](#)

Psychrophile

Laura Kelly
Ecogenomics of Interactions Lab,
Nancy, France

Keywords

Archaea · Bacteria · Enzymes · Eukaryote ·
Barophilic · Extremophiles · Halophilic · Low
temperature · Prokaryote

Synonyms

[Cryophile](#)

Definition

Psychrophiles (adj. psychrophilic), literally meaning cold-loving, are organisms adapted to growth at low temperatures, having an optimum growth temperature of $<15^{\circ}\text{C}$ and a maximum growth temperature of $<20^{\circ}\text{C}$. Psychrophiles are not to be confused with psychrotrophs (adj. psychrotrophic), also referred to as psychrotolerants, which are capable of growth at low temperature but grow optimally above 15°C .

History

The term “psychrophile” was first used in 1902 to refer to bacteria which could multiply at 0°C . The exact definition of a psychrophile has been disputed over time, with the definition suggested by Morita (Morita 1975) receiving general widespread acceptance. The exact parameters for classifying an organism as psychrophilic, however, are constantly under scrutiny (Feller and Gerday 2003).

Overview

Psychrophiles, also known as cryophiles, are considered to be extremophiles, flourishing in the coldest habitats on Earth and regarded as astrobiological models (Margesin and Miteva 2011). As $>80\%$ of Earth’s biosphere is permanently below 5°C (Russell et al. 1990), suitable environments for psychrophiles are widespread and include, among others, ocean waters, permafrost, glaciers, Antarctic rocks, snowfields, and polar ice caps. Although eukaryotic psychrophiles have been identified among algae (the snow algae *Chlamydomonas nivalis* being a well-studied example), yeast, fungi and protozoa, and some higher eukaryotes are considered to be psychrophilic, the prokaryotic domain (both ► [bacteria](#) and ► [archaea](#)) receives greater attention, containing the majority of known psychrophiles. Among the prokaryotes, psychrophiles are found in very diverse lineages that represent a wide variety of photosynthetic, heterotrophic, and autotrophic nutritional abilities (Scherer and Neuhaus 2006). Psychrophiles are particularly important to the ecology of permanently cold environments where they may be present in diverse bacterial assemblages. Prokaryotic psychrophiles vary in their requirement and indeed tolerance to oxygen and include (strictly) aerobic, (strictly) anaerobic, and facultative species. In addition to extremes of cold, many psychrophiles tolerate or in some cases require other extreme environmental conditions for growth and survival. Deep-sea

psychrophiles, for example, may require high pressures for growth, thus making them barophilic psychrophiles (baro-psychrophiles). Furthermore, salt-loving (halophilic) psychrophiles or halopsychrophiles have been identified inhabiting liquid brine within sea ice. Psychrophilic bacteria and archaea possess various adaptations, which allow them to thrive in cold environments (D'Amico et al. 2006; Casanueva et al. 2010). Cell integrity in many psychrophiles is maintained through increased flexibility of membranes by the inclusion of polyunsaturated fatty acids or the production of cryoprotectants such as exopolysaccharides (Méthé et al. 2005). Furthermore, cell integrity may be maintained through the production of antifreeze proteins, which protect the cells from destructive effects of ice crystals. Other psychrophile adaptations include enhanced protection against reactive oxygen species, a greater risk in cold environments due to the greater solubility of oxygen at low temperature. Psychrophile enzymes receive great industrial interest due to their high catalytic efficiency at low temperatures. Psychrophile enzymes are cold-adapted, having improved flexibility of the structural components involved in catalysis and a high specific activity at low temperatures (Feller and Gerday 1997; D'Amico et al. 2006; Scherer and Neuhaus 2006). These enzymes, however, have a low thermal stability, a factor that contributes to the heat sensitivity of psychrophiles, where exposure to even moderate temperature (e.g., room temperature) for even brief periods can result in death.

Cross-References

- [Barophile](#)
- [Extremophiles](#)
- [Halophile](#)
- [Prokaryote](#)

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Pulsar

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

A pulsar is a rapidly rotating and strongly magnetized ► [neutron star](#) that emits a (rotating) beam of electromagnetic radiation, observable when it points toward the Earth. The gravitational collapse of the neutron star's precursor (the iron core of a massive star) produces magnetic fields of $>10^{12}$ Gauss and rotational periods of down to a few ms (as precise as an atomic clock), due to conservation of magnetic flux and angular momentum, respectively. Pulsars decelerate because of radiation losses, but accretion from a companion star may spin them up. A few pulsars are known to have planets orbiting them. While the origin of such planets is still unknown, they probably form after the supernova explosion and, in all probability, they are uninhabitable because of the intense high-energy radiation emitted by the neutron star.

Cross-References

- [Neutron Star](#)
- [Pulsar Planets](#)

Pulsar Planets

Alexander Wolszczan

Department of Astronomy & Astrophysics and
Center for Exoplanets & Habitable Worlds, The
Pennsylvania State University, University Park,
PA, USA

Keywords

Millisecond pulsar · Neutron star · PSR
B1257+12 · Pulse arrival times

Definition

Planets that orbit ► [pulsars](#) have been detected by detecting the changes in the times of the arrival of the radio pulses from the spinning host ► [neutron stars](#), which serve as ultraprecise celestial clocks.

History

At a meeting of the International Astronomical Union in Buenos Aires in 1991, Andrew G. Lyne announced the discovery of a planet orbiting the ► [pulsar](#) PSR B1829-10, based on periodic changes in the times of the arrival of pulses from the host ► [neutron star](#), measured with the radio telescope at Jodrell Bank (Bailes et al. 1991). Regrettably, the 6-month periodic signal was due to a subtle error in the treatment of the motion of the one real planet involved, namely the Earth. Nevertheless, the intense interest in PSR B1829-10 motivated theoretical work on the survival and/or formation of planets in systems involving ► [supernova](#) events, which produce pulsars. This set the stage for the dramatic discovery of a system of three planets orbiting the 6.2-millisecond (ms) pulsar PSR B1257+12,

based on observations with the giant radio telescope at Arecibo (Wolszczan and Frail 1992). The planets were soon confirmed by the detection of their mutual gravitational perturbations (Wolszczan 1994). Extensive searches for additional pulsar planets have yielded one convincing example, in the globular cluster M4. That planet orbits a close pair of stars consisting of a ► [white dwarf](#) together with the neutron star PSR B1620-26.

Overview

The discovery in 1992 and confirmation in 1994 of three planets around a neutron star, the 6.2-ms pulsar PSR B1257+12, provided the first convincing evidence for a system of exoplanets. Although these pulsar planets are definitely not hospitable to life as we know it, their very existence led to optimistic speculations about the occurrence of exoplanets in general. First, the extreme nature of the host neutron star and its evolutionary history did suggest that planets might indeed be common around various types of stars and that their diversity could not be easily foreseen from extrapolations of our knowledge of the Solar System. This view was dramatically reinforced by the celebrated discovery of the first planet around a normal star – a ► [“hot Jupiter”](#) in the surprisingly tight 4.2-day orbit around 51 Pegasi (Mayor and Queloz 1995). Second, the existence of a system of three terrestrial-mass planets around the pulsar PSR B1257+12, dynamically strikingly similar to the inner Solar System, and with a clear signature of a disk origin, supported the speculation that the frequency of occurrence of small rocky exoplanets might also be quite high. Recent evidence from surveys both for ► [radial-velocity planets](#) and for ► [transiting planets](#) is revealing that such systems are indeed common.

Basic Methodology

Observations of a newly discovered pulsar involve precise pulse timing measurements, which provide a means to model the neutron

star's rotational, astrometric, and dynamical parameters. In the case of millisecond pulsars, which are extremely stable rotators, the arrival of their clock-like pulses can be measured and predicted with an unprecedented, microsecond (μs) precision. This property has made the timing of pulsar clocks a very efficient tool to study a variety of phenomena in physics and astrophysics, including detection and characterization of their possible planet-mass companions, all the way down to masses of large asteroids.

The topocentric time-of-arrival (TOA) measurements are made at the telescope, which takes part in the Earth's rotation and in its motion within the Solar System. The TOAs are determined in terms of the local time, usually with the observatory's hydrogen maser clock. To account for the effects of the Earth's motion in an inertial reference frame and to express the TOAs in the standard units of time, the initially measured TOAs are corrected to the Terrestrial Time (TT) and then referred to the Solar System ► [barycenter](#) to give the final arrival times in units of the Barycentric Dynamical Time (TDB). Practical translation of the topocentric TOAs to the barycentric pulse arrival times is accomplished with the aid of a Solar System ► [ephemeris](#), which is used to determine the exact position and motion of the telescope at the time of observation. These data are usually extracted from the Jet Propulsion Laboratory DE200 or DE405 ephemerides. All other effects influencing the pulse arrival time, which include classical and relativistic delays in the Solar System, a dispersive delay of the signal as it propagates through the ionized ► [interstellar medium](#), and errors in the pulsar position and proper motion, are corrected for in the process of calculating the barycentric TOAs (for details, see Lorimer and Kramer 2004).

In the analysis process, the number of pulses received over a time interval between some initial epoch and the barycentric arrival time is a measure of the accumulated pulse phase. Since for most of the millisecond and binary pulsars there is no evidence that processes other than the deterministic spin down caused by a gradual loss of the neutron star's rotational energy have a significant effect on their rotational stability (this is generally

not true for young pulsars with large spin-down rates), the pulsar spin behavior can be modeled in terms of the rotation frequency and its time derivatives as a mathematical Taylor series. The parameters of the timing model are then determined as corrections to their initial values computed by means of a linearized least-square fit of the model to the pulse arrival time data.

If the pulsar has a binary companion or orbiting planets, its reflex motion translates into ► [Doppler](#) shifts of the apparent pulsar period and the equivalent, varying time delay of pulse arrival times. In the case of a single Keplerian (elliptical) orbit, the delay is modeled in terms of the five standard orbital parameters: the orbital period, the eccentricity, the argument of periastron, the projected semi-major axis, and the time of periastron passage. For a circular orbit and planet mass, m_{pl} , assumed to be much smaller than the pulsar mass, M_{psr} , the maximum TOA amplitude, Δt , can be approximated as $\Delta t \sim 0.5 a_{\text{pl}} (m_{\text{pl}}/m_{\text{Jup}}) (M_{\text{psr}}/M_{\text{Sun}})^{-1}$ where a_{pl} is the orbital radius, m_{Jup} is the mass of Jupiter, M_{Sun} is the mass of the Sun, and Δt and a_{pl} are expressed in seconds and astronomical units, respectively. An Earth-mass planet orbiting a pulsar with a typical mass of $\sim 1.35 M_{\text{Sun}}$ would generate a ~ 1 ms TOA variation, which would be easily detectable given the typical $\sim 1 \mu\text{s}$ timing precision achievable with millisecond pulsars. In principle, because of its extraordinary precision, the millisecond pulsar timing is capable of detecting large asteroids on sufficiently wide orbits.

Key Research Findings

The 6.2-ms radio pulsar, PSR B1257+12, has three terrestrial-mass planets forming a compact system that is not much larger than the orbit of Mercury (Wolszczan 1994). The relative sizes of the orbits and the distribution of masses of planets b, c, and d are strikingly similar to those of the three inner planets in the Solar System (Mazeh and Goldman 1995).

The near 3:2 ► [mean motion resonance](#) between the orbits of planets c and d in the PSR B1257+12 system and the existence of detectable gravitational

Pulsar Planets, Table 1 Observed and derived parameters for the planets orbiting PSR B1257+12 (numbers in parentheses give standard error in last displayed digit)

Parameter	Planet b	Planet c	Planet d
Projected semi-major axis (ms)	0.0031 (2)	1.3097 (2)	1.4136 (1)
Eccentricity	0.0	0.0195 (3)	0.0259 (3)
Epoch of periastron (MJD)	49764.1 (8)	49768.7 (2)	49766.0 (2)
Orbital period (d)	25.274 (8)	66.5292 (8)	98.2408 (9)
Longitude of periastron (deg)	0.0	250.5 (9)	110.1 (7)
Mass (Earth masses)	0.020 (2)	4.3 (2)	3.4 (2)
Orbital inclination, solution 1 (deg)	–	52 (4)	57 (6)
Orbital inclination, solution 2 (deg)	–	128 (4)	123 (6)
Semi-major axis, AU	0.19	0.36	0.46

perturbations between the two planets (Rasio et al. 1992; Wolszczan 1994) provide the mechanism to derive their masses without a priori knowledge of the orbital inclinations. A semi-analytical model, in which perturbations between the two planets are parametrized in terms of the two planetary masses and the mutual orientation of their orbits, has been applied to the PSR B1257+12 timing data by Konacki and Wolszczan (2003). A least-square fit of this model to the data yielded the true masses and orbital inclinations of planets b and c, assuming the canonical pulsar mass $M_{\text{psr}} = 1.35 M_{\text{Sun}}$. The near 3:2 mean motion resonance between planets c and d and the fact that their orbits are nearly coplanar imply that this pulsar’s planetary system has been created as the result of a disk evolution similar to that invoked to describe planet formation around normal stars (e.g., Papaloizou and Terquem 2006). Together with the true mass measurements, these results offer a fairly complete dynamical characterization of the first known exoplanetary system shown to contain terrestrial-mass planets. Its existence provides evidence that ► [protoplanetary disks](#) beyond the Sun can evolve low-mass planets to a dynamical configuration that is similar to that of the planets in the inner Solar System.

The most recent update of the parameters of the PSR B1257+12 planets has been published by Wolszczan (2008) and is summarized in Table 1. Continuing observations of the pulsar have not changed this model in any substantial way.

The early theories of the PSR B1257+12-type planet formation have been summarized by Podsiadlowski (1993) and further discussed by

Phinney and Hansen (1993). More recently, Miller and Hamilton (2001) and Hansen et al. (2009) have examined the conditions of survival and evolution of pulsar protoplanetary disks. They have concluded that an initially sufficiently massive ($>10^{28}$ g) disk would be able to resist evaporation by the pulsar accretion flux and create planets on a typical, 10^7 -year timescale. Quick formation of a sufficiently massive disk around a pulsar could, for instance, be accomplished by tidal disruption of a stellar companion (e.g., Phinney and Hansen 1993), a supernova fallback (e.g., Currie and Hansen 2007), or, possibly, in the process of a white dwarf merger (e.g., Livio et al. 1992). The possible detection of a dust disk around the X-ray pulsar, 4 U 0142+61 (Wang et al. 2006), if confirmed, may present the first direct evidence for a disk formed by the supernova fallback mechanism. These processes, although entirely feasible, cannot be very common. In fact, with the exception of PSR B1257+12, no planetary companions have emerged from precise timing observations of the known Galactic millisecond pulsars (Lorimer 2008), suggesting their rarity, independently of the specific formation mechanism.

Cross-References

- [Barycenter](#)
- [Doppler Shift](#)
- [Ephemeris](#)
- [Extrasolar Planets](#)

- [Interstellar Medium](#)
- [Mean Motion Resonance](#)
- [Neutron Star](#)
- [Pulsar](#)
- [Radial-Velocity Planets](#)
- [Transiting Planets](#)
- [White Dwarf](#)

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Purine Bases

Michael P. Callahan

Astrochemistry Laboratory, Code 691,
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Keywords

Adenine · Guanine · Hypoxanthine · Nitrogen heterocycle · Xanthine

Definition

A purine is an aromatic heterocyclic nitrogen compound, composed of a pyrimidine ring system fused to an imidazole ring system, with the core molecular formula $C_5H_4N_4$. Purines are weakly basic compounds. Purines are stabilized by resonance among the atoms in the ring structure, which gives most of the bonds a partial double-bond character. As a result, purines are nearly planar molecules with a slight pucker and are characterized by a strong UV absorption typically near 260 nm. Purine bases may exist in different tautomeric forms depending on the pH. At neutral pH, purines are hydrophobic and therefore relatively insoluble. Substituted purines are components of ribonucleic acids (RNA), deoxyribonucleic acids (DNA), and ► [coenzymes](#) and are broadly distributed in nature.

Overview

Purines consist of a six-membered pyrimidine ring fused to a five-membered imidazole ring. Purines (along with pyrimidines) serve as the informational monomers of RNA and DNA, the molecular carriers of genetic information. ► [Hydrogen](#) bonding and base-stacking interactions of substituted purines are important for stabilizing the three-dimensional structure of ► [nucleic acids](#). The most important biological

substituted purines are ► [adenine](#) and guanine, which are the major purine bases found in RNA and DNA. In DNA, ► [guanine](#) and adenine ► [base pair](#) (see ► [“Watson-Crick pairing”](#)) with cytosine and thymine (see ► [“Pyrimidine Base”](#)), respectively. Adenine is also found in adenosine triphosphate (see ► [“ATP”](#)) and other coenzymes. Two other important biological purines are hypoxanthine and xanthine. While hypoxanthine and xanthine are not incorporated into nucleic acids, they are important intermediates in purine metabolism.

A plausible prebiotic synthesis of adenine was first demonstrated by Oró (1960) using a mixture of ► [hydrogen cyanide](#) (HCN) and ammonia in an aqueous solution. HCN undergoes self-condensation to form diaminomaleonitrile (DAMN), a tetramer of HCN. DAMN then reacts with formamidine (formed in situ) or by photochemical rearrangement to form 4-aminoimidazole-5-carbonitrile (AICN). Finally, AICN reacts with HCN to form the purine adenine. Other purines such as guanine, hypoxanthine, and xanthine can be formed by the addition of small molecules (e.g., ► [cyanogen](#) or cyanate) to AICN or its amide, aminoimidazole carboxamide (AICA), followed by various ► [hydrolysis](#) steps. However, one drawback to this synthesis is that relatively high concentrations of HCN are required. The likelihood of such high concentrations of HCN is unclear on the early Earth especially since HCN cannot be concentrated by simple evaporation because it is more volatile than water. Miller and Orgel proposed that eutectic freezing provides a plausible concentration mechanism. In the temperature range of 0 °C to −20 °C, HCN remains in the liquid phase and can concentrate in the voids between ice crystals.

Purines (and also pyrimidines) are formed as condensation products of formamide heated at 110–160 °C in the presence of metal oxides and minerals. Under these conditions, the diversity and yield of purine synthesis can be enhanced by UV light (even in the absence of inorganic catalysts). Purines are unlikely to form and survive in most interstellar and circumstellar environments

since they are unstable against UV radiation. Purines may be able to survive if located in a dense ► [interstellar cloud](#), although no positive detection has been made yet. Purines have also been reported in carbonaceous meteorites suggesting their formation in space is possible. Martins et al. (2008) have reported that xanthine (along with the pyrimidine uracil) has an extraterrestrial origin in the Murchison meteorite based on compound-specific carbon isotopic measurements.

Cross-References

- [Adenine](#)
- [Base Pair](#)
- [Carbonaceous Chondrite](#)
- [Codon](#)
- [Coenzyme](#)
- [Cyanogen](#)
- [Genetic Code](#)
- [Guanine](#)
- [HCN Polymer](#)
- [Hydrogen Cyanide](#)
- [Hydrolysis](#)
- [Hypoxanthine](#)
- [Interstellar Medium](#)
- [Miller, Stanley](#)
- [Nucleic Acid Base](#)
- [Nucleotide](#)
- [Prebiotic Chemistry](#)
- [Pyrimidine Base](#)
- [Ribonucleoside](#)
- [Ribonucleotide](#)
- [Watson-Crick Pairing](#)

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(PVED). Asymmetric enantiomer distribution in terrestrial biomolecules, with L-amino acids and D-sugars dominant, has been suggested to be the result of this effect. Calculations of the PVED between enantiomers of α -amino acids have suggested that the L-enantiomers are more stable than the D-enantiomers by an amount equivalent to 10^{-17} – 10^{-14} kT at room temperature. More recent calculations, however, have suggested that such conclusions may be ambiguous or erroneous, currently leaving both the direction and magnitude of the PVED an open question.

Cross-References

- [Chirality](#)
- [Enantiomers](#)
- [Parity Violation Energy Difference](#)

References and Further Reading

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1*H*-purine-2,6-dione

- [Xanthine](#)

PVED

Jun-ichi Takahashi
Yokohama National University, Faculty of Engineering, Yokohama, Japan

Synonyms

[Parity nonconservative energy difference](#); [Parity violation energy difference](#)

Definition

The effect of intrinsic differences in energy between biomolecular ► [enantiomers](#) due to the weak interactions mediated by neutral Z particles is known as parity-violating energy difference

Pyranose

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo, Japan
Blue Marble Space Institute of Science, Washington, DC, USA
Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

A pyranose is a cyclic six-membered ring form of a monosaccharide, formed as an intramolecular hemiacetal and containing an oxygen atom in the ring. Monosaccharides smaller than pentoses are incapable of forming pyranoses. Important biological pyranoses include glucose and mannose.

► [Ribose](#) in solution also adopts a pyranose form to a minor extent.

deoxyribonucleic acids (DNA), and ► [coenzymes](#) and are broadly distributed in nature.

Cross-References

- [Aldose](#)
- [Carbohydrate](#)
- [Ketose](#)
- [Ribose](#)

Pyranosyl-RNA

- [p-RNA](#)

Pyrimidine Base

Michael P. Callahan
Astrochemistry Laboratory, Code 691,
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Keywords

Cytosine · Nitrogen heterocycle · Thymine ·
Uracil

Definition

Pyrimidine is a six-membered nitrogen heterocyclic compound with the molecular formula $C_4H_4N_2$. Pyrimidine bases are weakly basic. Pyrimidines are stabilized by resonance among atoms in the ring, which gives most of the bonds a partial double-bond character. As a result, pyrimidines are planar molecules and are characterized by strong UV absorption generally near 260 nm. Pyrimidine bases may exist in different tautomeric forms depending on the pH. At neutral pH, pyrimidines are hydrophobic and therefore relatively insoluble. Substituted pyrimidines are components of ribonucleic acids (RNA),

Overview

Pyrimidines are aromatic nitrogen heterocycles with a structure similar to benzene but containing two nitrogen atoms at the 1 and 3 positions of the ring. Pyrimidines (along with purines) serve as the informational monomers of RNA and DNA, the molecular carriers of genetic information. ► [Hydrogen](#) bonding and base-stacking interactions of pyrimidines are important for stabilizing the three-dimensional structure in ► [nucleic acids](#). The most important biological substituted pyrimidines are ► [cytosine](#), ► [thymine](#), and ► [uracil](#). Cytosine and thymine are the two major pyrimidine bases in DNA and ► [base pair](#) (see ► [Watson-Crick Pairing](#)) with guanine and adenine (see ► [Purine Bases](#)), respectively. In RNA, uracil replaces thymine and base pairs with adenine.

The prebiotic synthesis of cytosine may have started with the precursor ► [cyanoacetylene](#), which is produced in spark discharge experiments of methane-nitrogen gas mixtures. The reaction of cyanoacetylene with cyanate produces cytosine. An alternative route uses cyanoacetaldehyde, which can be formed by the hydration of cyanoacetylene. Cyanoacetaldehyde reacts with urea, which is considered a common prebiotic molecule and is produced via Miller-Urey chemistry, to produce cytosine in excellent yields. Furthermore, cytosine is readily hydrolyzed to uracil. However, since cytosine is rather unstable, it raises the question if cytosine was used in the first genetic material.

A number of plausible prebiotic syntheses of uracil and thymine have been demonstrated in the laboratory. For example, uracil is liberated from ► [HCN polymers](#) upon acid hydrolysis. Schwartz and coworkers also produced uracil by UV irradiation of a mixture of urea and alanine in the presence of clay minerals. Thymine is produced via the methylation of uracil with formaldehyde and hydrazine. Thymine is also obtained from formamide in the presence of titanium dioxide heated at 160 °C.

Uracil has been identified in carbonaceous meteorites. Both pyrimidines and purines have been reported in ► [meteorites](#), which presents the tantalizing suggestion that some of the building blocks of genetic materials were delivered by meteorites (assuming these molecules do not originate from terrestrial contamination). Martins et al. (2008) have reported that uracil (along with the purine xanthine) has an extraterrestrial origin in the ► [Murchison](#) meteorite based on compound-specific carbon isotopic measurements.

Cross-References

- [Anticodon](#)
- [Base Pair](#)
- [Carbonaceous Chondrite](#)
- [Codon](#)
- [Coenzyme](#)
- [Cyanacetylene](#)
- [Cytosine](#)
- [Genetic Code](#)
- [HCN Polymer](#)
- [Hydrolysis](#)
- [Miller, Stanley](#)
- [Nucleic Acids](#)
- [Nucleotide](#)
- [Prebiotic Chemistry](#)
- [Purine Bases](#)
- [Ribonucleoside](#)
- [Ribonucleotide](#)
- [Spark Discharge](#)
- [Thymine \(T\)](#)
- [Uracil \(Ura\)](#)
- [Watson-Crick Pairing](#)

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Pyrite

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Synonyms

[Fool's gold](#)

Chemical Formula

FeS₂

Definition

Pyrite is an iron sulfide with the formula FeS₂. It has a metallic luster and a pale-yellow color as gold (hence the synonym “fool’s gold”). It is relatively hard and commonly forms cubic crystals. It is the most common sulfide mineral in nature and forms under a wide variety of conditions: a common accessory mineral in ► [igneous rocks](#) it segregates from magmas. It is found in ► [metamorphic rocks](#) as a product of contact metamorphism (i.e., in rocks at contact with hot magmatic bodies). It also forms as a hydrothermal mineral by precipitating from high-temperature solutions. In ► [sedimentary rocks](#), it occurs both as an authigenic mineral,

formed in the depositional environment, and as a secondary mineral, deposited during ► [diagenesis](#), i.e., the transformation of the sediment into rock. The formation of pyrite in sedimentary environments requires the presence of organic matter in the sediment (which decay contributes to a reducing environment by O₂ consumption), sulfate in the pore water, and an anaerobic environment. Pyrite figures prominently in many models in which the origin of life is related to hydrothermal vents. Pyrite formation has been for long time considered a source of energy for an autotrophic origin of life (Wächtershäuser 1988).

Cross-References

- [Diagenesis](#)
- [Igneous Rock](#)
- [Metamorphic Rock](#)
- [Sedimentary Rock](#)
- [Weathering](#)

References and Further Reading

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Pyroclastics (in Volcanology)

- [Ejecta](#)

Pyrolysis

Mark Dörr
University of Southern Denmark, Odense M,
Denmark

Synonyms

[Carbonization](#); [Thermal decomposition](#)

Definition

Pyrolysis (from Greek πυρ (pyr) = “fire” and λυσις (lysis) = “decomposition”) is a chemical process in which bonds of a compound are spontaneously broken by high temperatures (500–900 °C). Extreme *pyrolysis* of carbon-containing substances, which leaves mostly ► [carbon](#) as the residue, is called *carbonization*. The production of charcoal from wood is an example of *pyrolysis* and *carbonization*.

Cross-References

- [Carbon](#)
- [Combustion](#)

Pyrolysis Gas Chromatography Mass Spectrometry

- [Pyrolysis GC/MS](#)

Pyrolysis GC/MS

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Synonyms

[Pyrolysis gas chromatography mass spectrometry](#)

Definition

► [Pyrolysis](#) gas chromatography mass spectrometry (abbreviated as Pyr- ► [GC/MS](#)) is a method of chemical analysis. In Pyr-GC/MS, the sample is decomposed by heating at high temperatures

under an inert atmosphere or under vacuum to produce smaller molecules that are separated by gas chromatography and detected using a mass spectrometer. Pyr-GC/MS is widely used to characterize polymers and complex organic molecules such as ► [tholins](#).

Cross-References

- [GC/MS](#)
- [Pyrolysis](#)
- [Tholins](#)

Pyrometer

- [Bolometer](#)

Pyrophosphate

Matthew A. Pasek
XUniversity of South Florida, Tampa, FL, USA

Synonyms

[Diphosphate](#)

Definition

Pyrophosphate is a dimer of orthophosphate (PO_4^{3-}), linked by a single oxygen via a dehydration reaction. Pyrophosphate hydrolyzes in water to give two molecules of orthophosphate with the release of about 20 kJ/mol at standard state. Pyrophosphate is a potential precursor to ATP as the main metabolic energy carrier of life, as it is formed by transmembrane protein proton pumping using a much simpler mechanism. Pyrophosphate may have been synthesized on the early

Earth either by dehydration reactions; by the phosphorylation of phosphate by high-energy phosphate precursors, such as reduced forms of phosphorus; or by radical-driven reactions.

Cross-References

- [ATP](#)
- [Phosphates](#)

Pyrrolidine-2-carboxylic Acid

- [Proline](#)

Pyruvate

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

Pyruvate ($\text{C}_3\text{H}_4\text{O}_3$, $\text{CH}_3\text{COCO}_2\text{H}$) is the conjugate base of pyruvic acid (2-oxopropanoic acid), the simplest keto acid. It is a key component of intermediary metabolism in all extant organisms. It is derived principally from glycolysis of glucose in many organisms and serves as a major precursor of fatty acids via the synthesis of acetyl-CoA. It is also a feedstock for the citric acid cycle in which it is carboxylated to yield oxaloacetate. It can also be shunted into amino acid metabolism by reductive amination to yield alanine and is a transient species in alcoholic fermentation, in which it is decarboxylated to yield acetaldehyde, which is ultimately reduced to yield ethanol.

Cross-References

- ▶ [Acetaldehyde](#)
- ▶ [Alanine](#)
- ▶ [Amino acid](#)
- ▶ [Citric acid cycle](#)
- ▶ [Ethanol](#)
- ▶ [Fatty Acids, Geological Record of](#)
- ▶ [Fermentation](#)
- ▶ [Glycolysis](#)
- ▶ [Metabolism](#)

Q

Q (Orbital Parameter)

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The Q parameter is one of the parameters that may be used to describe the elliptical orbit of a planet around a star; it is the distance between the star and the planet apastron (or farthest distance from the star). The parameter q , the distance between the star and an orbiting object's periastron (closest distance to the star), is traditionally used for cometary orbits in the Solar System.

Cross-References

- [Aphelion](#)
- [Orbit](#)

Q (Tidal Quality Factor)

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

The tidal Q is a measure of a body's response to tidal distortion and is inversely proportional to the lag angle between the tidal bulge and the position of the perturbing body. For example, on a satellite orbiting close to a planet, the satellite becomes elongated as the force of gravity is stronger at the sub-planet point than on the opposite side. As the satellite orbits, this tidal bulge does not necessarily point toward the planet, due to the satellite's rotation. Rocky bodies tend to have Q-values near 100; giant planets and stars have Q-values near 10^6 . However, these numbers are very difficult to measure, and the above values are probably only accurate to about an order of magnitude. The orbital evolution of the planet-satellite (or star-planet, or star-star)

system is therefore a function of Q , with faster evolution for smaller Q -values.

Q (Toomre Parameter)

Yann Alibert¹ and Ravit Helled²

¹Space Research and Planetary Sciences, Physics Institute, University of Bern, Bern, Switzerland

²Geophysical, Atmospheric and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

Keywords

Gravitational instability · Disk instability (model for giant planet formation)

Definition

In the context of planet formation the Toomre parameter Q is defined by

$$Q = c_s \Omega / \pi G \Sigma,$$

where Ω is the angular velocity, c_s is the sound speed, G is the gravitational constant, and Σ is the gas surface density of the disk.

Typically when Q is equal or smaller than one, the disk will become gravitationally unstable. Such processes in the disk can lead to the formation of gaseous planets as suggested by ► [Disk Instability, Model for Giant Planet Formation](#).

Cross-References

- [Disk Instability, Model for Giant Planet Formation](#)
- [Gravitational Instability](#)
- [Planet Formation](#)

Q* (Specific Energy to Destroy an Object)

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux, CNRS, Universite de Bordeaux, Bordeaux, France

Definition

The symbol Q^* refers to the amount of energy per unit mass needed to disrupt an object. This determines the critical collision velocity above which planetesimal collisions are erosive rather than accretionary. Stronger materials have larger values of Q^* . Values of Q^* are derived from laboratory experiments as well as from numerical simulations. The weakest objects in the Solar System (smallest values of Q^*) are thought to be a few hundred meters in size.

Cross-References

- [Planetesimals](#)
- [Runaway Growth](#)

QCC

- [Quenched Carbonaceous Composite](#)

Quaoar

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

(50000) Quaoar is a large ► [trans-Neptunian object](#), located in the ► [Kuiper Belt](#) on a

quasi-circular orbit at a distance of 43 AU from the Sun. It is named for a Native American creator god, of the Tongva people who lived in the Los Angeles area. With a diameter of 1,280 km, it was, at the time of its discovery in 2002 by Chadwick Trujillo and Michael Brown of the California Institute of Technology, the biggest trans-Neptunian object. In 2004, crystalline water ice was detected on the surface of Quaoar, which might be a sign of ► [cryovolcanism](#). The albedo of Quaoar is low (0.07), which probably indicates a surface with a mixture of ices and rocks.

Cross-References

- [Kuiper Belt](#)
- [Trans-Neptunian Object](#)

Quarantine

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

Quarantine is the process of containing potentially hazardous materials or individuals until the level of hazard can be determined and mitigated. For ► [planetary protection](#), the quarantine was applied for a while to astronauts coming back from the ► [Moon](#) as well as for lunar samples. This quarantine will apply to PP Category V Restricted Earth Return missions. During the quarantine, samples returned, i.e., from ► [Mars](#), will be kept and analyzed under strict containment in BSL4 like premises that also prevent contamination of the samples by Earth biological material.

Cross-References

- [Biological Safety Level](#)
- [Planetary Protection Category](#)

Reference and Further Reading

http://www.nap.edu/catalog.php?record_id=10138

Quartz

Nicholas Arndt
Emeritus Professor, ISTERre, University Grenoble
Alpes, Grenoble, France

Chemical Formula

SiO₂

Definition

Quartz is a hard, transparent, white, or colored ► [mineral](#) with chemical formula SiO₂ (trigonal crystal system) and the hardness 7 in the Mohs hardness scale. It is an essential component of felsic intrusive (► [granite](#)) or effusive (rhyolite) ► [igneous rocks](#) and their sedimentary (sandstone) and metamorphic equivalents (► [gneiss](#)). Because of its hardness, common occurrence in the protoliths, and lack of cleavage, it is highly resistant to ► [weathering](#), erosion, and transport at the surface of the Earth. It is therefore the most common mineral in (meta) sediments and ► [sedimentary rocks](#).

Cross-References

- [Metasediment](#)
- [Mineral](#)
- [Sedimentary Rock](#)

Quasispecies

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

A quasispecies is a distribution of ► [mutant](#) genomes centered around one dominant or master sequence. Quasispecies theory was developed by M. Eigen as a general model to understand the dynamics of the first replicative molecules in the context of the origin of information and the early evolution of life (Eigen [1971](#)). Although they were initially conceived as steady-state distributions of infinite size in equilibrium, quasispecies dynamics – characterized by a continuous process of mutant generation, competition, and selection – have also provided an interpretation of the great adaptive potential of RNA viruses (Domingo and Holland [1997](#)). Indeed, experimental evidence has shown that, due to their error-prone replication, different current biological entities behave as quasispecies: ► [viroids](#), RNA viruses, and DNA viruses that use RNA as an intermediate molecule during their replicative cycle. The response of the evolving viral quasispecies to selective pressures, e.g., immune response of the infected host or antiviral treatment, is influenced by the ensemble of mutants that compose the population (Lauring and Andino [2010](#)).

Cross-References

- [Error Rate](#)
- [Evolution, Molecular](#)
- [Hypercycle](#)
- [Mutant](#)
- [Origin of Life](#)
- [RNA](#)
- [RNA World](#)
- [Viroid](#)
- [Virus](#)

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Quenched Carbonaceous Composite

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Synonyms

[QCC](#)

Definition

The organic residue produced in the laboratory from a hydrocarbon plasma was termed a quenched carbonaceous composite (QCC) by the Japanese chemist A. Sakata and his colleagues. They proposed that QCC, a possible component of ► [interstellar dust](#), might be the carrier of the 217.5-nm interstellar absorption feature (► [UV absorption bump](#)) and the origin of some of the infrared spectral features in the interstellar medium otherwise attributed to ► [polycyclic aromatic hydrocarbon](#) molecules. The latter seems to be supported by the laboratory results of Endo et al. ([2018](#)).

Cross-References

- [Interstellar Dust](#)
- [Polycyclic Aromatic Hydrocarbon](#)
- [UV Absorption Bump](#)

References

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Quencher

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In chemistry, a quencher is a substance that absorbs excitation energy from a ► [fluorophore](#). Most quenchers reemit much of this energy as visible light; dark quenchers dissipate the energy as heat, as they have no native fluorescence. Dark quenchers are used in molecular biology in conjunction with fluorophores, for example, in molecular beacons.

Cross-References

► [Molecular Beacon](#)

Quenching

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

In chemistry and physics, quenching mainly refers to the effect of rapid cooling, though is

used in various scientific fields to denote the rapid cessation of a reaction by rapid dilution, addition of another reagent, or change of temperature. In materials science, quenching is used to give special properties to materials by heating followed by rapid cooling. In optics, quenching refers to the decrease of ► [fluorescence](#) intensity which occurs when an acceptor fluorophore is brought into close proximity of an excited donor fluorophore. When coexisting substances decrease fluorescence intensity by some processes such as a collision and a chemical reaction, the process is called chemical quenching.

In chemical evolution studies, quenching (rapid cooling) is quite important in the formation of organic compounds. Organic compounds tend to decompose when exposed to excessive amounts of energy, such as high temperatures. For example, amino acids are decomposed when they are heated at high temperature for even brief periods of time. However, when heated amino acids are quenched (quickly cooled) after heating at 250 °C for very short times, peptides can be isolated (Imai et al. [1999](#)). Another example occurs in Miller-Urey-type reactions. Gases are excited by a high-frequency electric discharge to give a plasma of atoms and molecular fragments which quickly quench once they exit the electric discharge production zone to form larger metastable species such as HCHO and HCN.

Cross-References

► [Fluorescence](#)
► [Hydrothermal Reaction](#)
► [Hydrothermal Vent Origin of Life Models](#)

References and Further Reading

Imai E-I, Honda H, Hatori K, Brack A, Matsuno K (1999) Elongation of oligopeptides in a simulated submarine hydrothermal system. *Science* 283: 831–833

Quorum Sensing

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Cell communication](#)

Definition

Quorum sensing is a type of decision-making process used by decentralized groups to coordinate behavior. Many species of bacteria use quorum sensing to coordinate their gene expression according to the local density of their population by using small diffusible molecules that pass

between neighboring cells. Cells can thus undergo communication. Similarly, some social insects use quorum sensing to make collective decisions. Some of the best-known examples of quorum sensing come from studies of bacteria. Quorum sensing can occur within a single bacterial species as well as among diverse species and can regulate a host of different processes, essentially serving as a simple communication network. Quorum sensing is a mechanism that ensures that sufficient cell numbers of a given species are present before eliciting a cell response. A variety of different molecules can be used as signals, such as lactones in Gram-negative bacteria or ► [oligopeptides](#) in Gram-positive bacteria.

Cross-References

- [Biofilm](#)
- [Oligopeptide](#)

R

R-Process

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The r-process is one of the two main nucleosynthesis processes forming nuclei heavier than those of the iron peak, on the neutron-rich side of the nuclear stability valley. Neutron captures occur on timescales of ms, that is, short with respect to those of beta-decays (hence the r-, for *rapid*), driving the process far into the region of unstable, very neutron-rich nuclei (the “neutron-drip” line). The large neutron amounts required for the process are found either in the innermost regions of core collapse supernovae or in the collisions of neutron stars. About half of the natural nuclides heavier than iron, including the heaviest ones (thorium and uranium) are produced by the r-process.

Cross-References

- [Nucleosynthesis, Stellar](#)
- [S-Process](#)
- [Supernova](#)

Ross-128b

Emeline Bolmont
Observatoire de Genève, Université de Genève,
Chemin Pegasi 51, 1290, Sauverny, Switzerland

Definition

Ross-128b is a planet detected with the radial velocity technique with the HARPS spectrograph in 2018 (Bonfils et al. 2018). It has a minimal mass of 1.35 Earth mass and with its orbital period of 9.9 days, it sits close to the inner edge of the Habitable Zone of its small host star (17% the mass of our Sun).

Located at only 11 light years from our solar system, Ross-128b is one of the closest habitable zone planets (the closest being Proxima-b). However, the planet does not transit, so its atmosphere cannot be characterized using methods like transit spectroscopy (► [Planet Characterization: Transmitted Light](#)). Given its distance to our solar system, the best prospect for atmospheric characterization will come from high resolution spectroscopy at the European-Extremely Large Telescope.

Even though such observations will be challenging, Ross-128b has one advantage over Proxima-b and the TRAPPIST-1 planets: its star is much quieter. There are much less energetic radiations which could drive atmospheric escape

and desiccate the planet, or which could harm any potential life on the surface of the planet. In other words, Ross-128b might be better suited to host life than Proxima-b or the TRAPPIST-1 planets.

Cross-References

- ▶ [HARPS](#)
- ▶ [Planet Characterization: High-Resolution Spectroscopy](#)
- ▶ [Planet Characterization: Transmitted](#)
- ▶ [Proxima-b](#)
- ▶ [Radial Velocity](#)
- ▶ [Radial-Velocity Planets](#)
- ▶ [TRAPPIST-1 System](#)

References

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St. Petersburg, Russia. The core institutes are the Ioffe Physico-Technical Institute of the Russian Academy of Science (RAS), the Cytology Institute of the RAS, and the St. Petersburg Polytechnical State University, which houses the administration of the RAC in its Cosmic Research Department. The main research areas are factors affecting the existence of life in the Solar System and beyond, the interaction of the Solar System with dense interstellar clouds, the geochemical evidence for late accretion events and biogenic activity in ancient rocks, prebiotic chemistry and the formation of organic material on small Solar System bodies, and the deep cold biosphere on the Earth and potentially elsewhere in the Solar System.

Racemic Mixture

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla, CA, USA

Synonyms

[50:50 enantiomeric mixture](#)

Definition

A racemic mixture is a mixture containing equal amounts (50:50) of both enantiomers of a chiral chemical compound (e.g., of L- and D-alanine). By definition the enantiomeric excess of a racemic mixture is equal to zero. A racemic mixture will induce no rotation of the plane of polarization of polarized light. The term racemic should not be confused with the term *achiral*, which refers to compounds which are not chiral.

Cross-References

- ▶ [Chirality](#)
- ▶ [Enantiomeric Excess](#)
- ▶ [Enantiomers](#)

R40

- ▶ [Chloromethane \(CH₃Cl\)](#)

RAC, Russia

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Russian Astrobiology Center](#)

Definition

The Russian Astrobiology Center (RAC) was formed to provide a coordinating organization for astrobiological research and teaching in

Racemization

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

Racemization is a process wherein optically active compounds (which consist of only one ► [enantiomer](#)) are converted into an equal mixture of enantiomers with zero optical activity (a ► [racemic mixture](#)). Racemization rates are dependent on the molecule and conditions such as pH and temperature. For example, aqueous racemization of free protein amino acids takes place on timescales of 10^3 – 10^4 years at neutral pH and 25°C. For comparison, hydrocarbons that contain a hydrogen atom attached to a chiral carbon atom have racemization ► [half-lives](#) under similar conditions that are much longer.

Cross-References

- [Enantiomers](#)
- [Racemic Mixture](#)

Radial Drift

Yann Alibert¹ and Ravit Helled²
¹Space Research and Planetary Sciences, Physics
Institute, University of Bern, Bern, Switzerland
²Geophysical, Atmospheric and Planetary
Sciences, Tel Aviv University, Raymond and
Beverly Sackler Faculty of Exact Sciences, Tel
Aviv, Israel

Keywords

Planetesimals · Protoplanetary disk

Definition

Radial drift is a process in a ► [protoplanetary disk](#) where the semimajor axes of the orbits of solid particles/bodies are modified as a result of gas-solid interactions (e.g., gas drag). Radial drift is directed toward regions of pressure maxima (generally toward the star).

Cross-References

- [Gas Drag](#)

Radial Velocity

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Doppler shift](#); [Line-of-sight velocity](#)

Definition

In astronomy, the radial velocity is the velocity of an object along the line of sight (the line connecting the observer to the object), i.e., along the radius vector to the object.

The radial velocity is usually measured using the observed ► [Doppler shift](#) of spectral lines, given by the formula $\Delta\lambda/\lambda = v/c$, where $\Delta\lambda$ is the shift in wavelength observed for the object compared to the rest wavelength, λ , and v is the velocity of the object along the line of sight. The quantity c is the speed of light (299,792 km/s). From this formula, a positive velocity away from the observer results in a shift of the wavelength to larger values. This phenomenon is often called a redshift. Similarly, a negative velocity toward the observer causes the wavelength to shift toward smaller values, resulting in a blue shift. When

the velocity is significant compared to the speed of light, a relativistic version of the formula should be used. Radial velocities of stars are normally quoted relative to the Sun (heliocentric) or relative to the center of mass of the Solar System (barycentric) when very precise velocities are needed.

Radial velocities can also be calculated from other data. For example, the changing positions of minor planets in the Solar System have been followed very accurately for many years, and the resulting orbits can be used to calculate the expected radial velocities at any time. This has allowed astronomers to check the absolute scale of their radial velocities by observing the Doppler shifts of minor planets.

Cross-References

- [Radial-Velocity Planets](#)
- [Spectroscopic Orbit](#)

Radial-Velocity Planets

David W. Latham¹ and Nader Haghighipour²

¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA

Keywords

Doppler shift · Radial velocity · Spectroscopic orbit

Definition

Radial-velocity planets are those detected indirectly by observing the orbital motion of their host stars in response to the gravitational pull of the planets. The stellar motion is measured by the ► [Doppler](#) effect on the stellar spectral lines.

History

In a system consisting of a star and a planet, because of the gravitational force of the planet on the star, the planet and its host star orbit their common center of mass. This causes variations in the distance of the star to the observer, creating what is known as radial velocity. Measuring the velocities of stars along the line of sight dates back to more than a century ago. However, it has been only in the past couple of decades that technological advancements reached to the point where the precision was good enough to detect the very small accelerations of a host star induced by orbiting planets. The first serious survey using radial velocity to search for planets around other stars was pursued by a team of Canadian astronomers in the 1980s (Campbell et al. [1988a, b](#)). The team used a hydrogen fluoride gas absorption cell to achieve a very precise wavelength calibration. Although they failed to discover any convincing evidence for planets among their modest samples of a couple dozen stars, they did successfully pioneer the absorption cell technique, which was later adopted by other groups using iodine gas. Ironically, a very tentative detection of a planet orbiting the primary star of the spectroscopic binary system γ Cephei was indeed announced by this team. However, it took another 15 years for this detection to be confirmed (Hatzes et al. [2003](#)). For more details on this discovery, see the book *Planets in Binary Stars Systems* (Haghighipour [2010](#)).

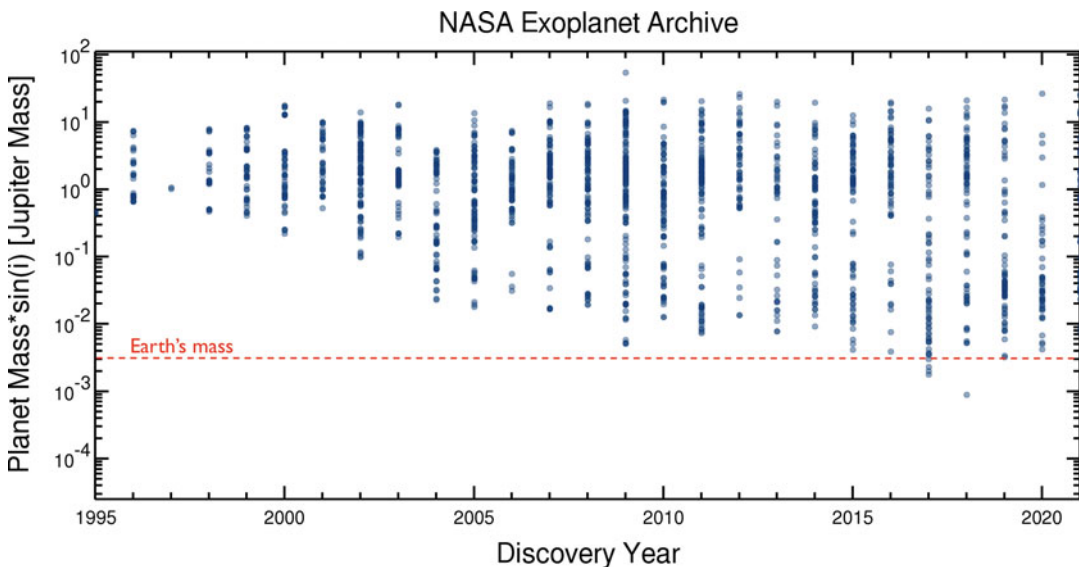
The first radial-velocity orbit for an unseen companion that could be called a giant planet (if the orbit happened to be oriented nearly edge on) was reported for star HD 114762 in 1989 (Latham et al. [1989](#)). However, the unseen companion defied conventional wisdom for being a planet on three counts. The orbital period of only 84 days placed it far inside the ► [snow line](#), where conditions would have been too hot for a ► [gas giant](#) to form; the orbit was eccentric, unlike any of the giant planets in the solar system; and the mass was at least ten times that of Jupiter, which was uncomfortably large (close to the boundary of brown dwarf regime). Thus, most astronomers

dismissed the unseen companion of HD 114762 as a star or ► [brown dwarf](#) in an orbit seen nearly face on. It was assumed that the observed orbital amplitude of 0.5 km/s was small because of the projection effects, not because the mass of the companion was small enough to be a planet.

That is how the search for planets around stars like the Sun stood until 1995, when an orbit of ► [51 Pegasi](#) was announced that implied an unseen companion with a mass half that of Jupiter and a remarkably short period of only 4.2 days (Mayor and Queloz [1995](#)). Initial resistance to accepting this discovery as a planet was soon overwhelmed by the announcement of several other low-Doppler-amplitude orbits implying ► [giant planets](#), often in eccentric orbits close to their parent stars, and some of them quite massive. At this time, a population of extrasolar planets was being revealed, although for any particular candidate, the actual mass could not be pinpointed until the inclination of the orbit to the line of sight could be established.

Ambitious Doppler surveys of hundreds and even thousands of solar-type stars rapidly

expanded the known population of radial-velocity planets. By June 2021, the total number of these planets, confirmed and with known orbital solutions, exceeded 800 (according to <https://exo.planetarchive.ipac.caltech.edu/>). As the surveys were sustained over longer durations, planets with longer periods were also discovered. As richer data sets were accumulated, systems with multiple planets were identified (there are currently almost 200 of such multiple planet systems). And, as the instrumental techniques improved, the velocity precisions improved as well and discoveries were extended to smaller masses, to the point where astronomers were able to detect planets with masses close to that of Earth's (see, for instance, the entry on "GJ 667C", ► ["Ross-128b"](#), and ► ["Proxima-b"](#)). The history of these discoveries is illustrated in Fig. 1, which plots the mass of each planet as a function of the year of discovery. In most cases, the masses are the minimum values, for orbits that happen to be viewed edge on. For those planets that transit their host stars, the ambiguity of the orbital inclination is removed, and the points give the actual masses.



Radial-Velocity Planets, Fig. 1 Diagram of radial-velocity planet masses as a function of the year of discovery. By the end of 2014, the technology had improved to the point where astronomers were able to detect planets

with masses close to that of Earth (shown as a red dashed line). In 2016, the first planet with a mass very similar to Earth's mass was detected in the habitable zone of its star: Proxima-b (Anglada-Escudé et al. [2016](#))

Basic Methodology

The most productive instruments for measuring very precise stellar radial velocities are all cross-dispersed echelle spectrometers with charge-coupled device (► [CCD](#)) detectors. For these instruments, the widths of the individual CCD pixels at the ► [spectrometer](#) focal plane correspond to a ► [Doppler shift](#) of typically 1 km/s, so to measure velocities with a precision of 1 m/s, it is necessary to determine the average position of the lines in the stellar spectrum to a precision of 1000th of a pixel or better. Planets have orbital periods that range from a fraction of a day to many years, but no spectrometer is stable at the level of 1 m/s over such time spans. Thus, it is necessary to measure and correct wavelength drifts very precisely.

Two approaches are in general used for wavelength calibration. One approach introduces a gas absorption cell into the beam of light from the telescope, usually a cell containing molecular iodine gas just before the spectrometer slit. The iodine absorption lines sample exactly the same path through the spectrometer as the stellar spectrum. Thus, any distortions in the optics or shifts in the illumination of the slit are faithfully recorded by the iodine spectrum impressed on top of the stellar spectrum. Using the iodine spectrum to correct the wavelength scale requires extensive numerical modeling in the data reduction, and separate exposures are needed of the star without iodine, to serve as a template. The other approach is to build a very stable spectrometer and to use an optical fiber to feed the stellar light into the spectrometer. If properly configured, the fiber scrambles the stellar light so that shifts due to guiding errors are reduced. Wavelength calibration is usually achieved with a thorium-argon hollow-cathode lamp, with either simultaneous calibration exposures in a separate fiber adjacent to the science fiber or sequential exposures through the science fiber before and after the science exposure. An important difference between these two approaches is the limited wavelength range of the iodine absorption spectrum, nominally in the window 500–600 nm. In contrast, the thorium-argon technique is limited

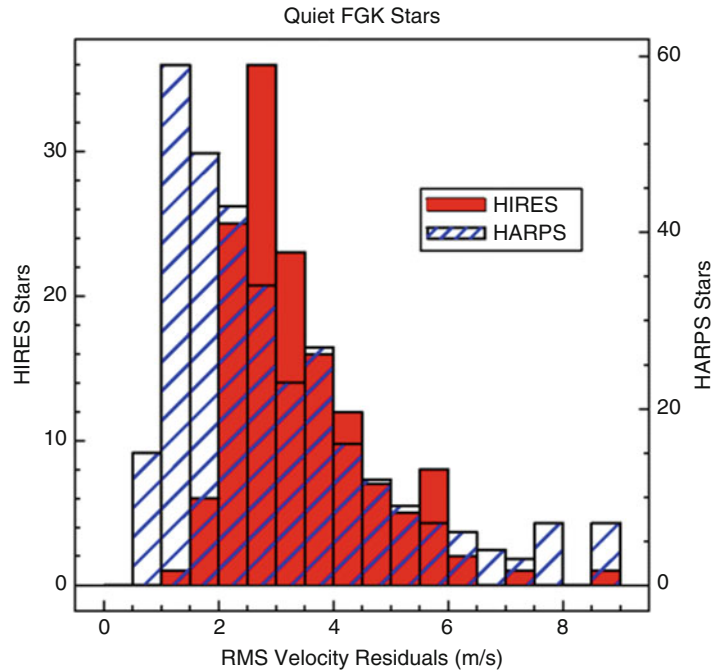
only by the stellar spectrum and the wavelength coverage of the spectrometer, which can easily span 380–900 nm.

The bulk motion of a star in orbit around the center of mass of a star-planet system is not the only possible source of Doppler shifts in the stellar spectrum. Stars with activity on their surfaces can have spots that are brought into view as the star rotates, leading to small distortions of the spectral lines and apparent Doppler shifts, and as the spot crosses from one side of the visible disk of the star to the other. Rapid rotation itself makes it difficult to measure precise radial velocities, because the rotation broadens the spectral lines and makes them shallower. Young stars tend to be active with rapid rotation, and hot stars also rotate rapidly, so they are difficult targets for the detection of radial-velocity planets. Bulk motions in the atmospheres, for example, due to convection, and global oscillations of the star can also introduce subtle shifts. Giant stars, especially the largest ones, exhibit velocity jitter due to these effects. At the other extreme, the smallest and coolest dwarf stars can also show activity, such as flares. These effects all imply that the ideal stars for large Doppler surveys for exoplanets are stars similar to the Sun, with spectral types F, G, and K.

The two most productive instruments for radial-velocity planets have been the High-Resolution Echelle Spectrometer (► [HIRES](#)) on the Keck I telescope on the summit of Mauna Kea in Hawaii and the High-Accuracy ► [Radial-Velocity](#) Planet Searcher (HARPS) on the 3.6-m ESO telescope on La Silla, Chile. HIRES uses the iodine cell approach on a general-purpose slit spectrometer, while HARPS uses thorium argon and a fiber-fed spectrometer designed to be very stable. For example, the temperature of HARPS is stabilized to a few mK, and the optics is housed inside a vacuum chamber. This eliminates the large wavelength shifts due to the changing index of refraction at the echelle grating as the ambient pressure of the local atmosphere changes. Both instruments have achieved a velocity precision for stellar observations at nominally the 1 m/s level over long time spans. This is illustrated in Fig. 2, which shows the histogram of the observed root-mean-square velocity residuals for two

Radial-Velocity Planets,

Fig. 2 Histograms of the root-mean-square velocity residuals for a sample of 143 quiet F, G, and K stars observed with HIRES and 321 quiet F, G, and K stars observed with HARPS, illustrating the quality of the data obtainable with these instruments



samples of quiet F, G, and K stars: 143 stars from the η -Earth project (Howard et al. 2010) with HIRES, and a similar but larger sample of 321 stars observed by the HARPS team. Both surveys span several years with typically at least two dozen observations per star. Recently, this fleet of instruments was joined by other spectrographs, like ESPRESSO, installed on the VLT in Paranal in Chile. ESPRESSO is now one of the most precise spectrographs available to the community. Searching for planets orbiting stars less massive than the Sun, CARMENES (Quirrenbach et al. 2016) and SPIRou are spectrographs which observe in the infrared where these stars emit more. For instance, the first CARMENES planet was a Neptune-size planet in the habitable zone of a dwarf (Reiners et al. 2018).

Key Research Findings

An orbital solution based on the spectroscopically observed radial velocities of a planet-hosting star is known as a ► [spectroscopic orbit](#). Although the orbital period and ► [eccentricity](#) can be determined unambiguously by a spectroscopic orbit,

the velocity amplitude of the orbital solution cannot, as it is not possible to determine the tilt of the orbital plane with respect to the line of sight from radial velocities alone. As a result, the velocity amplitude is only the component projected along the line of sight. That means, the true orbital amplitude and therefore the true mass of the planet (relative to the star) cannot be determined definitively. The best that can be done is to determine the minimum mass that the planet would have, if the orbit happened to be viewed edge on so that the observed velocity amplitude would be the true amplitude. Otherwise, some other techniques should be used to pin down the orbital inclination. In a few cases, astrometry has provided orbital inclinations for radial-velocity planets. However, the real breakthrough for deriving actual masses for planets came with the discovery of transiting planets; systems with orbits oriented close enough to edge on as seen from the Earth, where the planets transit across the faces of their host stars (see the entry ► [“Transiting Planets”](#)).

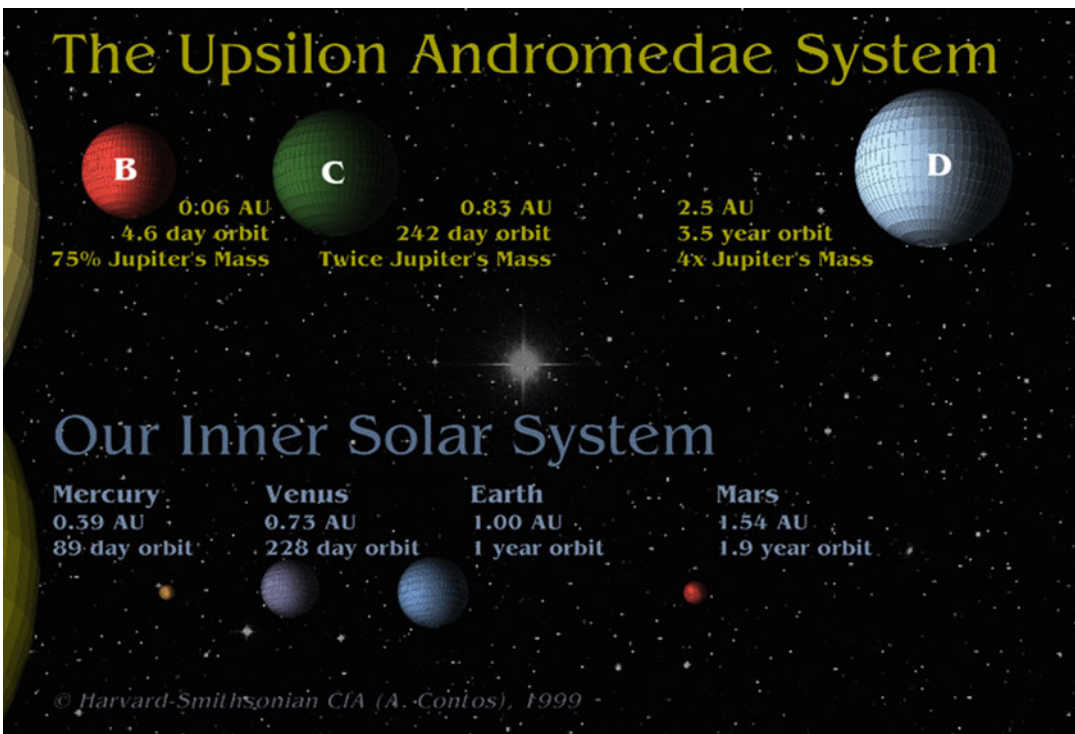
The amplitude of the radial velocity of a star due to the effect of its planet increases as one over the square root of the size of the orbit and one over the cube root of the orbital period. The velocity

amplitude also depends linearly on the ratio of the planet's mass to that of the star. That means, planets with large masses in short-period orbits (i.e., close to their central stars) are potentially easier to detect as they can induce larger reflex motions in the star than planets at larger distances. That has been the reason that the radial-velocity technique has been able to detect many gas giant planets similar to Jupiter in mass, in short-period orbits. Extensive Doppler surveys have shown that about 5–10% of solar-type stars are orbited by giant planets, and among these stars, those that show higher abundances of heavy elements in their atmospheres are more likely to host giant planets. The frequency of giant planets with periods longer than about 10 years is not well determined, because the surveys have not been in operation long enough yet.

One of the striking results of planet detection with radial-velocity technique is the discovery of systems with multiple planets. As suggested by theories of planet formation, planets form in

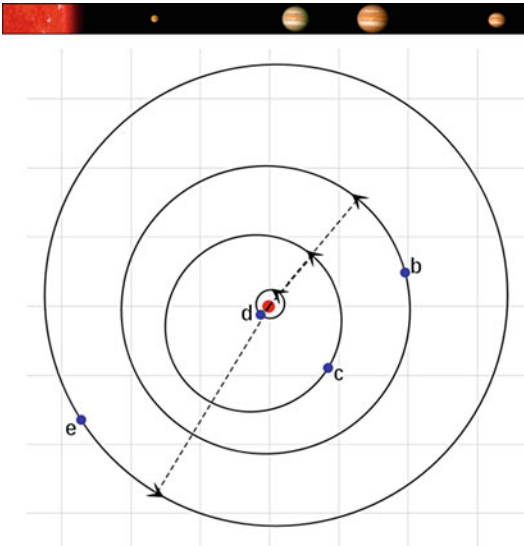
multiples. It was, therefore, expected that planetary systems around other stars would have multiple planets as well. The first multi-planet system was discovered around the star Upsilon Andromedae in 1999 (Fig. 3, Butler et al. 1999). Since then, radial velocity has been able to detect about 200 more multiple planet systems.

Another important achievement of radial-velocity surveys is the discovery of super-Earth planets (see the entry on ► “[Super-Earths](#)”), in particular around cool, low-mass stars (M dwarfs, see ► “[Spectral Type](#)”). With masses in the range of two to ten Earth masses, super-Earths may be rocky, in which case, if they orbit their host star in the Habitable Zone, they may have the potential to develop life as we know it. Around cool and low-mass stars such as M dwarfs, where the habitable zone is in a closer range (0.1–0.2 AU) compared to that around the Sun, these planets can induce large reflex motions in the star comparable with the sensitivity of radial-velocity surveys. Among the multiple



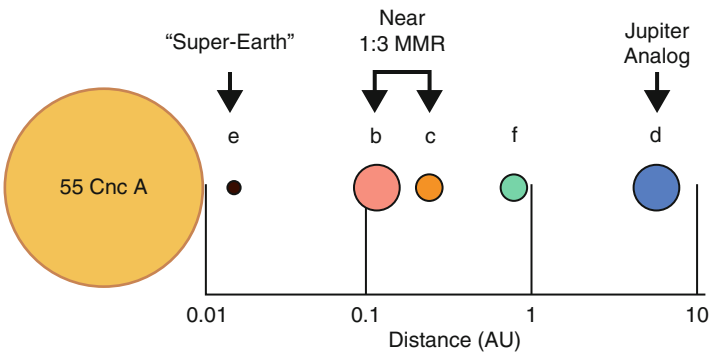
Radial-Velocity Planets, Fig. 3 The planetary system of Upsilon Andromedae, the first extrasolar multi-planet system detected (Butler et al. 1999)

planet systems discovered by radial velocity, a few have become of particular interest as they include super-Earth planets and have interesting orbital configurations. The M star Gliese 876 was the first star with two planets in a 2:1 resonance, hosting the first detected super-Earth, a 6.2-Earth-mass planet in a 2-day orbit (Marcy et al. 1998, 2001; Delfosse et al. 1998; Rivera et al. 2005). Currently, GJ 876 has four planets, including three giant planets as the only known planetary system in a 1:2:4 ▶ [Laplace resonance](#) (Fig. 4). Recently, several planets with an astrobiological interest and with masses close to that of the Earth were discovered around M dwarfs. For instance, Proxima-b (Anglada-Escudé et al. 2016) and Ross-128b (Bonfils et al. 2018). Of those two



Radial-Velocity Planets, Fig. 4 The orbits of the planets in the system of GJ 876

Radial-Velocity Planets, Fig. 5 The multi-planet system of 55 Cancri



planets, Proxima-b is by far the most promising one. Discovered around Proxima Centauri, it is the Habitable Zone planet the closest to our solar system. Its minimal mass is only 1.27 Earth mass and its atmosphere will be probed by future instruments using high-contrast and high-resolution spectroscopy (e.g., Lovis et al. 2017, see ▶ [“Planet Characterization: High-Resolution Spectroscopy”](#)).

The system of 55 Cancri is also another special multi-planet system. This system has two planets in a 1:3 resonance, one transiting super-Earth and one Jupiter analog (Fig. 5). Finally, the planetary system of Gliese 667C has also gained a great deal of attention. This system is the first planetary system with two confirmed super-Earths, one of which detected in the habitable zone.

Transiting radial-velocity planets offer the possibility of atmospheric characterization, via the disentangling of the planet from the stellar signal using a cross-correlation technique (Snellen et al. 2010). These observations allowed to detect various species in the atmospheres of ultra-hot Jupiters (e.g., Hoeijmakers et al. 2018, with the HARPS spectrograph). The advent of high-resolution spectrographs, like ESPRESSO, marked also the beginning of improvements in atmospheric characterization. Recently, using the same method, Ehrenreich et al. (2020) observed an asymmetry between the leading and trailing limb of the planet (the morning and evening limb, respectively). They interpreted it as evidence that iron condensation occurs on the night-side of the ultra-hot exoplanet WASP-76b. Although these types of observations are now only possible for hot giant planets, this is exciting

to see what high-resolution spectroscopy can achieve (see also ► [“Planet Characterization: High-Resolution Spectroscopy”](#)).

Future Directions

The orbital motion induced in a star like the Sun by a planet like the Earth in a 1-year orbit is on the order of 10 cm/s. Although it is not yet clear whether there are stars quiet enough to allow orbital motions to be detected at this level, the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) is a spectrometer built to be capable of 10 cm/s precision. Since 2017, this instrument is in operation on the Very Large Telescope at the European Southern Observatory in Chile. It has already contributed to interesting science and will continue for the years to come. Very soon, a new infrared spectrograph, NIRPS (seen as the “red arm” of HARPS) will be in operation at the 3.6 m telescope at La Silla Observatory in Chile. It will detect and characterize planets orbiting cool dwarfs.

Looking beyond ESPRESSO and NIRPS, a high-resolution spectrograph called HIRES (not to be confused with the High-Resolution Echelle Spectrometer on the Keck I telescope, also called HIRES) will have the potential to measure radial velocities at the level of 1 cm/s over time spans of many years. HIRES will be used with the European Extremely Large Telescope, with a start toward 2030. Note that E-ELT HIRES will also be used to characterize the atmosphere of small temperate planets around low-mass stars (such as Proxima-b, see also ► [“Planet Characterization: High-Resolution Spectroscopy”](#)).

Cross-References

- [51 Pegasi B](#)
- [CCD](#)
- [Doppler Shift](#)
- [Eccentricity](#)
- [ESPRESSO](#)
- [Exoplanets, Discovery](#)
- [Habitable Zone](#)

- [HARPS](#)
- [Hill Radius/Sphere](#)
- [HIRES](#)
- [Periastron](#)
- [Planet Characterization: High-Resolution Spectroscopy](#)
- [Proxima-b](#)
- [Radial Velocity](#)
- [Ross-128B](#)
- [Snow Line](#)
- [Spectral Type](#)
- [Spectrometer](#)
- [Spectroscopic Orbit](#)
- [Super-Earths](#)
- [Transiting Planets](#)
- [VLT](#)

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Radiation

► X-Rays (Stellar)

Radiation Biology

Christa Baumstark-Khan
German Aerospace Center (DLR), Institute of
Aerospace Medicine, Cologne, Germany

Keywords

DNA damage · Radiation chemistry ·
Radiation interactions · Radiation risk ·
Radiation sensitivity

Synonyms

[Radiation interactions with living matter](#)

Definition

Radiation biology is an interdisciplinary subject that describes the biological effects of ionizing radiations. It is based on studies in physics, chemistry, biology, and medicine.

History

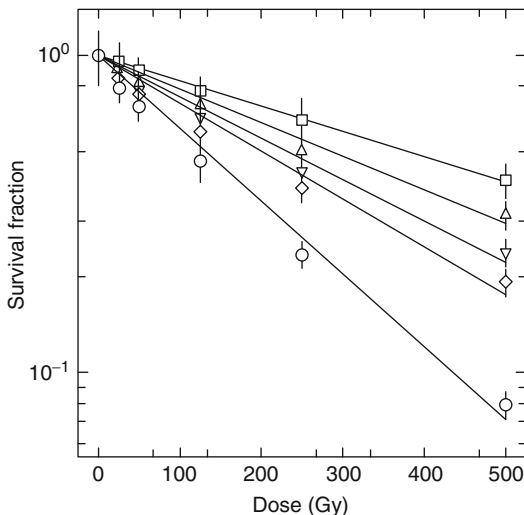
The history of radiation biology started shortly after the discovery of X-rays in 1895 by Wilhelm Conrad Röntgen, who was awarded the first Nobel Prize in Physics in 1901. Within short time, X-rays were being used not only to take pictures of the internal organs of living people but also to treat a variety of diseases. The discovery of natural radioactivity by Antoine Henri Becquerel in 1896 was the prerequisite for the detection of terrestrial and cosmic radiation. In 1903, Becquerel shared the Nobel Prize in Physics with Pierre and Marie Curie “in recognition of the extraordinary services he has rendered by the discovery of spontaneous radioactivity.” Interaction of radiation energy with living matter was observed, and the radiation sensitivity law was formulated by Jean Alban Bergonie and Louis Tribondeau as early as 1906. The genetic effects of radiation, including the effects on cancer risk, were recognized much later. In 1946, Hermann Joseph Muller was awarded the Nobel Prize in Physiology or Medicine, for the discovery of the production of mutations by means of X-ray irradiation.

Overview

Life on Earth has been shaped by interactions of the organisms with their environment, including radiation of terrestrial and cosmic origin, by numerous adaptive responses. Radiation biology describes the interactions of radiation with living matter through primarily ionization and excitation of electrons in atoms and molecules. Starting with the energy absorption of irradiated water molecules, a series of follow-up reactions is initiated (water radiolysis) in cells and tissue which give

rise to the indirect effects of radiation in addition to the direct energy absorption effects in biological key substances, such as proteins, RNA, and DNA. Direct consequences of molecular radiation damage on cellular level are inactivation or ► [mutation](#) induction. Dependent on the organizational level of life, cellular damage may result in tissue damage or even in the death of the exposed organism. Cell killing by ionizing radiation depends on different factors, such as DNA content (target size: number and size of chromosomes) and the quality of radiation (sparsely/densely ionizing radiation). The effect of radiation on inactivation (killing) is described in terms of ► [survival](#) curves. In radiobiological terms, cell survival is understood as the ability for indefinite cell reproduction. In dose-effect curves, the surviving fraction of irradiated cells relative to that of nonirradiated cells is plotted in a half-logarithmic manner, showing the number of survivors to decrease with increasing dose. The parameter D_0 describing radiation sensitivity is derived from the slope of the terminal part of the dose-effect curve as $-1/\text{slope}$ (Fig. 1). While human cells will be killed by doses of about 1.5 Gy (D_0), yeast cells

and bacteria tolerate doses up to 50–200 Gy (D_0). The most radiation-resistant bacterium is *Deinococcus radiodurans* ($D_0 > 5000$ Gy). In response to the harmful effects of environmental radiation, life has developed a variety of defense mechanisms, including the expression of stress proteins, the activation of the immune defense, and a variety of efficient repair systems for radiation-induced DNA injury. The radiation response of each life form is influenced by the physical properties of the radiation in question. The biological effectiveness of radiation largely depends on the local energy distribution, the ► [linear energy transfer](#) (LET, measured in keV/ μm). The relative biological effectiveness (RBE) is defined as the ratio of physical doses of the densely ionizing radiation (heavy ions, neutrons) compared to the doses of sparsely ionizing standard radiation (usually 250 kV X-rays) leading to the same effect. The RBE value is different for different biological systems and end points, depending on their stage in the growth cycle and a series of environmental factors, for example, oxygen content. For interplanetary space radiation, which is composed of different radiation types and qualities, RBE values are still to be investigated.



Radiation Biology, Fig. 1 Survival curves of *Bacillus subtilis* spores in response to X-rays (open squares) and accelerated heavy ions: helium (open triangles up), carbon (open triangles down), silicon (open diamonds), and iron (open circles). (From Moeller et al. 2010)

Cross-References

- [Cosmic Rays in the Heliosphere](#)
- [DNA Damage](#)
- [DNA Repair](#)
- [Ionizing Radiation, Biological Effects](#)
- [Linear Energy Transfer](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Radiation Dose](#)
- [Survival](#)

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Radiation Chemistry

Christopher R. Arumainayagam
Wellesley College, Wellesley, MA, USA

Keywords

Cosmic rays · Photochemistry · Ionization · Prebiotic molecules · Molecular panspermia · Interstellar ice

Synonyms

Radiolysis

Definition

Radiation chemistry involves chemical changes induced by ionizing radiation with energies typically above 10 eV. Ionizing radiation in cosmic chemistry includes high-energy particles (e.g., H^+ ions in cosmic rays) and high-energy photons (e.g., X-rays). Radiation chemistry of cosmic (interstellar, planetary, cometary, and satellite) ices and atmospheres leads to the extraterrestrial synthesis and destruction of prebiotic molecules. Low-energy (<20 eV) secondary electrons, the production of which is a signature characteristic of radiation chemistry, are the dominant species in condensed-phase radiation chemistry, which likely played a critical role in the extraterrestrial synthesis of prebiotic molecules in protostellar cores within dark, dense molecular clouds, facilitating molecular panspermia and possibly jump-starting life on Earth.

Overview

Extraterrestrial condensed-phase and gas-phase energetic processing to yield prebiotic molecules may occur via radiation chemistry, which is defined as the “study of the chemical changes produced by the absorption of radiation of sufficiently high energy to produce ionization” (Woods 1998). Radiation chemistry has been employed to model prebiotic chemical reaction networks (Adam et al. 2021). Ionizing radiation in extraterrestrial chemistry includes high-energy particles (e.g., MeV to TeV cosmic rays consisting mostly of protons) and high-energy photons (e.g., vacuum ultraviolet (6.2–12.4 eV), extreme ultraviolet (12.4–124 eV), X-rays (>124 eV), and γ -rays (100 keV to 1 TeV)) (Arumainayagam et al. 2019). Extraterrestrial condensed-phase radiation chemistry is thought to play an important role in the processing of (1) interstellar ices within dark, dense molecular clouds, (2) protoplanetary disk ices close to the central star (Ciaravella et al. 2020), (3) Martian subsurface environment (Atri 2020), and (4) water ice on the surface of moons such as Europa and

Enceladus. High-energy ion irradiation of cosmic ice analogs demonstrates that both synthesis (Tribbett and Loeffler 2021) and destruction (Gerakines et al. 2021) of prebiotic molecules may result from extraterrestrial condensed-phase radiation chemistry. Extraterrestrial gas-phase radiation chemistry includes gaseous molecular hydrogen ionization, leading to important interstellar processes such as proton transfer reactions followed by ion-molecule reactions (e.g., protonated methanol reacting with formaldehyde to yield methyl formate, a complex organic molecule (COM) detected in hot cores and hot corinos) (Horn et al. 2004).

Modeling radiation chemistry is extraordinarily challenging because of the associated large number of fundamental processes (Table 1).

In contrast to photochemistry, which also contributes to energetic extraterrestrial processing, radiation chemistry is characterized by four phenomena: (1) production of a cascade of low-energy (<20 eV) secondary electrons, which are thought to be the dominant driving force behind condensed-phase radiation chemistry, (2) reactions initiated by cations, (3) nonuniform distribution of reaction intermediates, and (4) nonselective chemistry leading to the production of multiple reaction products (Arumainayagam et al. 2019).

Studying Energy transfer from the ionizing radiation to the medium is key to understanding radiation chemistry (Hatano et al. 2010). Interactions of electromagnetic radiation and charged particles with matter primarily involve transferring energy to electrons and not the nuclei of the material's constituent atoms. At energies above the ionization threshold (~10 eV), photon interactions with matter occur via three processes: (1) the photoelectric effect, (2) the Compton effect, or (3) pair production (Arumainayagam et al. 2019). In contrast, protons, α particles, and heavy ions lose energy via Coulombic interactions between the ion's charge and the medium's electrons, resulting in excitations and ionizations (Arumainayagam et al. 2019). In addition to these two energy loss mechanisms, fast electrons can radiate energy by bremsstrahlung, the "braking" radiation (Arumainayagam et al. 2019).

Effects of radiation chemistry depend on the radiation type, which is determined by linear energy transfer (LET), the rate of energy deposition by an ionizing entity per unit length of track ($LET = -dE/dx$, where E is the energy of the particle and x is the distance traveled) (Arumainayagam et al. 2019). Low LET (0.2 eV/nm) gamma-ray or 1 MeV electron radiolysis of water and high LET (150 eV/nm) alpha-particle irradiation of water yield remarkably different results because the former produces isolated spurs (events hundreds of angstroms apart) (Burton 1969), while the latter produces dense tracks (events a few angstroms apart) which may allow for intraspur chemical reactions (Hatano et al. 2010). The dose-rate effect (when the results depend on not only the total energy dose but also the time required to deliver that dose) in radiation chemistry is often associated with high linear energy transfer radiation (Arumainayagam et al. 2019).

In addition to affecting the physical structure of interstellar ices via sputtering, lattice defect production, and non-thermal desorption, ionizing radiation may initiate chemical reactions in interstellar ices (Boyer et al. 2016). The dominant mechanism involves the interaction of high-energy radiation with molecules within ices, generating a cascade of low-energy electrons that can interact with the surface and bulk ice molecules (Boyer et al. 2016).

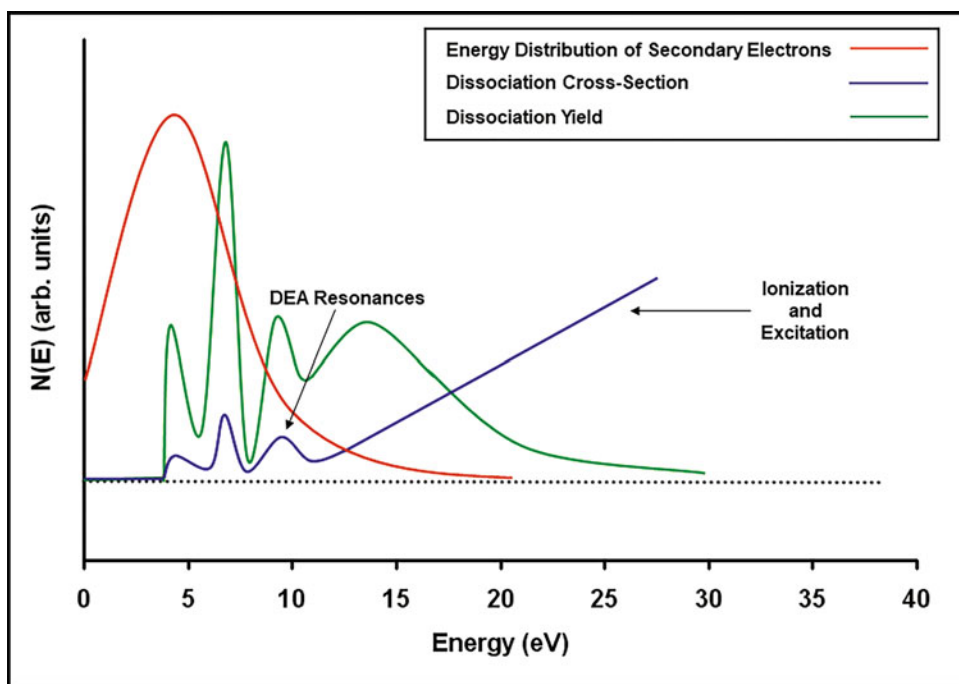
Within attoseconds, the interaction between high-energy radiation (e.g., cosmic rays) and matter produces copious numbers ($\sim 4 \times 10^4$ electrons per MeV of energy deposited) of non-thermal, secondary, low-energy (<20 eV) electrons (Arumainayagam et al. 2010). While secondary products such as excited species and ions produced from the high-energy radiation interacting with molecules cause some radiation damage, it is the secondary electron-molecule inelastic collisions that are thought to be the primary driving forces in a wide variety of radiation-induced chemical reactions (Pimblott and LaVerne 2007). Therefore, *high-energy condensed phase-radiolysis is mediated by low-energy electron-induced reactions.*

Radiation Chemistry, Table 1 Fundamental processes of radiation chemistry. (Adapted from Hatano et al. (2010) with permission from Taylor and Francis)

$AB \rightarrow AB^+ + e^-$	Direct ionization
$\rightarrow AB^{**}$	Superexcitation (direct excitation)
$\rightarrow AB^*$	Excitation (direct excitation)
$AB^{**} \rightarrow AB^+ + e^-$	Autoionization
$\rightarrow A + B$	Dissociation
$AB^+ \rightarrow A^+ + B$	Ion dissociation
$AB^+ + AB \text{ or } S \rightarrow \text{Products}$	Ion-molecule reaction
$AB^+ + e^- \rightarrow AB^*$	Electron-ion recombination
$AB^+ + S^- \rightarrow \text{Products}$	Ion-ion recombination
$e^- + S \rightarrow S^-$	Electron attachment
$e^- + nAB \rightarrow e_x^-$	Solvation
$AB^* \rightarrow A + B$	Dissociation
$\rightarrow AB$	Internal conversion and intersystem crossing
$\rightarrow BA$	Isomerization
$\rightarrow AB + h\nu$	Fluorescence
$AB^* + S \rightarrow AB + S^*$	Energy transfer
$AB^* + AB \rightarrow (AB)_2^*$	Excimer formation
$2A \rightarrow A_2$	Radical recombination
$\rightarrow C + D$	Disproportionation
$A + AB \rightarrow A_2B$	Addition
$\rightarrow A_2 + B$	Abstraction

Electron-induced dissociations proceed via one of three initial steps: electron impact ionization (typically occurring at energies above ~ 10 eV to yield an excited state cation, which may undergo ion-molecule reactions or fragment), electron impact excitation (a non-resonant process occurring at incident electron energies above

~ 3 eV), and electron attachment (to form a transient negative ion (TNI), which may undergo bond scission, a process known as dissociative electron attachment (DEA)). The electron-induced reaction yield plotted as a function of electron energy (Fig. 1) manifests maxima at specific energies (resonant scattering due to electron



Radiation Chemistry, Fig. 1 Schematic of (a) energy distribution of secondary electrons generated during a primary ionizing event (red dotted line); (b) cross-section for electron-induced dissociation for a typical molecule (blue

dashed line); (c) dissociation yield as a function of electron energy for a typical molecule (green solid line). (Reproduced from Arumainayagam et al. (2010) with permission from Elsevier)

attachment) superimposed on a smoothly increasing curve (non-resonant scattering due to electron impact ionization and/or excitation).

The production of low-energy secondary electrons during radiation chemistry may lead to reaction pathways not available to photochemistry (Arumainayagam et al. 2019). For example, while photon-induced singlet-to-triplet transitions are forbidden in the gas phase, electron-induced singlet-to-triplet transitions are allowed because the incident electron can be exchanged with those of the target molecule (Arumainayagam et al. 2010). Moreover, unlike photons, electrons can be captured into resonant negative ion states that dissociate. The resulting molecular fragments may then react with the parent molecule or other daughter products to yield products unique to electron irradiation (Arumainayagam et al. 2010). Condensed-phase extraterrestrial electron-induced reactions may predominate over photon-induced reactions because of the sheer number of

low-energy secondary electrons produced by high-energy irradiation. In contrast to photon excitation, electron excitation is not a resonant process; the incident electron transfers the fraction of its energy sufficient to excite the molecule, and any excess is removed by the scattered electron (Arumainayagam et al. 2019). This phenomenon enhances electron-induced reactions vis-à-vis photon-induced reactions (Arumainayagam et al. 2019). Reaction cross-sections can be several orders of magnitude larger for electrons than for photons, particularly at incident energies corresponding to resonances associated with dissociative electron attachment (Arumainayagam et al. 2010).

A common misconception in astrochemistry and astrobiology is that UV photons only induce photochemistry and do not initiate radiation chemistry. Reactions attributable solely to photochemistry are limited to those initiated by photons associated with far (deep)-UV (4.1–6.2 eV)

(300–200 nm), near-UV (3.1–4.1 eV) (400–300 nm), and, occasionally, visible (1.8–3.1 eV) light (Arumainayagam et al. 2019). While in photochemistry, a single low-energy (<10 eV) non-ionizing photon typically initiates one chemical reaction, in radiation chemistry, a single photon/charged particle initiates a cascade of energy-loss events such as ionization, excitation, and nuclear displacement (Arumainayagam et al. 2019). Vacuum-UV (6.2–12.4 eV) light may initiate radiation chemistry, in addition to photochemistry, because the threshold for producing secondary electrons is lower in the condensed phase than in the gas phase for a given molecule (Arumainayagam et al. 2019). Because about 40% of the flux of secondary UV photons is estimated to be ionizing (>10 eV), this UV light can produce secondary electrons and cations when interacting with interstellar ices. Therefore, secondary UV radiation and MDHL lamps typically initiate both photochemistry and radiation chemistry in cosmic ices and their analogs. While photodissociation by far-UV photons is dominated by electronic excitation (photochemistry), photodissociation by X-ray photons is mediated by ionization (radiation chemistry) (Arumainayagam et al. 2021). Therefore, photochemistry is a subset of photon-initiated chemistry. A fundamental understanding of extraterrestrial ice processing requires examining the difference in chemical effects of low-energy (<20 eV) secondary electrons (Boyer et al. 2016) – agents of radiation chemistry – and low-energy (<10 eV) photons – instigators of photochemistry.

According to a recently published book, *The Stardust Revolution*, we are in the midst of the third scientific revolution, after those of Copernicus and Darwin (Berkowitz 2012). This book espouses the astounding view that the origin of life can be traced back to the stars themselves. In 2016, unambiguous evidence for the presence of the amino acid glycine, an important prebiotic molecule, was deduced based on in situ mass-spectral studies of the coma surrounding cometary ice (Altwegg et al. 2016). This finding is significant because comets are thought to have preserved the icy grains originally found in the interstellar

medium before solar system formation. Energetic processing of cosmic ices via radiation chemistry is believed to be a dominant mechanism for the extraterrestrial synthesis of prebiotic molecules delivered to Earth via comets, asteroids, and meteorites.

Basic Methodology

Surface science techniques are typically used to analyze condensed-phase radiolysis processes relevant to astrobiology. Such experiments are usually conducted using nanoscale thin films of multilayer adsorbates under ultrahigh vacuum (UHV) conditions ($P \sim 10^{-9}$ torr). Electron-stimulated desorption (ESD) experiments, conducted *during* irradiation, have yielded vital information relevant to initial electron-induced processes. In addition, analyzing the products *following* high-energy irradiation has provided new insights into radiation chemistry. Surface science techniques such as temperature-programmed desorption (TPD), reflection absorption infrared spectroscopy (RAIRS), X-ray photoelectron spectroscopy (XPS), and high-resolution electron energy loss spectroscopy (HREELS) are particularly useful for post-irradiation analysis. The interactions of charged particles with cosmic ice analogs have been studied using multiple types of ion-beam sources, including ion implanters, van de Graaff accelerators, tandem accelerators, and cyclotrons. Synchrotron radiation sources (e.g., NSRRC in Taiwan, DESIRS beamline at SOLEIL in France) produce continuous intense photon emission capable of ionization.

Key Research Findings

1. Radiation chemistry of interstellar ices near star-forming regions likely leads to the extraterrestrial synthesis of prebiotic molecules.
2. Radiation chemistry is mediated by low-energy electrons, which may have reaction cross sections several orders of magnitude larger than those of photons.

3. Because the ionization threshold is lower in the condensed phase than in the gas phase, most “photochemistry” studies of astrochemistry likely involve radiation chemistry.

Future Directions

The newly deployed James Webb Space Telescope (JWST) should provide new insights into the mechanisms responsible (e.g., radiation chemistry) for the extraterrestrial synthesis of prebiotic molecules.

Cross-References

- Comet
- Complex Organic Molecules
- Cosmic Rays
- Electron Attachment
- Enceladus
- Europa
- Hot Core
- Hot Corino
- Interstellar Chemical Processes
- Interstellar Dust
- Interstellar Ices
- Interstellar Medium
- Origins of Life, History of
- Photochemistry
- Photodissociation
- Photoionization
- Photolysis
- Prebiotic Chemistry
- Proton Irradiation
- Protostars
- Radiation Biology
- Radiochemistry

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Radiation Dose

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Definition

Ionizing radiation is measured in the SI (International System of Units, abbreviated "SI" from the French *Le Système International d'Unités* as the modern metric system of measurement)-derived unit of absorbed dose per mass unit, the gray (Gy), with 1 Gy equal to the net absorption of 1 J in 1 kg of material (water), compared to the previously used radiation unit "rad", 1 Gy = 100 rad. The biological effectiveness of radiation largely depends on the local energy distribution in the target material, the ► [Linear Energy Transfer](#) (LET). The quality factor Q is the biological weighting function of ionizing radiation in relation to the LET of the radiation. The product of Q and the absorbed dose is the dose equivalent. The SI-derived unit for the dose equivalent is the sievert (Sv).

Cross-References

- [Linear Energy Transfer](#)
- [Radiation Biology](#)
- [Space Environment](#)

Radiation Interactions with Living Matter

- [Radiation Biology](#)

Radiation Pressure

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan

Blue Marble Space Institute of Science, Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In astronomy and physics, radiation pressure is the pressure exerted upon a surface exposed to electromagnetic radiation. The pressure is the power flux density divided by the speed of light if it is absorbed. If the radiation is reflected, the radiation pressure is doubled. Radiation pressure is about 10^{-5} Pa at Earth's distance from the Sun and decreases by the square of the distance from the Sun. Though weak, such pressures produce significant effects on small particles like ions, electrons, and cometary dust particles.

Cross-References

- [Panspermia](#)

Radiative Attachment

Stefanie N. Milam

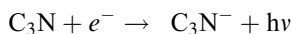
Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Synonyms

[Photoattachment](#)

Definition

Radiative Attachment is the process in which the emission of radiation allows the formation of anions from neutral species and electrons. An example of this process is



Where, $h\nu$ represents a photon.

Cross-References

- [Electron Attachment](#)
- [Photochemistry](#)
- [Photodetachment](#)

Radiative Forcing

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Radiative forcing is the difference between the radiant energy received by a planet from its sun and the energy radiated back to space. This parameter is very important for the planet's climate because positive radiative forcing will warm the planet and negative radiative forcing will cool it. There are several factors controlling the radiative forcing, such as greenhouse gases, aerosols in the atmosphere, the planetary albedo, and the ozone layer. In the early Earth, greenhouse gases, methane oozes, and albedo could have played a key role in regulating the radiative forcing and controlling ancient climates when the radiant energy from the Sun was only 70% of the present-day level (faint young Sun paradox).

Cross-References

- [Albedo](#)
- [Faint Young Sun Paradox](#)
- [Greenhouse Effect](#)

Radiative Processes

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon, Meudon, France

Keywords

Radiation · Electromagnetic radiation · Radiative transfer · Blackbody · Free-free · Photon

Definition

The expression “radiative processes” encompasses all the various physical processes by which a medium releases energy in the form of ► [electromagnetic radiation](#). At the microscopic level, this involves the emission of a photon by an elementary particle, as the result of specific interactions with other particles or particular conditions of temperature, acceleration, and/or excitation. Several radiative processes producing ► [continuum](#) emission can be identified: on one side, blackbody and ► [bremsstrahlung radiation](#) which are the source of *thermal* emission and, on the other side, cyclotron, gyrosynchrotron, and synchrotron emission, which are linked to the spiraling of charged particles in a magnetic field and considered as *nonthermal* processes. Note that we do not consider in this entry ► [spectral line](#) emission, which results from quantum transitions between energy levels of an atom, molecule, or ion.

Overview

Since the quasi-unique source of information on celestial objects is the electromagnetic radiation they emit and which is captured by telescopes, understanding and identifying the physical processes which are at the origin of this emission are essential. Usually, the continuous emission processes that are met in astrophysics are classified into two groups: thermal and nonthermal processes. Blackbody and bremsstrahlung emissions belong to the first group. This is so because the emission is due to particles (atoms, ions, electrons) which are in thermal equilibrium, that is, whose velocities are essentially distributed according to a Maxwellian distribution.

Blackbody emission. This corresponds to the conversion into electromagnetic radiation of the heat, that is, the kinetic energy, of charged particles (electrons and protons in ordinary matter) in a material at a certain temperature. The larger the temperature, the larger the intensity of the emitted radiation, and indeed, we easily feel on our skin the thermal radiation from the Sun or from an open oven. A blackbody exhibits very well-defined thermal emission. This is a hypothetical ideal object, in thermal equilibrium at a given temperature, and that is a perfect radiator, that is,

no other object at the same temperature could emit more energy at a given wavelength. It is also a perfect absorber and thus looks black, hence its name. In the laboratory, a good approximation of a blackbody is a small hole entrance to a cavity with absorbing walls within a block (for instance, of metal), maintained at a fixed temperature.

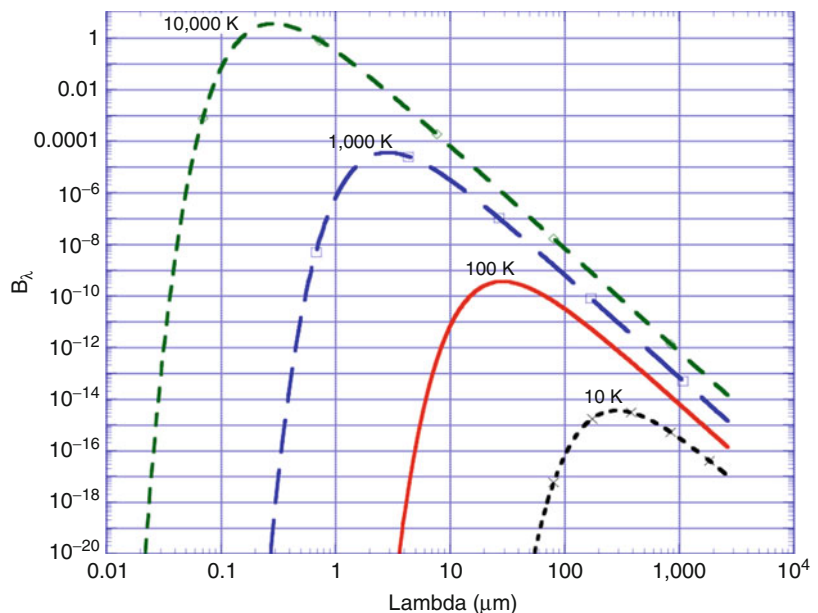
The spectral distribution of the blackbody emission is described by the Planck law and depends only on the temperature of the object. Its main feature is to be peaked with a maximum at a wavelength given by Wien's law, approximately $\lambda(\mu\text{m}) = 3000/T(\text{K})$. On the short wavelength side, the intensity decreases very fast with an exponential behavior, while it varies in a smoother way (as a power law) at wavelengths beyond the maximum (Fig. 1).

The total power radiated by a blackbody is proportional to the fourth power of the temperature (Stefan's law).

As a first approximation, stars' and planets' emission can be described by blackbody radiation. The most perfect astrophysical blackbody is without any contest the Universe itself, which is filled with radiation peaking in the millimeter range, the cosmic microwave background (CMB); it fits Planck's law (at $T = 2.73 \text{ K}$) to within one part per thousand, as revealed by the

Radiative Processes,

Fig. 1 The spectral distribution of the blackbody emission as a function of wavelength λ for different temperatures, from 10 K (a cold dark interstellar cloud) to 10,000 K (a hot A-type star). The X and Y scales are logarithmic. One notes that the blackbody curves are nested and never cross each other. We also note the strong asymmetry between the short wavelength side where the decrease is fast (exponential) and the long wavelength side where it diminishes as λ^{-4}



satellite COBE. However, approximately black-body emission is observed in a large variety of celestial objects at very different wavelengths. To give several examples, the emission of a star as the Sun, with $T = 6000$ K, peaks at $\lambda(\mu\text{m}) = 0.5$ μm (visible); a planet like the Earth, with $T = 300$ K, emits mainly at $\lambda(\mu\text{m}) = 10$ μm (infrared); the hot gas in clusters of galaxies, with $T = 30 \times 10^6$ K, peaks at $\lambda(\mu\text{m}) = 10^{-4}$ μm , that is, in the X-ray domain. Obviously, celestial objects are not black in general; this is why an approximation called the ► **gray body** radiation is often used in models.

Bremsstrahlung. The word is German for “braking radiation.” This emission shares several characteristics with the blackbody emission, but its main feature is to be produced by a plasma of electrons and ions. Here, the emission is due to the acceleration of electrons that are deviated by electrostatic forces when they approach an ion (see Fig. 2). According to Maxwell’s equations, any charge that suffers an acceleration, in direction or in magnitude, must radiate proportionally to the square of the acceleration (Larmor’s equation).

In most cases, the plasma is made of protons and electrons (HII regions, planetary nebulae), and the derivation of the spectrum can be formulated in a rather simple way. The path of an electron is continually wiggling due to slight deviations as it passes each proton, and each wiggle produces radiation in a broad spectrum (related to the energy lost or gained in each collision). One can then consider all the cases for the minimum approach of the electron with respect to the proton and all the possible velocities for the electrons (distributed according to a Maxwell distribution) to compute the distribution of the intensity of the emission versus the frequency.

An additional complexity is introduced by the fact that the radiation is self-absorbed in the plasma, but this can be taken into account. The resulting spectrum exhibits some behaviors similar to blackbody radiation: a power law decreases at large wavelengths and an exponential one at short ones, but between those two regimes, there is no peak but rather a characteristic plateau of almost constant value on a broad range of wavelengths (Fig. 3).

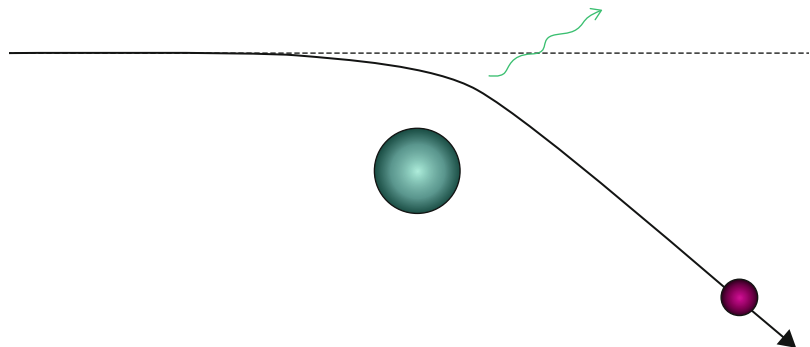
Bremsstrahlung emission is seen in a variety of astrophysical plasmas: the solar corona, HII regions where it dominates over all other mechanisms in the radio domain, and the central regions of clusters of galaxies where a tenuous and very hot gas (30×10^6 K) produces an emission mainly seen in the X-ray domain.

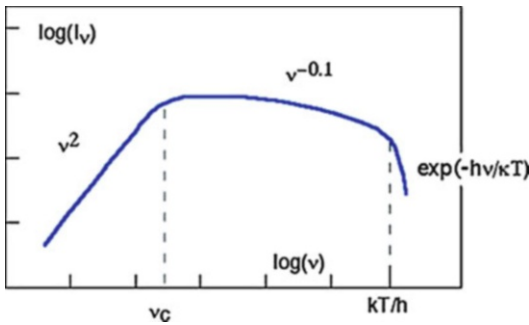
There is another way to accelerate free particles, by considering the effects of the magnetic field. We are now facing a second family of radiative processes called nonthermal because the particles that produce them are not at local thermal equilibrium.

Gyro-emission. In a plasma, there is usually no macroscopic electric field; however, there could be a magnetic field (the plasma is then termed a magnetized plasma), and in this case, an electron of speed v will be accelerated perpendicular to its speed and to the magnetic field by the so-called Lorentz force. Again, the acceleration of the charged particle is responsible for producing radiation, but now, the movement is regular, and the electron gyrates around the direction of the magnetic field (Fig. 4). In the nonrelativistic case (low electron velocity, i.e., low temperature), the gyration is done at a fixed frequency, independent of the speed, called the gyrofrequency which depends only on magnetic field strength. The emission

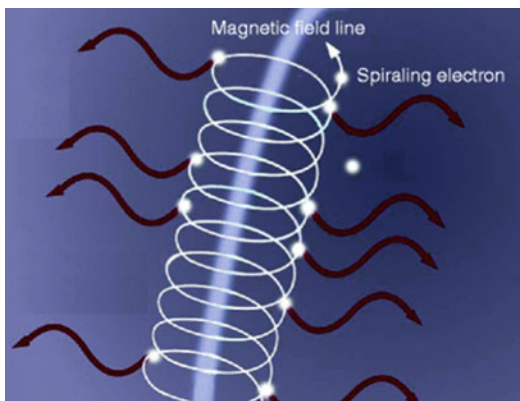
Radiative Processes,

Fig. 2 An electron (red) approaching an ion (blue) deviates under the electrostatic force and then produces electromagnetic radiation because of the associated acceleration





Radiative Processes, Fig. 3 The spectrum of a plasma-emitting bremsstrahlung emission features three distinct domains (indicated on the graph) and especially a broad plateau of quasi-constant intensity. Log intensity (I_v) is plotted versus log frequency (ν)



Radiative Processes, Fig. 4 An electron spiraling in a magnetic field produces radiation as does any accelerated charged particle

from a single electron is thus uniquely determined at this frequency, giving rise to a cyclotron line at the gyrofrequency, $\nu_B = 2.8 \times 10^6 B \text{ Hz}$ (where the magnetic field B is in gauss).

At higher electron velocities (corresponding to temperatures of typically $T = 10^5\text{--}10^6 \text{ K}$), a relativistic effect appears that changes the emission pattern to a slightly asymmetric shape, and this gives rise to harmonics of the cyclotron line (so-called gyroresonance lines). Solar active regions of the corona do exhibit this type of emission.

Gyrosynchrotron emission. At mildly relativistic speeds (electron temperatures of $T = 10^9\text{--}10^{10} \text{ K}$), the asymmetric effect becomes stronger, and many harmonics appear. In parallel,

the lines become broader so that they blend together into a continuum emission. Called gyrosynchrotron emission, this type of radiation is seen in solar and stellar flares.

Synchrotron emission. When electrons reach highly relativistic speeds, the emission becomes a narrow beam in the direction of motion, including many harmonics. The resulting spectrum, after averaging over the velocity distribution of the electrons, is shifted toward high frequencies (1000 times the cyclotron frequency) and is a continuous one, whose slope is characteristic of the electrons' energy distribution. Synchrotron emission is seen in extreme energy environments such as black holes, neutron stars, and some ultra-massive black holes at the center of galaxies.

Cross-References

- [Blackbody](#)
- [Bremsstrahlung Radiation](#)
- [Cosmic Background Radiation](#)
- [Electromagnetic Radiation](#)
- [Electromagnetic Spectrum](#)
- [Free-Free Emission](#)
- [Grey Body](#)
- [HII Region](#)
- [Photon](#)
- [Radiative Transfer](#)

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Radiative Recombination

► Electron Radiative Recombination

Radiative Transfer

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Radiative processes · Opacity · Scattering

Definition

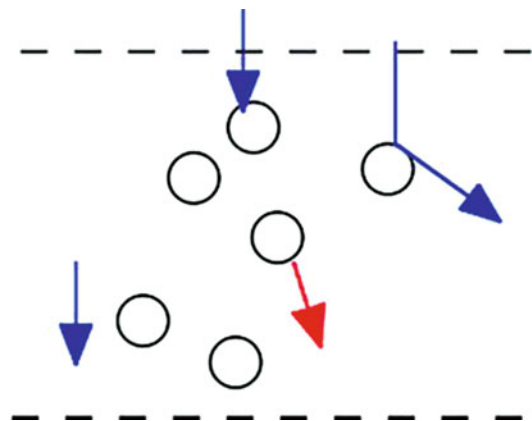
Radiative transfer is the theory describing how electromagnetic radiation is created, transmitted, absorbed, and scattered in a medium such as a planetary atmosphere, stellar photosphere, or interstellar medium. The medium can emit, absorb, and scatter radiation with a behavior that could vary strongly with wavelength according to the different species composing the medium and their physical state.

Overview

In astrophysics, if we except the objects of the solar system visited by probes, the intrinsic properties of a celestial object must be derived from the only available information: the observed radiation. To interpret the spectrum that is emerging from the atmosphere of a planet, an interstellar cloud or from the outer layer of a star, called the photosphere, it is necessary to model not only the production of radiation at any point of the medium but also the way it is locally absorbed or scattered in any direction. The emerging radiation, which the observer will collect, is the sum of the weighted contributions of all cells within the medium.

In addition, this modeling must be done at each wavelength, since most often emission, ► [scattering](#), or absorption processes exhibit a spectral dependence, generally related to the quantum properties of the species constituting the medium; these species will have very specific signatures, for instance, absorption or emission lines. The spectral information carried by the emerging radiation is generally very rich in terms of identification of species and of their physical state (temperature, density, ionization state): this is why it is generally admitted that astrophysics was truly born with ► [spectroscopy](#). The radiative transfer theory is thus a basic tool to interpret the spectra of stars, planets, or interstellar matter and to derive properties such as composition, temperature, and density in those media.

The radiation that propagates at a given point in a medium can appear, disappear, or change, as illustrated in Fig. 1. It appears when emitted by the particles of the medium: for instance, blackbody radiation by solid tiny particles or de-excitation of an atom between two quantum states. It disappears when it undergoes absorption by the inverse mechanisms; by the way, in that case, it contributes to heating the medium and thus to increasing emission, generally at other wavelengths. It changes when it undergoes scattering (Rayleigh, Thomson, or Mie scattering, depending on which



Radiative Transfer, Fig. 1 A photon, the basic *quantum* of light, that crosses a slab in a medium can suffer three types of interaction with the particles of the medium: it can be created (*red*), be absorbed, or be scattered (*blue*)

process is dominant), which modifies its direction of propagation and sometimes its frequency.

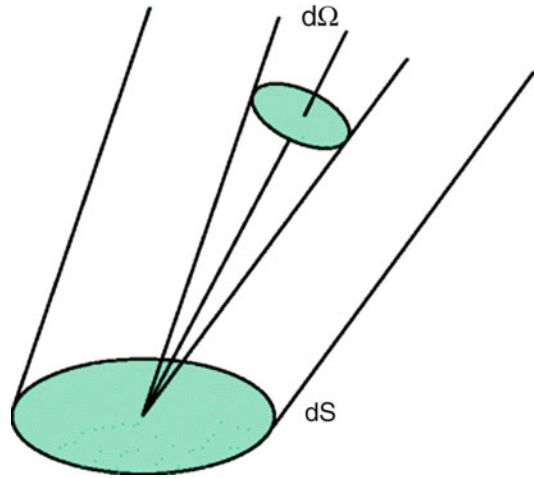
The radiation field intensity variations, in a given direction of propagation, can be described by a differential equation containing derivatives with respect to variables of position, direction, and time: the equation of radiative transfer. Most generally, a steady state is assumed, so that the dependence upon time is not considered. Despite this simplification, the multiplicity of parameters makes it generally difficult to solve analytically the radiation transfer equation, and numerical codes must be used.

Moreover, the radiation has an influence on the matter through which it is passing, causing heating that retroactively affects radiation emission. It follows that the problem is nonlinear and must be solved iteratively in most cases. In some situations, the number of position variables can be reduced to two or one if the geometry of the system permits (e.g., spherical symmetry). Another important simplification is to assume that certain quantities do not depend on wavelength. This approximation can be difficult to justify when it comes to constructing a spectrum in wavelength; however, the approximation called the *gray case*, which consists in ignoring the variation of absorption properties of the medium with wavelength, often allows us to obtain interesting and reliable results.

Basic Methodology

The three main quantities appearing in the transfer equation are the intensity of radiation, the ► **optical depth**, and the source function.

The intensity of radiation I_ν , also called specific intensity, characterizes the energy crossing a surface in a given direction. It is defined as follows: consider radiation contained in a solid angle $d\Omega$ in a frequency interval from ν to $\nu + d\nu$, crossing an elementary area dS perpendicular to the direction of propagation (see Fig. 2). It corresponds to a flux of radiant power dP , which clearly is proportional to dS , to $d\Omega$, and to $d\nu$, so that we can write $dP = I_\nu dS d\Omega d\nu$. The intensity of radiation I_ν is thus the energy per unit area per



Radiative Transfer, Fig. 2 In a given direction, one can consider the amount of radiation that crosses a surface dS and is contained in a solid angle $d\Omega$

unit time per unit frequency per unit solid angle, crossing a surface perpendicular to the beam of radiation. If radiation propagates in vacuum without interacting with the material, its intensity remains constant.

Optical thickness (=optical depth). When the radiation passes through a medium containing particles (dust grains, molecules, neutral or ionized atoms, electrons, etc.), this material can absorb or emit luminous energy. We characterize the absorptive capability of the medium by its absorption coefficient $|\nu$ which has the dimension of the inverse of a length (and is therefore measured in m^{-1} or more usually in cm^{-1}) and is defined so as the dimensionless quantity $|\nu ds$ represents the fraction of radiation absorbed along a path of length ds . This quantity defines the optical thickness of an infinitesimal slab, $d\tau_\nu = |\nu ds$, and the absorbed intensity is $dI_\nu = I_\nu d\tau_\nu$. For a finite slab, the optical thickness is $\tau_\nu = \int_0^s |\nu ds$.

There are several advantages to using this dimensionless quantity τ_ν rather than the space variables. One is that τ represents the actual number of particles of the medium accumulated in the beam, regardless of how the density of particles varies along the beam.

Finally, one introduces the quantity ϵ_ν which characterizes the luminous energy produced

within the medium itself: ε_v is the power per unit frequency per unit volume per unit of solid angle and therefore is expressed in $\text{W cm}^{-3} \text{sr}^{-1} \text{Hz}^{-1}$. Obviously, ε_v depends on the local density of emitting particles, while one could wish to deal with a function that describes the intrinsic emission per particle: this function, called the source function S_v , is simply the ratio ε_v/κ_v . An approximation often used in astrophysics is that the source function is equal to the Planck function. This hypothesis is known as local thermodynamic equilibrium (LTE) and assumes that the different energy levels of the atoms that can emit radiation are populated as if thermodynamic equilibrium prevailed. When scattering occurs, the source function is augmented by a term which is proportional to the intensity of radiation itself.

Using those three ingredients, I_v , τ_v and S_v , one can now write the radiative transfer equation, which is nothing but the energy balance in a small slab of given thickness and surface crossed by a beam of radiation:

$$dI_v/d\tau_v = -I_v + S_v.$$

This differential equation, when integrated along the direction of a given beam, leads to:

$$I_v = I_v(0)e^{-\tau_v} + \int_0^{\tau_v} S_v(t_v)e^{-t_v} dt_v$$

where $t_v = \int_{s_1}^{s_2} \kappa_v ds$ is the optical thickness between the point s_1 and the point s_2 . The physical meaning of this formula is almost straightforward: the first term represents the intensity of the input radiation attenuated by the crossing of the medium, and the second represents the added emissions of the different elementary volumes whose contribution is weakened by absorption between the emitting point and the point where the intensity is evaluated. The simplicity of the transfer equation is, however, apparent only; for instance, one must not forget that the source function itself may depend on the intensity, implicitly when radiative heating occurs and explicitly when scattering is present, leading to a nonlinear problem.

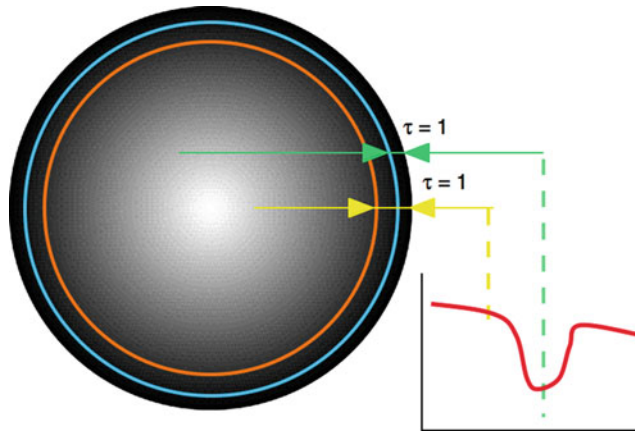
Despite this hidden complexity, there are several classical results that can be derived in simple cases. We mention here two of the most used.

The Beer-Lambert law. If there is no emission by the medium ($S_v = 0$), then the intensity follows the simple law: $I_v = I_v(0)e^{-\tau_v}$. The exponential declines mean that the extinction can be extremely efficient as soon as τ_v becomes larger than 1. For instance, consider the center of our Galaxy, which is seen through the layer of dust particles contained in the plane of the Galaxy. If the region is only dimmed by a mere factor of 10 in the near infrared where the optical depth is about 2.5, the same layer becomes a fully opaque wall at visible wavelengths with an attenuating factor of 10^{-10} , despite the fact that the optical depth is only ten times larger.

The Barbier-Eddington approximation. Let us assume that the source function S is a linear function of the optical depth measured along the line of sight: $S(\tau) = a + b\tau$. The integral form of the transfer equation reads then:

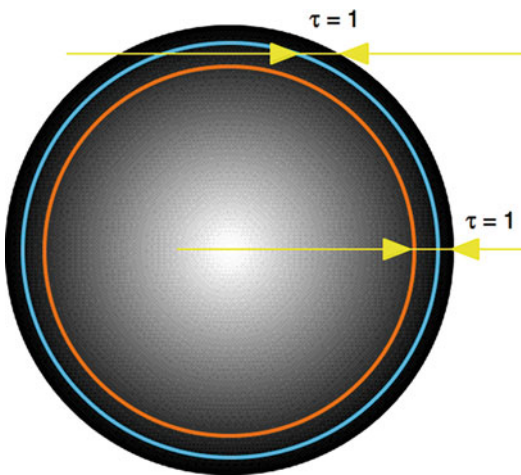
$$\begin{aligned} I &= \int_0^\infty S(\tau)e^{-\tau} d\tau = \int_0^\infty (a + b\tau)e^{-\tau} d\tau \\ &= a + b \equiv S(\tau = 1). \end{aligned}$$

The intensity I along a line of sight is then equal to the source function at the point along this line of sight located at unit optical depth. In other words, it looks as if the medium were best summarized by the layer at optical depth 1: deeper layers are too much attenuated to be seen, and shallower ones are too tenuous to be significant contributors. It happens that even when the assumption of linearity is not valid, the Barbier-Eddington approximation still gives very good orders of magnitude estimates, and, for instance, the spectrum of planetary atmospheres is qualitatively well explained when using this relation. Conversely, the temperature profile of a planet's atmosphere can be retrieved from the infrared spectrum by an inversion scheme based for its first steps on the Barbier-Eddington approximation. The Barbier-Eddington approximation explains also why



Radiative Transfer, Fig. 3 The absorption coefficient κ_ν is maximum at the center of a spectral line and decreases in the wings. The consequence is that – at the frequency corresponding to the center of the line – the layer of the star where $\tau = 1$ is closer to the star’s surface and thus

colder (the temperature increases toward the interior of the star). The emission from this cold layer is less intense than from the deeper and thus hotter layers: the *line* appears as a dip of intensity in the spectrum (*red curve*)



Radiative Transfer, Fig. 4 If we consider a beam of radiation coming from the edge of the stellar surface, the layer where $\tau = 1$ (the distance between the *arrow heads*) on the line of sight is closer to the star’s surface (*blue layer*) and thus colder than for the beam coming from the center of the stellar disk (*the orange layer*). The edge of the disk, also called the limb, thus appears darker than the center

absorption lines are seen in the spectra of stars, as illustrated in Fig. 3.

The Barbier-Eddington relation is also used to describe qualitatively and quantitatively the limb-darkening effect, providing a fairly good agreement with observations (see Fig. 4).

Cross-References

- ▶ [Absorption Cross Section](#)
- ▶ [Blackbody](#)
- ▶ [Bremsstrahlung Radiation](#)
- ▶ [Electromagnetic Radiation](#)
- ▶ [Electromagnetic Spectrum](#)
- ▶ [Extinction, Interstellar or Atmospheric](#)
- ▶ [Flux, Radiative](#)
- ▶ [Grey Body](#)
- ▶ [Limb Darkening](#)
- ▶ [Optical Depth](#)
- ▶ [Radiative Processes](#)
- ▶ [Scattering](#)
- ▶ [Spectral Line](#)
- ▶ [Spectroscopy](#)

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Radiative Transfer (Atmospheres)

Emmanuel Marcq

LATMOS/IPSL, UVSQ Université Paris-Saclay,
Sorbonne Université, CNRS, Guyancourt, France

Keywords

Processes: Extinction, Absorption, Scattering (Mie, Rayleigh), Emission · Concepts: Spectral radiance, Spectral flux, Stokes vector, Black body, Local thermodynamical equilibrium, Optical depth, Optical thickness, Single scattering albedo, Phase function, Phase matrix · Laws: Beer-Bouguer-Lambert law, Kirchhoff's law, Schwarzschild's law, Planck's law, Stefan's law, Wien's law · Methods: N-stream approximation, Single scattering approximation, Gray approximation, δ -Eddington approximation

Definition

Radiative Transfer is the study of the interaction between electromagnetic radiation and matter. Within planetary atmospheres, it is a major source of information (chemical composition, temperature, pressure, condensate characteristics such as density, rugosity, particle size, etc.).

Overview

General Concepts

Spectral Radiance

It is arguably the core concept of radiative transfer. $I_\nu(M, \hat{\mathbf{u}})$ represents the amount of electromagnetic power per elementary frequency $d\nu$ around a frequency ν , per elementary solid angle $d\Omega$ around the direction unit vector $\hat{\mathbf{u}}$, and per elementary surface dS around a point M orthogonal to $\hat{\mathbf{u}}$.

Depending on the unit system used for the spectral dimension, the previous definition may

swap frequency ν with wavelength λ or wavenumber $\tilde{\nu}$ instead.

$I_\nu(M, \hat{\mathbf{u}})$ can be thought as the mathematical idealization of an intuitive pencil beam of monochromatic light, and is conserved along $\hat{\mathbf{u}}$ in vacuum.

Spectral Flux Density

$I_\nu(M, \hat{\mathbf{u}})$ is an abstract quantity that cannot be directly measured. On the other hand, the derived quantity named *spectral flux density* $F_\nu(M, \hat{\mathbf{n}})$ and defined by:

$$F_\nu(M, \hat{\mathbf{n}}) = \iint_{4\pi \text{ sr}} I_\nu(M, \hat{\mathbf{u}})(\hat{\mathbf{u}} \cdot \hat{\mathbf{n}}) d\Omega(\hat{\mathbf{u}}) \quad (1)$$

can be (destructively) measured by a detector surface located in M and orthogonal to the unit vector $\hat{\mathbf{n}}$, since $F_\nu(M, \hat{\mathbf{n}})$ represents the net transport of radiative energy per unit area through the detector.

Radiative Processes

Emission occurs when energy is transferred from matter to the local radiation field.

Absorption occurs when energy is transferred from the radiation field to the local matter content.

Scattering occurs when the matter content alters the propagation of the radiative field (mainly its direction). In the usual case of *elastic* scattering, no net energy is transferred between matter and radiation, and the frequency of the scattered radiation remains unchanged.

Absorption and scattering both deplete any incident radiation beam entering a medium. For this reason, they are often grouped together under the umbrella term *extinction*.

Emission

Emission processes in planetary atmospheres fall into two main categories: *thermal* and *non-thermal*. Nonthermal processes, such as Brehmsstrahlung or airglows, usually involve charged particles found in upper atmospheres, whereas thermal emission is dominant in neutral atmospheres, which are dense enough to reach local thermodynamical equilibrium (LTE).

Blackbody

When photons and matter are fully coupled through numerous absorptions/emissions for all radiation frequencies, they adopt a common thermodynamical temperature T . The medium is then said to behave as a *blackbody*, and the radiation spectrum within obeys *Planck's law*:

$$I_\nu(M, \vec{u}) = B_\nu(T) = \frac{2h\nu^3}{c^2} \left[\exp\left(\frac{h\nu}{kT}\right) - 1 \right]^{-1} \quad (2)$$

or, using the equality $B_\lambda(T) d\lambda = B_\nu(T) d\nu$:

$$I_\lambda(M, \vec{u}) = B_\lambda(T) = \frac{2hc^2}{\lambda^5} \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1 \right]^{-1} \quad (3)$$

Brightness Temperature For any frequency ν , The function $T \rightarrow B_\nu(T)$ provides a one-to-one correspondence between spectral radiance and temperature. It then follows that this function can be inverted, so that there is always a well-defined T_ν^B value such as:

$$I_\nu = B_\nu(T_\nu^B) \quad (4)$$

T_ν^B is called *brightness temperature*, and can be thought as a conversion of the spectrum I_ν in temperature (Kelvin) units. When I_ν is of thermal origin, T_ν^B is often easier to discuss and interpret (see section “[Near-Nadir Thermal Sounding](#)”).

Wien's Law $B_\lambda(T)$ exhibits an absolute maximum for a wavelength $\lambda_{\max}(T)$. It can be shown that:

$$\lambda_{\max}(T) \times T \approx 2898 \mu\text{m} \cdot \text{K} \quad (5)$$

which provides a useful way to measure the temperature of a radiating black body or good natural approximations thereof (e.g., stars).

$B_\nu(T)$ also exhibits a maximum for a frequency $\nu_{\max}$, but $\nu_{\max} \neq c/\lambda_{\max}$

Stefan-Boltzmann Law Integrating of all frequencies and computing the thermal flux emitted per blackbody surface area over a hemisphere yields:

$$\int_\nu \int_{2\pi \text{ sr}} B_\nu(T) (\hat{\mathbf{u}} \cdot \hat{\mathbf{n}}) d\Omega(\hat{\mathbf{u}}) d\nu = \sigma T^4 \quad (6)$$

where $\sigma \approx 5,670 \cdot 10^{-8} \text{ W/m}^2/\text{K}^4$ is known as the *Stefan-Boltzmann constant*.

Kirchhoff's Law of Thermal Radiation In practice, physical bodies do not behave like blackbodies. Their emitted thermal radiation can be expressed as:

$$I_\nu(T) = \varepsilon_\nu(T) B_\nu(T) \quad (7)$$

where the dimensionless $0 \leq \varepsilon_\nu(T) \leq 1$ factor is called *emissivity*. The fraction of radiation absorbed by a medium $0 \leq a_\nu \leq 1$, called *absorptance*, is equal to the emissivity according to Kirchhoff's law.

If $a_\nu(T) = \varepsilon_\nu(T)$ does not depend on ν , then the object is sometimes referred as a *gray body*. Generally speaking, the adjective *gray* is synonymous with *independent from frequency/wavelength* in a radiative transfer context.

Beer-Bougher-Lambert Law

When an incident radiation beam enters a material medium, it is progressively weakened through extinction (absorption and scattering away from its direction). This weakening can be written:

$$\frac{dI_\nu}{ds} = -k_{\text{ext},\nu} \cdot I_\nu \quad (8)$$

where s is the spatial coordinate following the beam (curvilinear abscissa). The above equation is a definition of the *extinction coefficient* $k_{\text{ext},\nu}$. Beer-Bougher-Lambert law links the beam extinction to the local matter density following:

$$k_{\text{ext},\nu} = \sigma_{\text{ext},\nu} \cdot n = \kappa_{\text{ext},\nu} \cdot \rho \quad (9)$$

n being the local number density of particles responsible for the extinction, and $\sigma_{\text{ext},\nu}$ being

the extinction *cross-section* of these particles. Alternatively, one can define the *mass extinction coefficient* $\kappa_{\text{ext},\nu}$ and use the medium mass density ρ instead. Strictly speaking, Beer-Bougher-Lambert law is valid only wherever absorbers/scatterers are diluted in an otherwise transparent medium, like a gaseous planetary atmosphere.

Optical Depth and Optical Thickness

Section “[Beer-Bougher-Lambert Law](#)” suggests that dimensionless quantity τ_ν , whose elementary variation $d\tau_\nu$ is defined as:

$$d\tau_\nu = k_{\text{ext},\nu} ds = \sigma_{\text{ext},\nu} n ds \quad (10)$$

should be used. $\tau_\nu(s)$ is known as the *optical depth* along the radiation pencil beam in the medium. Also, the related quantity:

$$\Delta\tau_\nu(s_1, s_2) = \int_{s_1}^{s_2} d\tau_\nu = \tau_\nu(s_2) - \tau_\nu(s_1) \quad (11)$$

is known as the *optical thickness* of a material slab along the beam path. The limits $\Delta\tau_\nu \ll 1$ ($\Delta\tau_\nu \gg 1$ resp.) are called *optically thin* (*thick* resp.).

Radiative Transfer Equation Without Scattering

Formulation

Substituting τ_ν for s in Eq. (8) directly yields:

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu \quad (12)$$

valid for I_ν when no radiation source at frequency ν exists in the medium. Otherwise, a more general radiative transfer equation can be formulated:

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \quad (13)$$

where S_ν is known as the *source term*. Neglecting scattering, and when LTE at a temperature T is reached, then it can be shown that $S_\nu = B_\nu(T)$.

Formal Solution

Equation (13) can be integrated along the beam path, between, for example, $\tau_\nu = 0$ and $\tau_\nu = \tau^*$, yielding:

$$I_\nu(\tau^*) = I_\nu(0)e^{-\tau^*} + \int_{\tau'=0}^{\tau^*} S_\nu(\tau')e^{\tau^*-\tau'} d\tau' \quad (14)$$

whose interpretation is straightforward: the intensity at the exit of the pencil beam is the sum of two contributions, first the incoming intensity attenuated by the optical thickness of the whole medium, and second the contribution of all sources along the pencil beam, each attenuated according to the remaining optical thickness.

Equation (14) is valid only when S_ν is independent from the existing radiation field I_ν . This is the case at LTE when scattering can be neglected.

Absorption and Spectroscopy

Beer-Bougher-Lambert law does not deal with the variations of σ_ν (or equivalently κ_ν) with respect to ν , which is the central topic of *spectroscopy*. For extinction caused by condensed matter (e.g., aerosols in planetary atmospheres), these spectral variations are usually smooth and well understood if particle shapes, sizes, and complex refractive index are known (see section “[Scattering](#)”). Gaseous absorption is usually ascribed to whether line or continuum opacities.

Line Frequencies

A line is defined as a spectrally sharp opacity feature centered on a frequency ν_0 . This central frequency is directly related to the difference in energy between initial and final quantum states of the gas molecules: $h\nu_0 = hc\tilde{\nu}_0 = |E_{\text{[final]}} - E_{\text{[initial]}}|$. Spectral lines in gases are therefore associated with *transitions* between quantum states, and are usually classified into three categories:

Electronic Transitions between molecular electronic orbitals. Typical transition energy is a few eV, yielding photons in the visible/UV range.

Vibrational Transitions between quantum states of molecular bonds stretching. Typical transition energy is less than 0.1 eV, yielding photons in the infrared range.

Rotational Transitions between quantum states of molecular rotation. Typical transition energy is below 1 meV, yielding photons in the microwave range.

Moreover, rotational and vibrational levels are usually coupled according to *quantum selection rules*, creating *rovibrational* line systems grouped in two (or three) *branches*:

P-branch $\nu < \nu_c$ where ν_c is the frequency associated with the pure vibrational transition (no change in rotational levels).

Q-branch $\nu \approx \nu_c$. Not always present, depending on quantum selection rules for the molecules.

R-branch $\nu > \nu_c$.

Line Shapes

Spectral lines are not purely monochromatic. In planetary atmospheres, two main phenomena contribute to broadening them to neighboring frequencies.

Doppler broadening: Individual molecular lines are blue/red shifted due to their random thermal speed with respect to the observer. Results in a *Gaussian* broadening, with $\Delta\nu/\nu \propto \sqrt{T}$.

Collisional broadening: Loss of phase coherence according to the typical mean free path lifetime occurs due to collisions between molecules. Results in a *Lorentzian* broadening, with $\Delta\nu/\nu \propto P/\sqrt{T}$.

Doppler broadening dominates in high- T , low- P conditions typically found in upper atmospheres. Elsewhere, both kinds of broadening are of similar strength and must be taken into account together. This yields the so-called *Voigt profile* resulting from the convolution of the Gaussian and the Lorentzian line shape functions. However, the validity of Voigt profiles degrades quite quickly far away from the central frequency,

with most gases being somewhat less opaque than the Voigt profile would predict (*sub-Lorentzian* behavior).

Continuum Opacity

Even at frequencies far from spectral lines centers, dense and relatively cold gases exhibit some opacity, labeled *collision-induced absorption* (CIA). The underlying mechanisms are multiple and notoriously hard to model: summation of multiple wings from far-away spectral lines, formation of short-lived dimers during molecular collisions, with their own transient energy levels and line systems, mutual polarizations of otherwise non-polarized molecules, opening new “forbidden” lines, etc.

The final result is a spectrally smooth opacity occurring in all dense enough planetary atmospheres (typically a few bars or more), decreasing with T and ν , and proportional to P^2 (rather than P like spectral line opacities). They are named by listing involved molecular or atomic species (two or three at most): for example, H_2-H_2 , H_2-He , H_2O-CO_2 . One can note that even gaseous species without significant line absorption (such as noble gases or diatomic homonuclear molecules like N_2 and O_2) can and do contribute to the continuum opacity.

Scattering

Single Scattering Albedo ϖ_0

It is a dimensionless quantity which expresses the relative importance of absorption and scattering in local extinction. Defining k_{abs} and k_{sca} the local absorption (scattering resp.) coefficients, ϖ_0 is defined by:

$$\varpi_0 = \frac{k_{\text{sca}}}{k_{\text{sca}} + k_{\text{abs}}} \quad (15)$$

with previously (Eq. 8) defined $k_{\text{ext}} = k_{\text{sca}} + k_{\text{abs}}$. Therefore, $0 \leq \varpi_0 \leq 1$, with $\varpi_0 = 0$ implying no scattering as previously considered. For clarity's sake, the spectral index ν was omitted, although ϖ_0 depends on ν , usually increasing with increasing ν .

Phase Function P

It describes the angular distribution of scattered radiation, depending on both incoming $\hat{\mathbf{u}}$ and outgoing $\hat{\mathbf{v}}$ directions. More specifically,

$$dp(\hat{\mathbf{u}}, \hat{\mathbf{v}}) = P(\hat{\mathbf{u}}, \hat{\mathbf{v}}) \frac{d\Omega(\hat{\mathbf{v}})}{4\pi \text{ sr}} \quad (16)$$

where dp is the probability for a photon to be scattered from the direction $\hat{\mathbf{u}}$ to the direction $\hat{\mathbf{v}}$ within an elementary solid angle $d\Omega(\hat{\mathbf{v}})$. The normalizing factor $(4\pi \text{ sr})^{-1}$ is not mandatory but follows the most usual convention, leading to simpler expressions (e.g., the isotropic phase function becomes simply $P(\hat{\mathbf{u}} \cdot \hat{\mathbf{v}}) = 1$, and phase functions are always dimensionless).

Asymmetry Parameter g For the simplest scattering cases (see, e.g., *Rayleigh scattering* and *Mie scattering* entries), P is a function of the only variable $\cos(\Theta) = \hat{\mathbf{u}} \cdot \hat{\mathbf{v}}$. Θ is called the *scattering angle*.

The average value of the scattering angle, g , defined as:

$$\begin{aligned} g &= \langle \cos \Theta \rangle \\ &= \frac{1}{4\pi \text{ sr}} \iint_{4\pi \text{ sr}} (\cos \Theta) P[\cos(\Theta)] d\Omega \\ &= \frac{1}{2} \int_{-1}^1 \mu p(\mu) d\mu \end{aligned} \quad (17)$$

with the standard substitution $\mu \stackrel{\text{def}}{=} \cos(\Theta)$. g is called the *asymmetry parameter*. $g = 1$ is equivalent to purely forward scattering, whereas $g = -1$ would be purely backwards scattering. Isotropic scattering implies $g = 0$, but the reciprocal assertion is not valid.

Source Term Expression Including Scattering

Taking scattering into account in Eq. (13) is possible, but requires a change in the expression of the source term S_v , namely:

$$\begin{aligned} S_v(\hat{\mathbf{u}}) &= (1 - \varpi_0) B_v(T) \\ &+ \frac{\varpi_0}{4\pi} \iint_{4\pi \text{ sr}} P(\hat{\mathbf{v}}, \hat{\mathbf{u}}) I_v(\hat{\mathbf{v}}) d\Omega(\hat{\mathbf{v}}) \end{aligned} \quad (18)$$

The fact that the source term for any beam direction $\hat{\mathbf{u}}$ includes contributions from spectral radiances in all directions $\hat{\mathbf{v}}$ implies that there is no more closed-form solutions when $\varpi_0 \neq 0$ ($\varpi_0 = 0$ leads to Eq. (14)). Various approximations to deal with this inconvenient fact are described in section “[Solving Methods and Approximations](#).”

Common Scattering Regimes

The two most common scattering regimes will be discussed in separate entries:

Rayleigh scattering is valid when the size of scatterers is much smaller than the radiation wavelength.

Mie scattering is valid for homogeneous, dielectrical and spherical scatterers of any radius.

An often used analytical phase function is the *Heney-Greenstein* phase function $P_{HG}(\Theta)$ defined by:

$$P_{HG}(\Theta) = (1 - g^2)(1 + g^2 - 2g \cos \Theta)^{-3/2} \quad (19)$$

which depends only on its asymmetry parameter g and the scattering angle Θ , and qualitatively similar to more physically realistic (albeit more complex) phase functions.

Polarization

All previous sections considered a *scalar* model of radiation, where knowing the sole (scalar) quantity I_v completely defined the radiation field. This model works well in absence of scattering and with purely thermal (therefore unpolarizing) sources, but scattering often leads to *polarization* of radiation, yielding additional insights on the scattering medium.

Stokes Formalism

The most common formalism to deal with polarization in atmospheric radiative transfer is to use the *Stokes* formalism, replacing I_v with a so-called

Stokes vector: (I_v, Q_v, U_v, V_v) , dependent on a local reference frame.

I : Total radiative intensity, equivalent to I_v the scalar formalism.

Q, U : Linearly polarized intensity components.

The dimensionless quantity $\frac{\sqrt{Q^2+U^2}}{I}$ is called *degree of (linear) polarization*.

V : Circularly polarized intensity. In planetary atmospheres, $V \ll U, Q$ usually.

Since scattering is the main cause of polarization in planetary atmospheres, a scalar phase function must be replaced by a *phase matrix* operating on the four components of the Stokes vector. Another technical difficulty arises from the necessity of aligning the Stokes reference frame with the scattering geometry, requiring the use of rotation matrices.

Basic Methodology

Observational Geometries

Angles

Except for in situ observations from the surface of solar system planets (Earth especially), most of our planetary atmospheric observations are performed remotely. From any location within a planetary atmosphere, there are therefore at least two (more often three) privileged directions:

- First, since planets are by definition in hydrostatic equilibrium, there is a well-defined local upwards (zenith) direction.
- Second, toward the observer's location.
- Third, if the radiation source is external (e.g., a star), toward this external illumination source.

These directions define the following angles:

- Between the upwards direction and the star's: *stellar (or solar) zenith angle (SZA)*
- Between the upwards direction and the observer's: *emission angle*

- Between the star's and the observer's: *phase angle*

Typology of Observations

When the emission angle is small enough so that the beam path in the atmosphere is comparable with the atmospheric vertical thickness, then observations are said to be *near nadir* (or *nadir* if emission angle is close to 0).

When emission angle approaches 90° , then observations are performed in *limb* geometry. Special sub-cases of limb observations arise when source-target-observer are nearly aligned:

- If the apparent source size is small compared to the observation target (e.g., a faraway star compared to a much closer planet), then it is an *occultation* observation.
- If the apparent source size is comparable or even larger than the target, then it is a *transit* observation, primary transit if the source is located behind the target ($\approx 180^\circ$ phase angle), secondary transit if the target is located behind the source ($\approx 0^\circ$ phase angle).

Plane-Parallel Approximation

In case of a near nadir observation, and since most planetary atmospheres are thin (more precisely, their scale height is small compared to the planetary radius), then the planetary curvature may be neglected in computations, with the atmosphere being divided in horizontal, homogeneous layers – only the vertical variations are considered. These simplifying assumptions are known as the *plane-parallel approximation*, and yield quantitative results that are valid up to a few percents when both emission angle (and SZA when relevant) do not exceed $\sim 70^\circ$.

In this approximation, it is customary to use a common τ_v coordinate along the vertical axis ($\hat{\mathbf{z}}$ unit vector in the local upwards direction), set to 0 in outer space and increasing downwards. In such a case, the slant optical depth τ_v^s for a radiation beam (along $\hat{\mathbf{u}}$) must be corrected by the *airmass* factor μ : $d\tau_v^s = -\mu d\tau_v$ with $\mu = \hat{\mathbf{z}} \cdot \hat{\mathbf{u}}$. Equation (13) using this new vertical τ_v coordinate then becomes:

$$\mu \frac{dI_v}{d\tau_v} = I_v - S_v \quad (20)$$

1D Spherical and Pseudo-spherical Geometry When emission angle and/or stellar zenith angles are too large for the plane-parallel approximation, it is possible to take into account the planetary curvature, while still ignoring horizontal variations. This is known as the *1D (radial) spherical geometry*. As a compromise, when the curvature may be taken into account only for the incoming and outgoing radiation beams by altering the expression of μ accordingly, while still computing multiple scattering within the atmosphere according to the plan-parallel formalism. Such a choice is labeled *pseudo-spherical geometry*.

Solving Methods and Approximations

Monte Carlo Methods

Monte Carlo (MC) methods provide approximate solutions to radiative transfer problems by simulating the history of a large (but finite) number of “photons” chosen to be representative of the whole radiation field. Radiative processes are modeled as random events (absorption, emission, scattering) following probability distributions matching the known medium properties (phase function, extinction, etc.).

Advantages These models can rely on very few simplifying assumptions. Therefore, they offer a “last resort” solution for complex situations (e.g., 3D scattering within spatially resolved clouds with no obvious symmetries). Another major advantage is that they can be shown to converge to the exact solution when the number of simulated photons becomes arbitrarily large.

Drawbacks The above mentioned convergence is a special case of the law of large numbers, and so improves very slowly with the number N of simulated photons ($\propto N^{-1/2}$). MC methods then require much longer computation times compared to other methods. As a consequence, their use is somewhat restricted to specific situations where

other methods fail and/or as validation schemes against which other methods are validated.

N -th Order Scattering Approximations

Another way to solve the radiative transfer equation with scattering is to distinguish between the order of scattering: first, the radiative transfer equation is analytically solved neglecting any scattering (zeroth order). Then, using this radiation field, the extra scattering source term may be estimated using Eq. (18), calculating a corrected radiation field (first-order approximation). This process may then be iterated and will converge to an exact solution.

Unfortunately, convergence is very slow and works well only in the limit of vanishing scattering optical depths ($\omega_0\tau \ll 1$). It is also quite cumbersome to compute past the very first most terms, so that only the first order *single scattering approximation* is encountered in practice.

N -Stream Approximations

N -stream approximations are a family of radiative transfer solving methods that parameterize the angular dependency of I_v . Common ways to proceed are (Acquista et al. 1981):

- Assigning constant values to I_v in several discrete angular intervals. A common form of the *two stream* approximation is given by, for example, $I(\tau, \mu > 0) = I^+(\tau)$; $I(\tau, \mu < 0) = I^-(\tau)$. This yields in turn $F(\tau) = \pi [I^+(\tau) - I^-(\tau)]$.
- Assuming a polynomial variation of $I(\tau, \mu)$ with respect to μ , also known as *Eddington approximation* (for a first degree polynomial).
- Choose a finite number of “representative” angles μ_i , and weights w_i , to compute angular integrals; $\int_{-1}^1 f(\mu) d\mu \approx \sum_{i=-M}^M w_i f(\mu_i)$. These are known as *quadrature approximations*.

All the aforementioned methods are computationally equivalent with the right choice of assumptions. Most numerical solvers use a special case known as the *discrete ordinate method*, where I_v is expanded in a truncated series of orthogonal Legendre polynomials with respect to μ . In such a case, integrals found in the source

function are transformed into a finite sum of Legendre polynomials components of I_v . Solving the radiative transfer equation therefore becomes a finite dimension linear algebra problem that can be solved through matrix inversion.

Doubling-Adding Method In realistic situations, optical properties of the atmosphere (ϖ_0 , phase function, etc.) are varying with (optical) depth, that is, planetary atmospheres are inhomogeneous media. In such a case, it is customary to divide the atmosphere into a finite number of optically thin and homogeneous layers, where radiative transfer equations can be solved to yield transmission/reflection matrices that link the angular components of I_v below and above these layers.

These transmission/reflection matrices for two given layers may then be used to compute the transmission/reflection for the two layers taken as a whole. A homogeneous, optically thick layer can therefore be divided in 2^n optically thin layers, with n iterations of *doubling*, whereas inhomogeneous media will require *adding* layers of different properties. In the two stream approximation, matrices R and T become scalar: $I^+(\tau_{\text{top}}) = RI^-(\tau_{\text{top}})$ and $I^-(\tau_{\text{bottom}}) = TI^+(\tau_{\text{top}})$. In this case, combining layers 1 and 2 yields:

$$T_{1+2} = \frac{T_1 T_2}{1 - R_1 R_2}; \quad R_{1+2} = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \quad (21)$$

The process is iterated until the transmission/reflection properties of the whole atmosphere are computed.

δ -Eddington Approximation Most phase functions exhibit a strong forward scattering peak that may be difficult to take into account with quadrature-based N -stream methods for reasonable values of N . A common way to circumvent this issue is to separate the forward peak, modeled as a Dirac δ distribution centered on $\Theta = 0$, from the smoother phase function $\tilde{P}$ at other scattering angles: $P(\Theta) = f\delta(\Theta) + (1 - f)\tilde{P}(\Theta)$. This is called the δ -Eddington approximation (Joseph et al. 1976).

Since purely forward scattering is equivalent to no scattering at all, this approximation results in scaling laws applied to derive new values τ' and ϖ'_0 of τ and ϖ_0 to be used with the smooth $\tilde{P}$ phase function, with:

$$\tau' = (1 - \varpi_0 f)\tau \quad (22a)$$

$$\varpi'_0 = \frac{(1 - f)\varpi_0}{1 - \varpi_0 f} \quad (22b)$$

k -Correlated Methods

The most exact and straightforward way to compute a full spectrum is the *line-by-line* method, where the spectrum is discretized in a finite number of frequencies, and radiative transfer equation solved independently for each frequency. A major drawback of this method arises when the optical properties of the medium exhibit strong spectral variations (e.g., multiple narrow spectral lines). In such a case, the required narrow spectral sampling results in prohibitively long computation times, even when the fully resolved spectrum is not needed (e.g., to compute spectrally integrated radiative heating rates in a general circulation model).

In such a case, within spectral bands where optical properties other than line absorption can be averaged smoothly, it becomes more interesting to compute the cumulative distribution of opacity in the considered spectral band. This distribution can be discretized, yielding a finite number of paired values ($\tau_i, \Delta g_i$) where Δg_i is the relative measure of the spectral interval where opacity (including line opacity) is close to τ_i , (with $\sum_i \Delta g_i = 1$ by definition). Radiative transfer equation may then be solved for each τ_i (yielding a “partial” radiance I_i) and the proper average value of I in the spectral band is finally given by $I = \sum_i \Delta g_i I_i$. This is called the k -distributed (or k -correlated) method. The main advantage of this method is that the number of total g_i bins required (typically a dozen) to reach a satisfying agreement with fully resolved line-by-line calculations is much smaller than the number of frequencies required to resolve the full spectrum.

Key Research Findings

Due to the ubiquity of radiative transfer in all astronomy-related fields, almost all of our observational knowledge about exoplanetary atmospheres makes use of radiative transfer at some point.

Applications

Near-Nadir Thermal Sounding

In plane-parallel formalism and for an optically thick atmosphere, the thermal emission measured by a remote observer can be expressed as:

$$\begin{aligned} I_v(\tau_v = 0, \mu) &= \int_{p=0}^{\infty} WF_v(\mu, p) B_v[T(p)] d \ln p \\ &= \int_{p=0}^{\infty} CF_v(\mu, p) d \ln p \end{aligned} \quad (23)$$

WF (CF resp.) is named *weight (contribution resp.) function*. Under simplifying hypotheses (isothermal hydrostatic atmosphere, no scattering, well mixed absorber whose cross-section is independent from pressure), it can be shown that WF follows a *Chapman function*, peaking within an atmospheric scale height around an altitude where $\tau_v = \mu$. Therefore, in pure nadir viewing, thermal sounding is most sensitive to the $\tau_v = 1$ level, and higher emission angles probe higher altitudes $\tau_v < 1$ due to the airmass factor which magnifies slant absorption.

It must be however noted that when the atmosphere is not isothermal, CF and WF can differ significantly due to the strong variation of $B_v(T)$ at higher frequencies. Also, scattering must be negligible for proper retrievals of temperature and composition detailed hereafter.

Temperature Sounding

When the absorber is well-mixed (e.g., CO_2 on Mars and Earth), the thermal spectrum can be used to retrieve the temperature profile within a given range of pressures: at frequencies where the absorber is less (more resp.) opaque, most of the

thermal emission originates from deeper (shallower resp.) layers, possibly including a surface contribution for optically thin atmospheres around telluric planets. In other words, the thermal spectrum, converted in brightness temperatures (see section “[Blackbody](#)”), is indicative of the physical temperature at the $\tau_v = \mu$ level.

As a consequence, and somewhat counter-intuitively, thermal spectrum may display *emission* as well as absorption lines, depending on the temperature gradient within the probed region ($dT/dz > 0$ leads to emission lines, since the probed altitude is located higher near the center of spectral lines; and conversely $dT/dz < 0$ leads to absorption lines). A corollary is that an isothermal profile $dT/dz = 0$ results in a featureless thermal spectrum whose brightness temperature is equal to the isothermal temperature.

Composition Sounding

Once the temperature profile $T(P)$ is known, for example, using the method above, information about the vertical profile of other absorbing species in the thermal spectrum may be measured, provided their spectral properties are known (through theoretical computations and/or laboratory measurements). The basic idea is as follows: measuring the brightness temperature in spectral lines caused by a given species of unknown vertical profile yields the pressure corresponding to the $\tau_v = \mu$ level, since $T(P)$ is known. This, in turn, can be converted into the column density of this absorbing species above the probed level. Therefore, the thermal spectrum contains information about the column densities over different levels as τ_v differs with ν , and differentiating these column densities yields the vertical abundance profile of the absorbing species within the probed pressure range.

Near-Nadir Scattered Light

Optically Thin Atmospheres

A commonly encountered situation is when clear, upper atmospheric layers (optically thin) are located above an optically thick “floor” (e.g., a planetary surface, or an optically thick cloud deck). In such a case, and provided that the

bidirectional reflectance distribution function (BRDF) $R(\hat{\mathbf{u}}, \hat{\mathbf{u}}')$ between the incidence direction $\hat{\mathbf{u}}$ and the emergence direction $\hat{\mathbf{u}}'$ (μ and μ' airmasses resp.) of the floor is known, scattering in the clear atmosphere can be safely neglected. Any absorption features in the reflected spectrum can then be used to retrieve the *column density* a of the absorbing species above the backscattering floor:

$$I(\tau = 0, \hat{\mathbf{u}}') = I(\tau = 0, \hat{\mathbf{u}})R(\hat{\mathbf{u}}, \hat{\mathbf{u}}') \times \exp\left[-\left(\frac{1}{\mu} + \frac{1}{\mu'}\right)\sigma_{\text{abs}}a\right] \quad (24)$$

In this case, absorbing species always exhibit absorption lines (dT/dz does not matter), since, unlike the thermal emission, no radiation sources are present in the atmosphere which is only illuminated from above.

Optically Thick Atmospheres

For a semi-infinite homogeneous atmosphere in the two stream formalism, it can be shown that its albedo Λ is given by:

$$\Lambda = \frac{1 - \sqrt{1 - \varpi_0}}{1 + \sqrt{1 + \varpi_0}} \quad (25)$$

and the average maximal optical depth $\langle\tau\rangle$ visited by backscattered photons is such as $\langle\tau\rangle \propto (1 - \varpi_0)^{-1/2}$. Therefore, observed albedo Λ is a good proxy for the maximal optical depth probed by the back-scattered radiation, which in turn can be used to estimate column densities of species located above this effective backscattering level as described above. Also, this implies that for nearly conservative scattering ($\varpi_0 \approx 1$), $\langle\tau\rangle \gg 1$, so that taking into account very deep atmospheric layers becomes mandatory.

Limb Observations

Opacity Amplification

In a purely limb geometry where the radiation beam has an impact parameter z_0 (closest approach altitude), and assuming that the atmospheric opacity is decreasing following a scale height H (equal to the atmospheric scale height for a well-mixed constituent), then the ratio

between the slant opacity along the tangent beam and the nadir optical depth above z_0 is given by:

$$\frac{\tau_{\text{slant}}(z_0)}{\tau_{\text{nadir}}(z_0)} \approx \sqrt{\frac{2\pi(R + z_0)}{H}} \quad (26)$$

Since $R \gg H$, this results in a dramatic opacity amplification that is especially well-suited to measure minute amounts of absorbers/scatterers in a narrow altitude range centered on z_0 . Conversely, layers located below an optical depth $\tau_{\text{nadir}} \sim \sqrt{H/R} \ll 1$ cannot be accessed through limb observations, unless using a very powerful illumination source (e.g., the Sun for solar system atmospheres) visible even through large values of τ . This is also the case for transit spectroscopy of extrasolar atmospheres.

Inhomogeneous Atmospheres

When spherical symmetry can be assumed and occultation geometry can be precisely measured, a commonly used method to retrieve vertical profiles of opacity is the *onion peeling method*: during the ingress/egress of a star through a planetary atmosphere, the properties of the topmost atmospheric layer where extinction can be measured can be derived assuming a homogeneous layer. Once the topmost layer is characterized, then observations within the second layer located immediately below can also be retrieved, and the process can be repeated until extinction becomes too large. This method requires an excellent knowledge of the tangent altitude of the occulted star through the planetary atmosphere, and a suitable trade-off between signal-to-noise and vertical resolution through the required integration time.

Refractivity Measurements

In the radio range where atmosphere is almost transparent, the differential refraction of tangent radio beams originating from, for example, an orbiter – the lower part of the beam being more refracted than the upper part – leads to a divergent spread and additional dimming of the incoming beam compared to straight-line propagation out of the atmosphere, as well as an additional phase shift. This additional dimming is inversely proportional to the atmospheric scale height, so that

temperature profiling (assuming hydrostatic equilibrium) is possible in atmospheric layers that are located too deep for their thermal radiation to be used.

Radiative Balance

Besides remote sensing, radiative transfer is fundamental to understand the energy fluxes within an atmosphere and its thermal structure. As an example, when the effective altitude of stellar radiation absorption is located below the effective altitude of thermal infrared emission to outer space, then the infamous phenomenon of *greenhouse effect* occurs.

Another quantity derived from radiative transfer calculations and important to assess the dominant physical processes occurring in a planetary atmosphere is the *radiative time constant* t_{rad} , defined as:

$$\frac{\partial \Delta T}{\partial t} = -\frac{\Delta T}{t_{\text{rad}}} \quad (27)$$

where ΔT is a small temperature disturbance with respect to the local radiative equilibrium temperature T : $\Delta T \ll T$. t_{rad} can thus be thought as a relaxation time toward radiative equilibrium. It can be shown that $t_{\text{rad}} \propto \frac{\rho C_p}{T^3}$, so that radiative processes act much faster for hotter atmospheres.

Future Directions

The ever-increasing available computing power enables more and more sophisticated and exact approximations in solving the radiative transfer equation. Therefore, most of the effort goes into a better determination of the optical properties of atmospheric layers:

- Better determination of aerosol phase functions, beyond the simpler models (Rayleigh, Mie).
- Better theoretical models of absorption line shapes.
- Theoretical improvements and laboratory measurements of continuum gaseous absorption for a wider range of temperature and pressure. These two latter items together constrain the spectral location and transparency of so-called

atmospheric windows and therefore crucial for radiative budget balance and remote sensing.

- Expand and improve the existing databases for absorption lines and continuum gaseous opacity with weaker lines and a more diverse array of gaseous species, especially for “exotic” exoplanet atmospheres from a solar system centered point of view.

Cross-References

- [Absorption Cross Section](#)
- [Atmospheric Modeling, Radiative-Convective Equilibrium](#)
- [Atmospheric Retrieval for Exoplanets](#)
- [Greenhouse Effect](#)
- [Mie Scattering](#)

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Radical

Steven B. Charnley
Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Free radical](#)

Definition

Chemically, a radical is an atom, molecule, or ion containing an unpaired electron. As such, radicals are very reactive.

Radio Astronomy

Philippe Zarka
LESIA, Observatoire de Paris, CNRS, PSL, SU,
UPC, Meudon, France

Keywords

Antennas · Arrays · Coherence · Coherent detection · Correlation; Heterodyne · Interferometry · Noise · Plasmas · Polarization · Propagation · Radio waves · Receivers · Protoplanetary disks · Exoplanetary radio emission · Star-planet interaction

Synonyms

[Astronomy using radio waves](#); [Long wavelength astronomy](#)

Acronyms

ALMA	Atacama Large Millimeter/ submillimeter Array (ESO, Chile)
ASKAP	Australian Square Kilometre Array Pathfinder (Australia)
ATCA	Australia Telescope Compact Array (Australia)
COBE	Cosmic Background Explorer
DM	Dispersion measure: $DM = \int_L N_e \, dL$
DSP	Digital signal processor
f_{ce}	Cyclotron frequency: $f_{ce} = eB/2\pi m_e$; $f_{ce} \text{ (Hz)} = 2.8 \times 10^{10} \text{ B (T)}$
FIR	Far infrared
f_{pe}	Plasma frequency: $f_{pe} = (1/2\pi)$ $(N_e e^2/\epsilon_0 m_e)^{1/2}$; $f_{pe} \text{ (Hz)} = 9 \, N_e^{1/2}$ (m^{-3})

FoV	Field of view
FPGA	Field-programmable gate array
IRAM	Institut de Radio Astronomie Millimétrique (France)
LH	Left-handed (circular or elliptical polarization)
LOFAR	LOw Frequency ARray (the Netherlands & Europe)
LWA	Long Wavelength Array (USA)
mm/sub- mm	Millimeter/sub-millimeter wavelength ranges
MWA	Murchison Widefield Array (Australia)
NenuFAR	New extension in Nançay upgrading LOFAR (France)
RAE	Radio Astronomy Explorer 1 & 2 satellites (1968–1973)
RFI	Radio frequency interference
RH	Right-handed (circular or elliptical polarization)
SKA	Square Kilometer Array (Australia & South Africa)
SPI	Star-planet interaction
UTR-2	Ukrainian T-Shape Radiotelescope, mark II (Ukraine)
VLA	Very Large Array (USA)
VLBI	Very Long Baseline Interferometry

Definition

Radio astronomy describes the techniques employed, from antennas to receivers, to receive and measure long wavelength electromagnetic radiation (radio waves). The specificity of these techniques, by contrast with optical or high-energy astronomy, is the coherent detection of the wave electric field (amplitude E and phase φ), instead of the mere intensity ($\langle E^2 \rangle_{\Delta t}$). This makes ► [interferometry](#) easier, compensating for the poor angular resolution intrinsic to long wavelengths. Radio emissions are produced by processes often different from those in the optical range. These include cyclotron and synchrotron emissions, bremsstrahlung, molecular and atomic transitions, and various coherent processes. Radio astronomy is especially adapted to probing ► [plasmas](#) (ionized/magnetized matter) as well as cold matter.

History

Radio astronomy is a recent branch of astronomy, born in the 1930s at low frequencies (22 MHz) with K. Jansky's detection of the radio emission from terrestrial lightning and from the Galactic center. It strongly developed along with RADAR techniques during World War II, after which detection of the Sun at 0.15, 3, and 10 GHz was reported. Discoveries accumulated during the late 1940s and 1950s, with the discovery of the radio emissions from the Moon (thermal), radio galaxies (nonthermal), and Jupiter (coherent). A major milestone was the discovery of the ubiquitous 21-cm line due to the hyperfine structure of neutral hydrogen (H_I), allowing astronomers to map the Milky Way as well as to observe the distant Universe. Major radio observatories were created in the 1950s (Cambridge, Jodrell Bank, Westerbork, Parkes, Greenbank, Arecibo, Nançay...). The 1960s saw the discovery of pulsars, quasars, the natural radio emission of the Earth itself, the first measurements of molecular lines, and the discovery in 1965 of the famous 3 K radiation, relic and proof of the Big Bang. In the 1960s and 1970s, arrays of antennas and interferometers were developed, along with the underlying theory (aperture synthesis). The 1970s and 1980s brought the first era of radio astronomy from space, with RAE satellites, Voyager space probes, and many others. Radio astronomy conquered ever-higher frequencies, with the IRAM instruments dominating the millimeter range since the 1980s. The 1990s saw the discovery of the fluctuations of the 3 K radiation by COBE, as well as the discovery of the first extra-solar planet (around a pulsar in 1992). The years 2000–2010 mark the start of giant arrays (LOFAR, ► [ALMA](#), precursors for SKA...) as well as always more sophisticated spaceborne radio instruments (onboard Cassini, Stereo, Parker Solar Probe, or Planck...).

Overview

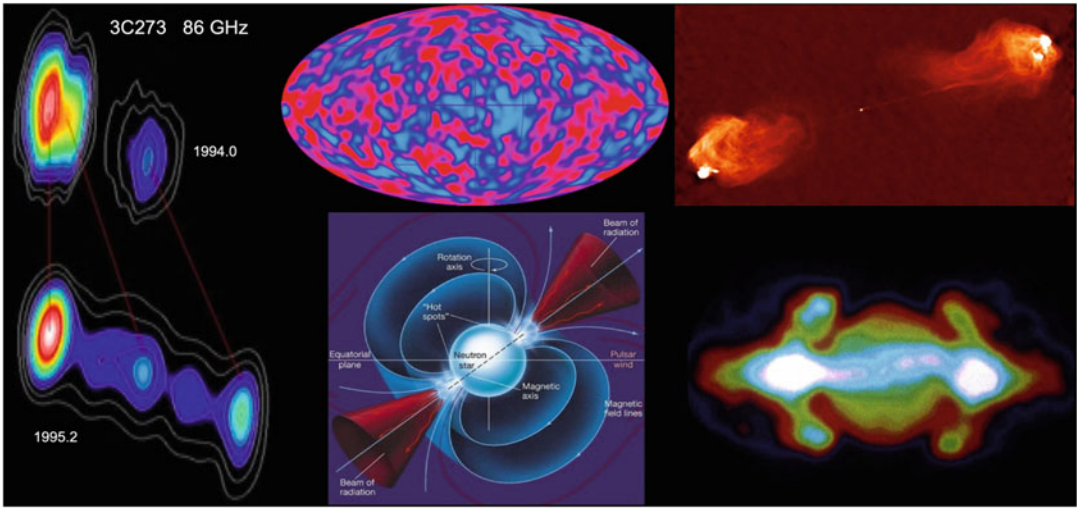
Specificity

The radio frequency range is defined by two criteria: (1) the transparency of the Earth's

atmosphere, between atmospheric absorption at short wavelengths and ionospheric reflection at long wavelengths defining a broad window $\sim 10 \text{ MHz} - 1 \text{ THz}$ ($\lambda = 30 \text{ m}$ to $\sim 0.3 \text{ mm}$); (2) the capability to coherently detect the wave electric field (amplitude E and phase ϕ), instead of its mere intensity ($\langle E^2 \rangle_{\Delta t}$), only limited by available technology (oscillators, mixers...). The upper frequency limit increases with time, reaching presently the THz range. For example, the instrument HIFI onboard the Herschel satellite covers the range 490–1902 GHz, using coherent (heterodyne – see below) detection techniques and superconducting (SIS) mixers.

Radioastronomy permits us to investigate sources and physical processes different from the optical range. For example (Fig. 1), radio images of Jupiter are dominated by its huge radiation belts, emitting intense polarized synchrotron emission; radio galaxies are generally two-lobed in radio, revealing immense jets; pulsars (rotating magnetized neutron stars) were discovered and long known only in the radio range. About physical processes, the Planck and Wien laws tell us that the thermal emission of cold bodies (typically $< 100 \text{ K}$) dominates in the radio range, in which the spectrum is simply proportional to frequency squared (Rayleigh-Jeans law). But many nonthermal emission processes are also active: cyclotron and synchrotron, bremsstrahlung (free-free), atomic and molecular lines, and various coherent processes. Wave scattering by dust or atomic Hydrogen varies as $1/\lambda^n$ and is thus weak in the radio range, permitting the observation of a large fraction of the Milky Way, including its central regions.

Technical specificities of the radio range include a low photon noise even at low fluxes (each photon carries little energy), poor angular resolution (λ/D at large λ), high temperature of the sky (Galactic background at longer wavelengths, of temperature $T_{\text{sky}} \sim 60/\lambda^{2.55} \text{ K}$ with λ in m), and strong pollution by natural and man-made radio frequency interference (RFI), particularly at longer wavelengths. These inconveniences are compensated by the data processing possibilities offered by coherent detection and high time and frequency resolutions, e.g., using a combination



Radio Astronomy, Fig. 1 Radio astronomical sources (from left to right and top to bottom): Very Long Baseline Interferometry (VLBI) observations of quasar 3C273 at two epochs; 3 K fluctuations map by Cosmic Background

Explorer (COBE); Radio image of the lobes of the Cygnus A radio galaxy at 5 GHz; Sketch of a pulsar environment and radio beams; Jupiter's synchrotron map from radiation belts

of phased arrays of antennas, interferometry, and RFI mitigation techniques. Both RFI and the sky background are lower in the mm/sub-mm domains, while emission from dust grains becomes important in the far infrared (FIR). Ground-based mm/sub-mm/FIR observations are strongly affected by the Earth's atmospheric emission and absorption. Observations at these wavelengths require space observatories, such as the ESA cornerstone mission Herschel which observes in the 55–670 μm range (490 GHz–6 THz).

Polarization and Propagation

Coherent detection allows for accurate measurements of wave polarization (which characterizes the wave electric field in the plane perpendicular to the wave vector). Polarization may linear, circular in the right-hand or left-hand sense, or elliptical. A fraction of the wave energy may be unpolarized, i.e., correspond to wave packets with random E-field orientation in the wave plane. Wave intensity and polarization is fully described by the 4 Stokes parameters I (intensity), Q, U (linear polarization), and V (circular polarization), the polarized fraction being $(Q^2 + U^2 + V^2)^{1/2}/I$. It should be noted

that wave polarization can be uniquely decomposed on an orthogonal basis formed by two perpendicular linear polarizations or two opposed circular (RH and LH) polarizations.

Radio propagation depends on the electron density N_e and the magnetic field B of the traversed media, which in return allows astronomers to probe magnetized astrophysical plasmas. There are three important propagation effects for a wave at frequency f propagating at angle θ from the ambient B-field:

- Cutoff of radio waves with $f \leq f_{pe}$, and reflexion for $f \leq f_{pe}/\cos\theta$, where $f_{pe} \propto N_e^{1/2}$ is the plasma frequency and θ is the wave incidence angle relative to the normal to the plasma boundary; this explains the ionospheric cutoff at ~ 10 MHz, preventing ground-based observation of radio waves of lower frequency, as well as permitting terrestrial short wave propagation by reflection below the ionosphere.
- Dispersion of broadband signals, leading to an arrival time delay proportional to f^{-2} and to the dispersion measure $DM = \int_L N_e dL$, the integral along the line of sight of the electron density; this explains the time-frequency shape of pulsar signals.

- Rotation of the linear polarization plane of a linear or elliptical wave traveling through a magnetized plasma (Faraday effect), where the angle of rotation is proportional to DM, f^{-2} , and the magnetic field $B_{\parallel}$ along the propagation path.

Additionally, random fluctuations of plasma parameters such as the electron density lead to weak or strong scintillation of radio waves, resulting in fluctuations of source intensity and position and in temporal and spectral broadening of radio emissions.

Basic Methodology

Basics

Radioastronomy consist of collecting, detecting, and measuring weak natural radio signals in the presence of noise, natural (sky background, lightning...) or man-made (radars, radio/TV broadcasting, computer clocks, etc.), including the noise produced by the radio telescope itself. The receiving antenna element (electric dipole or horn) can be preceded by a collector (e.g., a parabola) concentrating the incident energy. It is characterized by a radiation pattern or directional gain $G(\theta, \varphi)$, and an effective area $A_{\text{eff}}(\theta, \varphi) = G(\theta, \varphi) \lambda^2 / 4\pi$, where θ and φ are angular coordinates defining a position on the sky. After integrating over all angles, these quantities satisfy the relations:

$$\int_{4\pi} G(\theta, \varphi) d\Omega = 4\pi \quad \text{and} \quad \int_{4\pi} A_{\text{eff}}(\theta, \varphi) d\Omega = \lambda^2$$

For a directional antenna with quasi-constant gain $G = 4\pi/\Omega$ over the solid angle Ω (called the main lobe) and negligible elsewhere (secondary lobes), one has $A_{\text{eff}}\Omega = \lambda^2$ in the direction of the main lobe. The spectral power $P(f)$ [WHz^{-1}] received by a radio telescope can be expressed as a temperature, called antenna temperature, via $P = k T_A$ (with k the Boltzmann constant). In the general case of a radio source of brightness

described by $T(\theta, \varphi)$, the measured antenna temperature is

$$T_A = 1/4\pi \times \int_{\text{source}} T(\theta, \varphi) \times G(\theta, \varphi) d\Omega$$

As a consequence, the antenna temperature measured by a directional radio telescope is simply the source temperature averaged over the main antenna lobe ($T_A = \langle T \rangle$) if the source is more extended than the main lobe, or this quantity affected by a dilution factor ($T_A = \langle T \rangle \Omega_{\text{source}} / \Omega_{\text{main lobe}}$) otherwise. When observing an extended black body, the measured T_A is the brightness temperature and, thus, physical temperature of the source. Conversely for an unresolved source (unknown Ω_{source}), the antenna temperature can be determined, but not the brightness temperature.

The flux density received by the radio telescope is S [$\text{Wm}^{-2}\text{Hz}^{-1}$] = (2) kT_A/A_{eff} . The factor (2) expresses the fact that a polarized antenna observing an unpolarized source transmits only half of the incident intensity or power to the receiver.

Due to the small size and weak intensity of natural radio sources, T_A is often very small. Source detection requires T_A to be larger than the fluctuations – generally Gaussian – of the noise, whose dominant origin may be the sky background of temperature T_{sky} (dominant at low frequencies) or the Nyquist noise of resistive parts of the instrument of temperature T_{system} (dominant at high frequencies). When measuring a signal or noise of average temperature T with a time integration τ and a spectral bandwidth b , the standard deviation of consecutive measurements is $\sigma \approx T/(b\tau)^{1/2}$. Hence, the definitions of the “noise temperature” $T_N = (T_{\text{sky}} + T_{\text{system}})/(b\tau)^{1/2}$, of the signal-to-noise ratio $\text{SNR} = T_A/T_N$, and of the minimum detectable flux density $S_{\text{min}} = (2) kT_N/A_{\text{eff}}$. The latter formula shows that the sensitivity increases with the effective area of the radio telescope. The limitation due to T_{sky} can be reduced only by temporal and spectral integration, whereas that due to T_{system} can be reduced via low-noise electronics or cryogeny (down to 10–20 K).

Receivers

Parameters defining a receiver include total observable frequency range, temporal and spectral resolution, gain, stability, dynamic range and linearity, system temperature, and output data rate. Practical implementations are very diverse, analog or digital, swept-frequency or multi-channel. . . , each with specific advantages and inconveniences.

As digitization rate is presently limited to $f_{\text{sampling}} \sim 1$ GHz, coherent receivers generally rely on the heterodyne technique, in which the frequency band of width Δf centered at frequency f (i.e., $f \pm \Delta f/2$) is mixed with a local oscillator (f_{LO}) for downshifting to low frequencies ($f - f_{\text{LO}} \pm \Delta f/2$), before digitization at f_{sampling} . Digitization of signals at frequencies $> f_{\text{sampling}}/2$ can also be performed via direct down conversion associated to adequate band filtering. Spectrometers for modern digital receivers include correlators, fast Fourier transform spectrometers, polyphase filter banks, or waveform samplers. Receiver chips (DSPs, FPGAs) are increasingly used to run real-time RFI mitigation or burst detection.

Antennas, Arrays, and Imagery

Radio telescopes often consist of large reflectors (there is no radio lens) such as the one in Fig. 2, equipped with a single focal antenna or an antenna

array (see below). At centimeter-to-decimeter wavelengths, single dishes have dimensions typically $D \leq 100$ m and thus an angular resolution no better than $\sim 1'$. A way to increase the size, and hence the resolution, is to build the radio telescope as an array of N antennas with maximum separation $d \gg D$, whose signals are coherently summed or multiplied, giving access to an angular resolution $\sim \lambda/d \ll \lambda/D$. The sensitivity also increases as the number of antennas in the array (i.e., $\propto N \times A_{\text{eff}}$).

When the array is used as an interferometer, signals from pairs of antennas are correlated (multiplied). The contrast and phase of the resulting interference fringes is simply related to the Fourier transform of the spatial distribution of source intensity. The Fourier coordinates (u, v) describing the spatial (angular) frequencies of the interference pattern are never completely explored. Aperture synthesis deals with optimization of the (u, v) plane coverage. In order to reach very high angular resolutions (down to 10^{-4} arcsec), very long baseline interferometry (**VLBI**) uses intercontinental baselines. The signal is then recorded at each antenna along with an accurate time reference (e.g., atomic clock) and correlated offline.

As the field of view (FoV) decreases with increasing telescope size, interferometers made of large antennas are not adapted to sky surveys.

Radio Astronomy,

Fig. 2 The 100-m Effelsberg radio telescope



A way to combine high sensitivity, good angular resolution, and a large FoV is to form a phased-array from many near-isotropic antennas (e.g., electric dipoles). Beamforming is the coherent summation of antenna signals, phased to produce a narrow beam pointed at a selected direction in the sky, within the envelope imposed by the diagram of each elementary antenna. In addition to the ability to steer electronically and near-instantaneously the radio telescope main beam, modern electronics allows one to form simultaneously a large number of narrow beams pointed at different directions. Such multibeam techniques are used in focal plane arrays to provide multipixel matrices (up to tens of pixels) at the focus of large reflectors, expanding their FoV, as well as in “aperture arrays” of many thousands of antennas able to produce hundreds of simultaneous beams. The latter enable fast and sensitive wide-field surveys, as well as RFI-nulling techniques.

Key Research Findings

Large Instruments and Perspectives for Astrobiology

The revolution in digital calibration and imaging techniques in the past 25 years enabled the construction and exploitation of several antenna arrays.

At high frequencies, the Atacama Large Millimeter/submillimeter Array (ALMA, 40–950 GHz) is the major millimeter-submillimeter interferometer since 2013, in which 66 parabolas of 7 and 12 m forming baselines up to 16 km and ensuring subarcsecond resolution. Astrobiology-related observations of ALMA especially consist in the direct imaging of young forming giant planets in protoplanetary disks (as hot clumps and the gaps that they form within disks), and possibly very young systems in the nearest star-forming regions, via their thermal emission. Several images of protoplanetary disks were obtained following the first spectacular image of the HL Tau system (Fig. 3). Other interferometers such as the VLA or ATCA aim at detecting circularly polarized cyclotron-Maser radio emission produced at the local cyclotron frequency f_{ce} by magnetized stars or star-planet interactions (SPI).

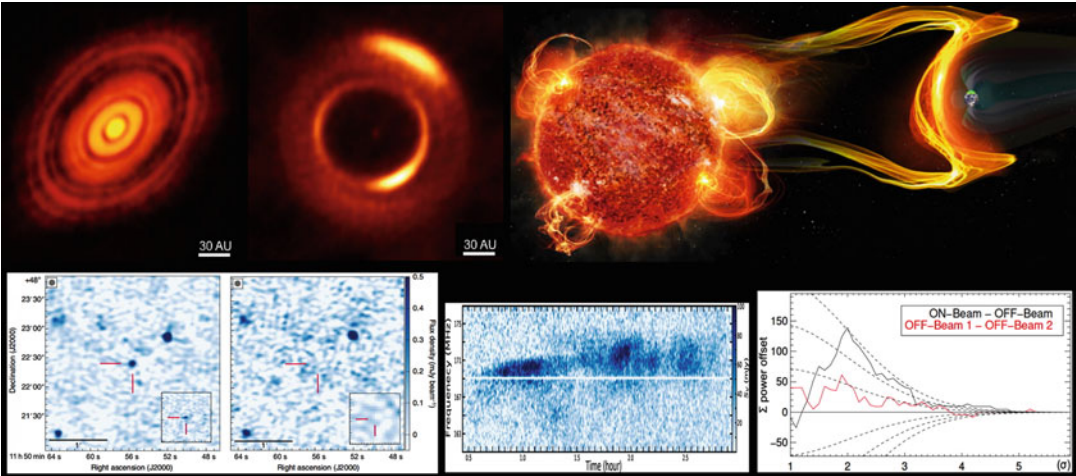
At low frequencies, the major instrument is the LOW Frequency ARray (LOFAR), a European interferometer of phased arrays in the range 30–250 MHz (Fig. 4). Other arrays include the LWA, MWA, UTR-2, and NenuFAR (the large low-frequency – 10–85 MHz – extension of LOFAR in Nançay). Circularly polarized radio emission has been recently detected in LOFAR imaging surveys (e.g., from GJ 1151 or CR Draconis) and in targeted beamformed observations (Tau Boötes), and interpreted as the nonthermal auroral Jupiter-like radio emission from exoplanetary magnetospheres or resulting from plasma SPI (Fig. 3).

Applications

When confirmed and expanded, the above detections at low frequencies will open the new field of compared exo-magnetospheric physics. Theoretical predictions of radio emission power are based on a radio-magnetic scaling law. An interpretative frame of their characteristics has been proposed on the basis of simulations developed from Solar system radio emissions (from Jupiter, Saturn. . .), that show that radio detection of exoplanets will bring information of their magnetic field (amplitude, offset, tilt), rotation period, orbit inclination, and on the physics of SPI. The existence of a magnetosphere around an exoplanet is considered as a factor favoring its habitability.

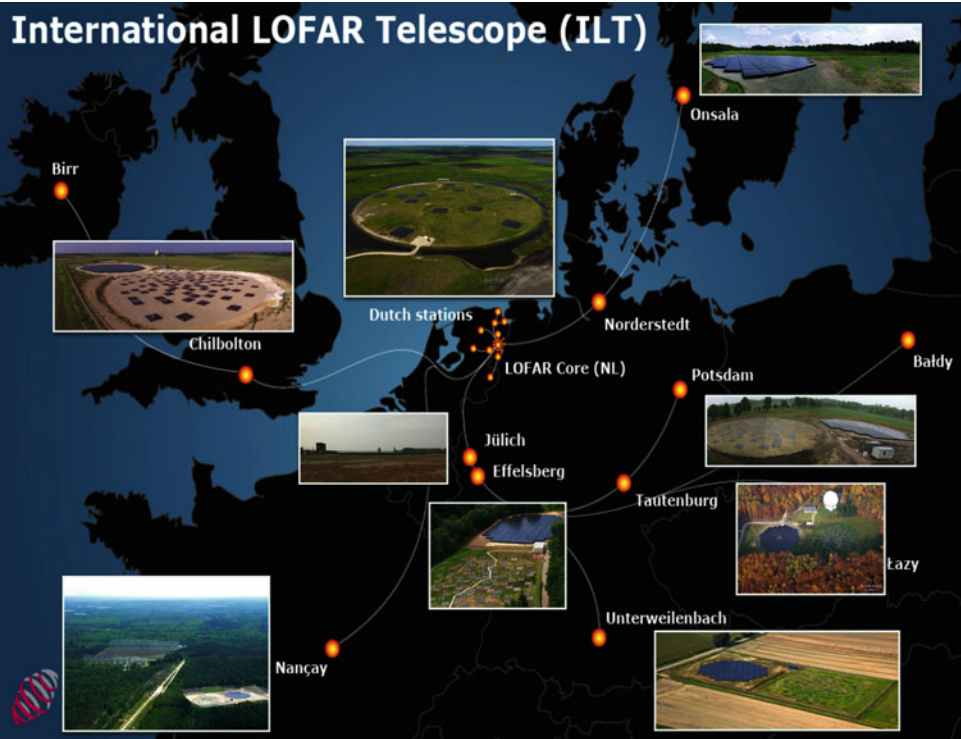
Future Directions

Most of the recent radio arrays cited above, plus instruments such as ASKAP in Australia or MeerKAT in South Africa, are pathfinders and precursors of the giant Square Kilometer Array (SKA), presently in construction in these two countries, and that will be the world’s ultimate twenty-first century radio telescope in the range 50 MHz – 15 GHz. It will gather hundreds of thousands low-frequency antennas and hundreds of ~ 15 m parabolas to reach $A_{\text{eff}} \sim 4 \times 10^4$ to $> 10^6 \text{ m}^2$ and provide thus an extreme sensitivity across its entire band. SKA will address both planetary formation and



Radio Astronomy, Fig. 3 Radio astronomy observations relevant to Astrobiology (from left to right and top to bottom): ALMA images at $\lambda \sim 1$ mm of HL Tau and of MWC 758 (stars surrounded by a protoplanetary disk showing planet formation gaps and clumps – ALMA/Brogan et al. 2015, Dong et al. 2018); Artist view of stellar wind-magnetosphere interaction expected to drive auroral

radio emission; LOFAR detection of the polarized variable source GJ 1151 (Vedantham et al. 2020), and dynamic spectrum of CR Draconis (Callingham et al. 2021), in imaging mode; LOFAR tentative detection of weak Tau Boötis radio bursts (Turner et al. 2021) in beamforming mode



Radio Astronomy, Fig. 4 LOFAR, the LOw Frequency ARray: insets show individual stations across Europe, with their low-frequency antennas and high-frequency antenna tiles

magnetospheric or star-planet driven radio emissions. For future decades, a “LOFAR-on-the-Moon” project is under study, which would benefit from a radio-quiet environment and of the quasi-absence of an ionosphere, allowing us to explore the frequency range below 10 MHz. As an alternative, large clusters of low-frequency antennas in space forming a free-flying interferometer are under study.

Cross-References

- [ALMA](#)
- [Interferometry](#)
- [Plasma](#)
- [VLBI](#)

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Radio Astronomy and Radio Telescopes, History of

Stéphane Le Gars

Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Atacama Large Array Millimeter (ALMA) ·
Cosmic background radiation · Interstellar
chemistry · Interstellar medium · Molecules in
space · Radio astronomy · Radio telescope ·
Very large base interferometry

History

During the second half of the nineteenth century, the electromagnetic theories of James Clerk Maxwell (1831–1879) and the experiments of Heinrich Hertz (1857–1894) permitted scientists to consider the possibility of an emission of radio waves by the stars or the Sun. According to the German physicist Hermann Ebert (1861–1913) in 1892, the observation of electric discharges in vacuum tubes were conducted to investigate the possible existence of Hertzian (radio) waves emitted by the Sun. Admitting the validity of Maxwell's theory, the French physicist Charles Nordmann (1881–1940) was convinced that high-altitude observations might succeed in detecting those solar radio waves. But despite using a 175-m antenna placed almost at the top of Mont Blanc, he detected no waves because of a lack of sensitivity.

The detection of “cosmic static”, i.e., radio waves of extraterrestrial origin, was made for the first time by the American radio engineer Karl Guthe Jansky (1905–1950) in 1932. Working for the Bell Laboratories, Jansky made this discovery while identifying the sources of the static which interfered with radiotelephones. He found that this static was composed of emission from both local sources such as thunderstorms and an extraterrestrial source. After a year of study, Jansky could come to the conclusion that this extraterrestrial emission was radio emission from the center of

the Milky Way. Although the announcement of this discovery was highly popular, it had no response from the astronomical community.

The only one who seemed interested to pursue the Jansky's work was the American radio engineer Grote Reber (1911–2002). Reber wanted to achieve two objectives: to determine the variation with the position on the sky of the intensity of extraterrestrial radio emission at any given wavelength and to determine the variation with wavelength of this intensity at any given position. So, he needed simultaneously both high angular resolution and a wide band of wavelengths. For this, he decided to construct a paraboloidal reflector, and he tried to make the first radio map of the sky, at a wavelength of 160 MHz. He questioned current optical astronomy because he found that the position of the maximum radio emission was some 30° off the then-accepted galactic center. These results were obtained during World War II, but after the war, the investigations in celestial radio waves were much slower in the USA than in Britain or Australia.

The main wartime discoveries were made in Britain by James Stanley Hey (1909–2000), and his colleagues at the Army Operational Research Group. Working to improve the effectiveness of army radar equipment by studying sources of interference, this group made three unexpected discoveries: the detection of radio emission from the Sun, the detection of radar echoes from meteor trails, and the localization of a radio noise in the direction of Cygnus. Hey's work became common knowledge within two groups in the UK after war: the department of physics in Manchester and the Radiophysics Group at the Cavendish Laboratory, Cambridge. After the failure of the study of cosmic rays by means of radio waves, radio physicists in Manchester became concerned with the determination of radar echoes from meteors, to know if meteor showers were of interstellar origin or were confined to the solar system. By the early 1950s, this line of investigation began to decline, and groups in Manchester and Cambridge all became interested in the study of “radio stars.” This was the same in Australia, where radio engineers such as John Gatenby Bolton (1922–1993) and Gordon James Stanley (1921–2001), working at the Radiophysics Laboratory in Sidney, made

important studies of a source in Cygnus. Above all, they made the first identification of a radio source, Taurus A, with an optical object, the Crab Nebula, leading to the first intimate link between the radio investigator and the classical astronomer. British and Australian successes paved the way to a new science, radio astronomy and incited scientists in other countries to enter the new field. By the mid-1950s, an international community emerged, particularly in France, Canada, the USA, USSR, and Japan.

From a technical point of view, three types of radio telescopes have been used until now. The first one consists of a single antenna, often associated with a paraboloidal reflector. This type of radio telescope only permits observation of objects whose angular extension is higher than 100 arcsec (certainly no longer true, and in any case not a fundamental limit of single dish radio telescopes). Larger and larger collecting areas were reached during the 1960s, permitting astronomers to go to ever shorter wavelengths. The radio telescope of Arecibo (Porto Rico) is emblematic of this evolution: this spherical reflector, 300-m in diameter, was finished in 1965.

The second type of radio telescopes is constituted of a number of antennas that are physically connected so that the electrical signals may be directly compared. This type of instrument is called an interferometer, since it uses the principles of interferometry to synthesize a very large effective aperture from a number of small elements. The signals from a source alternately arrive in phase and out of phase as the Earth rotates and cause a change in the difference in path from the radio source to the different elements (telescopes) of the interferometer, producing interference fringes similar to the ones in an optical interferometer. This is the case of the method called "aperture synthesis" invented and developed by the British radio physicist Martin Ryle (1918–1984) in 1962 and that led him to the Nobel prize in 1974, shared with Antony Hewish (1924–). This technique permits the mapping of radio objects with high angular resolution. Examples of such facilities are the Westerbork Synthesis Radio Telescope (WSRT) built in Holland in 1972, which operates with eight 13-m dishes, and

the Very Large Array (VLA), opened in 1980 near Socorro, New Mexico, which achieves an angular resolution below 0.1 arcsec with its twenty-seven 25-m antennas.

The third type of radio telescope is made of independent and separate antennas synchronized by the means of atomic clocks: by this means, sub-milliarcsecond angular resolution became possible. This is illustrated by the very long baseline interferometry technique (VLBI), in which antennas are spaced more than a few tens of kilometers apart.

It's important as well to note that a radio telescope consists of an antenna and a radio receiver used to detect and amplify the signals. The sensitivity of the receiver was thus a crucial element in the development of radio astronomy. At the beginning (Jansky, Reber), valve receivers were used (diode, triode), which then gave way to transistors. Some unusual receivers such as the parametric amplifier and the maser were also employed at centimeter wavelengths; it can be noted that the discovery of the cosmic background radiation by Arno Allan Penzias (1933–) and Robert Wilson Robert Woodrow Wilson (1936–) in 1964 (for which they received the Nobel Prize in 1978) was made using a very low noise maser amplifier. Further developments of field-effect transistors (FET) and high electron mobility transistors (HEMT) resulted in receivers with nearly quantum noise when cooled to 15 K: nowadays, HEMTs can pick out, from a sea of noise, minor 10 K signals sent out by interstellar molecules.

Historically, radio observations started at meter wavelengths and were extended to centimeter, then to millimeter, and finally to sub-mm wavelengths. The large range of wavelength has permitted achievement of important and numerous results in astrophysics, cosmology, and, now, astrobiology. As far back as 1942, the Sun had been identified by Hey as a radio emitter, followed by Reber and Southworth. A critically important step has been the development of radio spectroscopy, particularly when centimeter and shorter wavelengths were available for study: for instance, the first detection of the atomic hydrogen line at 1427 MHz (21 cm) made by Harold Irving Ewen (1922–) and Edward Mills Purcell

(1912–1997) (who received the Nobel prize in 1952 for his research in nuclear magnetism) inaugurated a new era of galactic investigations. This discovery opened up possibilities to detect hydrogen clouds in the galactic plane and to determine the spiral structure of our galaxy and of galactic kinematics by application of the Doppler effect. In the short centimeter and millimeter wavelengths, molecular lines could be studied and have given important information on the composition and physical state of the interstellar medium in our galaxy and external galaxies, as well as on solar system objects such as comets and planetary atmospheres. OH was the first molecule to be detected by radio observation in 1963 by Weinberg; it was subsequently analyzed as a natural maser in 1965. Numerous organic molecules were then detected: H_2CO in 1969; CO, CN, HCN, and CH_3OH in 1970; H_3COH and H_2CS in 1971; $(\text{CH}_3)_2\text{O}$ in 1972; etc.: these discoveries have constituted important steps in the emergence of interstellar chemistry and astrobiology. Radio astronomy has as well permitted the identification of new stellar objects: in the 1960s, for instance, pulsars and quasars were identified as powerful radio emitters.

Nowadays, the Atacama Large Array Millimeter (ALMA) is the most recent international project in the field of radio astronomy and is viewed as permitting a new age of research in astronomy. A joint project between Europe (ESO), North America (NSF), and Japan, ALMA will encompass 64 interconnected 12-m antennas at a unique high-altitude site at Chajnantor in the Atacama region of northern Chile. By studying mm and sub-mm wavelength radiation, ALMA will try to understand such processes as planet and star formation, formation of early galaxies and galaxy clusters, and the formation of organic molecules in space.

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Radioactive Heating

Tilman Spohn
 International Space Science Institute, Bern,
 Switzerland

Definition

Radioactive heating refers to the energy dissipated in the interiors of planets, satellites, or ► [asteroids](#) as a consequence of the radioactive decay of

radioactive isotopes (see ► [radiochemistry](#)). Radioactive ► [isotopes](#) are characterized by their decay energies and their ► [half-lives](#). The radioactive isotopes of importance on the timescale of a billion years are the so-called long-lived isotopes uranium ^{238}U , ^{235}U , thorium ^{232}Th , and potassium ^{40}K . Short-lived isotopes may have heated the planets in their early evolutions. The most effective short-lived isotope is ^{26}Al , because of its abundance and decay energy. The concentrations of these elements differ between planets depending on their formation and chemical evolution. Partial melting and differentiation is a mechanism for redistributing radioactive isotopes between ► [crust](#) and ► [mantle](#) reservoirs.

Cross-References

- [Asteroid](#)
- [Crust](#)
- [Decay Constant](#)
- [Differentiation, Planetary](#)
- [Half-Life](#)
- [Isotope](#)
- [Mantle](#)
- [Moon, The](#)
- [Planet](#)
- [Radioactivity](#)
- [Radiochemistry](#)
- [Satellite or Moon](#)

Radioactivity

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Keywords

Atoms · Radioactive decay

Definition

Radioactivity is a spontaneous and irreversible transformation of the atomic nucleus. It is the

source of ionizing particles (α particles, comprising two protons and two neutrons; β^- rays or electrons; and strong electromagnetic radiations (γ rays)). Radioactive decay is archetypal of Poisson processes, which take place with a constant probability per unit of time. Radioactivity powers the energy flow of planetary interiors. It is also the theoretical basis of dating methods that are used to measure the age of rocky planets (geochronology).

History

After a serendipitous discovery by French physicist Henri Becquerel in 1896, radioactive elements were methodically investigated by Marie Curie. In 1928, George Gamow demonstrated that α decay was due to quantum mechanical tunneling, and in 1934 Enrico Fermi provided a successful explanation of the β^- decay involving neutrinos.

Overview

Radioactivity involves the gigantic energies of the strong, short-range, nuclear force, which are on the order of a few millions of eV (electron volt) per nucleon. In contrast, mineral reactions and thermal agitation involve energies in the eV range. Rates of decay are therefore independent of the chemical, thermal, and mineralogical environment of the element in question and are also insensitive to pressure, which only affects the outermost electron shells. Decay rates have not measurably varied with time. The three most common radioactive decay processes are the following:

1. The α (alpha) process is the emission of an alpha particle (He nucleus). The nucleus is held together by the short-range attractive strong force between adjacent protons and neutrons, and the total binding energy increases linearly with mass. In contrast, the electromagnetic force, which tends to pry the positively charged protons apart, is weaker but acts over a

broader range, so that it involves the entire nucleus: it varies with the total number of proton pairs and therefore with the *squared* number of protons. Heavy nuclei become knobby and wobbly and some parts tend to detach. Because both the neutrons and protons are paired, the α particle does not transport angular momentum and its ejection from the nucleus is facilitated. The α process is a consequence of the quantum tunnel effect: although the potential barrier opposing the ejection of an α particle is much greater than the energy gain resulting from separation, there is still a non-zero probability that ejection will occur. The alpha particle is a helium nucleus and alpha decay is the source of essentially all the ^4He in the Earth. Mass loss between the original nucleus and the resulting particles is compensated by emission of γ rays, which account for most of the heating of planetary interiors (from U and Th). For example, $^{147}\text{Sm} \rightarrow ^{143}\text{Nd} + \alpha$.

- The β^- (beta minus) process involves the emission of an electron and is most common for neutron-rich [▶ nuclides](#). It calls for the effect of the unfamiliar short-range weak interaction. The lower energy of the proton-neutron interaction with respect to that of similar nucleons favors a nucleus with an equal number of protons and neutrons. When $N > Z$ (atomic number), excess energy is therefore released by converting a neutron into a proton and a W^- boson, which itself decays into an electron and an antineutrino. Neutrinos have no mass and do not interact with matter, yet they carry a large fraction of the decay energy, which often renders the measurement of beta decay constants imprecise. For example, $^{87}\text{Rb} \rightarrow ^{87}\text{Sr} + e^- + \bar{\nu}$ (e^- is an electron and $\bar{\nu}$ an antineutrino).
- Capture of an electron of the K shell is a less frequent process. For example, $^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar}$.

A nuclide may be unstable with respect to two decay processes simultaneously, and the probabilities of decomposition by each process are additive. For example, ^{40}K decays dually into ^{40}Ca by β^- emission and into ^{40}Ar by electron capture; this is known as a branched mode of radioactive decay.

Cross-References

- ▶ [Decay Constant](#)
- ▶ [Earth, Age of](#)
- ▶ [Geochronology](#)
- ▶ [System Solar Formation, Chronology of](#)

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Radiochemistry

Jun-ichi Takahashi
Faculty of Engineering, Yokohama National University, Yokohama, Japan

Keywords

Cosmic rays · Radioactive isotope · Radioactivity

Definition

Radiochemistry is a field of chemistry concerned with radioactive materials. Research objectives of radiochemistry include the following:

- Distributions and transformations of radioactive nuclides
- Synthesis of artificial nuclides
- Separation and purification of radioactive isotopes
- Chemical properties of radioactive elements and their compounds
- Chemical action of knock-on atoms associated with radioactive decay
- Utilization of radioactive isotopes, i.e., utilization as a radioactive tracer or for isotope dating

This field was launched by the discovery of radioactivity by Becquerel in 1896.

Overview

Radioactive isotopes transform via nuclear decay and emit mainly three types of radiation, which are called alpha, beta, or gamma radiation.

1. Alpha radiation – the emission of an alpha particle (which contains 2 protons and 2 neutrons) from an atomic nucleus. When this occurs, the atom's atomic mass will decrease by 4 units and atomic number will decrease by 2.
2. Beta radiation – the transmutation of a neutron into an electron and a proton. After this happens, the electron is emitted from the nucleus into the electron cloud.
3. Gamma radiation – the emission of electromagnetic energy from the nucleus of an atom. This usually occurs during alpha- or beta-radioactive decay.

These three types of radiation can be distinguished by their differences in penetrating power. An alpha particle, the equivalent to a helium nucleus, is stopped quite easily by, for example, a few centimeters in air or a piece of paper. Beta particles are electrons, and they can be stopped by an aluminum sheet a few millimeters thick. Gamma radiation consists of high-energy photons and has no mass or charge. It is the penetrating of the three and is stopped only by an appreciable amount of heavy metal radiation shielding (usually lead or barium based).

Radiochemistry also includes the study of the behavior of radioactive isotopes in the atmospheric environment. Collision of cosmic rays, mainly protons, with nuclei of nitrogen, oxygen, and argon in the upper atmosphere produces nucleons (protons and neutrons) and mesons. Secondary nuclear reactions between the produced nucleons and the atmospheric atoms are responsible for the formation of radioisotopes, such as ^{14}C through the reaction $^{14}\text{N}(\text{n}, \text{p})^{14}\text{C}$. The produced ^{14}C becomes incorporated into atmospheric carbon dioxide, resulting in uniform distribution in terrestrial biological body. The ^{14}C method is widely utilized as a dating method in archeology and anthropology. Other radioactive nuclides in the atmosphere, such as ^3H , ^7Be , ^{10}Be , ^{22}Na , ^{32}Si ,

^{32}P , ^{33}P , ^{35}S , and ^{36}Cl , are also derived from cosmic rays.

Cross-References

- [Alpha Rays](#)
- [Beta Rays](#)
- [Gamma Rays](#)
- [Geochronology](#)
- [Radioactivity](#)

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Radiochronology

- [Geochronology](#)

Radiogenic Isotopes

Thorsten Kleine

Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Münster, Germany

Keywords

Age dating · Age of the Earth · Age of the Moon · Carbonaceous chondrites · Core formation · Late veneer · Mantle-crust evolution · Meteorites · Water

Synonyms

[Radiogenic nuclides](#)

Definition

Radiogenic isotopes or radiogenic nuclides are produced by the decay of radioactive nuclei (e.g., ^{87}Sr

produced by the decay of ^{87}Rb). The abundances of radiogenic isotopes are commonly reported relative to that of a stable, non-radiogenic isotope of the same element (e.g., ^{86}Sr) as isotope ratios (e.g., $^{87}\text{Sr}/^{86}\text{Sr}$). In ► [geochronology](#), radiogenic isotopes are used for determining the timing and duration of geological events. They also provide tracers for chemical fractionations of parent and daughter elements by past geological processes, such as the chemical differentiation of the Earth.

Overview

Radiogenic isotopes are versatile tools in Earth sciences. In geochronology, they are used to determine the timescales of geological processes ranging from ages of individual minerals to the timescales of large-scale chemical differentiation of asteroids and terrestrial planets. As tracers of geological processes, radiogenic isotopes provide information on rates and pathways of geological processes, including the compositional evolution of the Earth and other planetary bodies, processes of planetary differentiation, as well as identifying the origin of Earth’s water.

Basic Methodology

Geochronology

Based on their half-lives, radioactive nuclides can be subdivided into long-lived nuclides with half-lives of more than ~ 100 Myr (e.g., $^{238}\text{U} \rightarrow ^{206}\text{Pb}$, ► [half-life](#) of 4.47×10^9 years) and short-lived or

extinct nuclides with half-lives of less than ~ 100 Myr (e.g., $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$, half-life of 7.3×10^5 years) (Table 1). Owing to their short half-lives, short-lived nuclides only existed during the early stages of Solar System evolution and have since then decayed away (a ► [nuclide](#) is considered effectively extinct after about seven half-lives).

The basic equation for using long-lived decay systems in geochronology is

$$R = R_0 + R^{P/D} \times (e^{\lambda t} - 1) \tag{1}$$

where R is the ratio of the radiogenic isotope to a non-radiogenic isotope of the same element (e.g., $^{206}\text{Pb}/^{204}\text{Pb}$), R_0 is the initial ratio [$^{206}\text{Pb}/^{204}\text{Pb}$] $_0$, $R^{P/D}$ is the parent-to-daughter ratio at the present day (e.g., $^{238}\text{U}/^{204}\text{Pb}$), λ is the decay constant, and t is time running backward from present. R and $R^{P/D}$ of a sample can be directly measured for a sample, but the determination of the initial ratio R_0 is more difficult. However, Eq. 1 and Fig. 1 illustrate that in a plot of R versus $R^{P/D}$ cogenetic samples having the same age t and an initial isotopic composition R_0 plot on a straight line, termed an isochron. An age t can be determined from the slope of such an isochron, which is equivalent to $e^{\lambda t} - 1$.

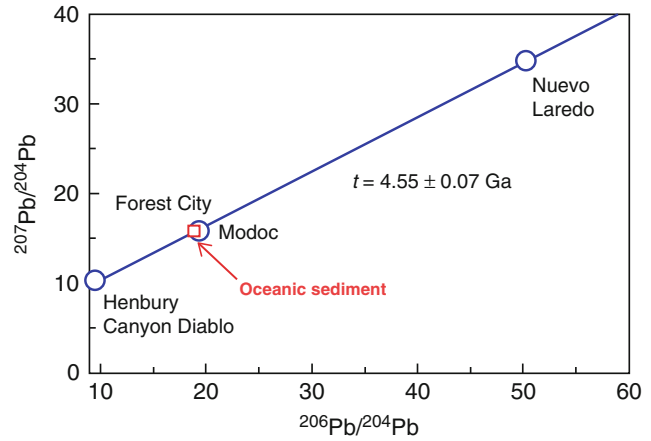
Figure 1 shows an example of one of the first isochrons obtained for meteorites (Patterson 1956). Patterson observed that different groups of meteorites (open circles) have different Pb isotopic compositions that correlate with their U/Pb ratios. Recent oceanic sediments, which at the time of Patterson’s study were thought to

Radiogenic Isotopes, Table 1 Some important radioactive decay systems and selected applications

Parent	Daughter	Reference isotope	Half-life (years)	Selected applications
^{26}Al	^{26}Mg	^{24}Mg	7.3×10^5	CAI and chondrule formation
^{107}Pd	^{107}Ag	^{109}Ag	6.5×10^6	Core formation; volatile depletion
^{182}Hf	^{182}W	^{184}W	8.9×10^6	Core formation
^{146}Sm	^{142}Nd	^{144}Nd	1.03×10^8	Early crust-mantle differentiation
^{147}Sm	^{143}Nd	^{144}Nd	1.06×10^{11}	Formation of crust; evolution of the mantle
^{176}Lu	^{176}Hf	^{177}Hf	3.7×10^9	Crust-mantle differentiation
^{187}Re	^{187}Os	^{188}Os	4.23×10^{10}	Late accretion history
^{235}U	^{207}Pb	^{204}Pb	7.07×10^8	Earth’s core formation; geochronology
^{238}U	^{206}Pb	^{204}Pb	4.47×10^9	

Radiogenic Isotopes,

Fig. 1 $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ isochron determined by Patterson (1956) for meteorites. Henbury and Canyon Diablo are iron meteorites, Forest City and Modoc chondrites, and Nuevo Laredo a basaltic meteorite



represent the Pb isotopic composition of the bulk silicate Earth, plot next the isochron defined by the meteorites. This led Patterson to conclude that the Earth and meteorites must have the same age and origin. However, subsequent work has shown that pelagic sediments only provide a rough approximation of the true composition of the bulk silicate Earth. The current best estimates for the Pb-Pb [age of the Earth](#) are younger but within experimental error of Patterson's original determination and range from ~ 4.52 to ~ 4.44 Ga (Allègre et al. 1995; Rudge et al. 2010; Wood and Halliday 2010).

The basic equation for using short-lived nuclides is.

$$R = R_0 + R_s^{P/D} \times P_0^{ij} \quad (2)$$

where $R_s^{P/D}$ is the parent-to-daughter ratio of two stable nuclides and P_0^{ij} is the initial abundance ratio of a short-lived nuclide. In case of the ^{26}Al - ^{26}Mg system, Eq. 2 reads:

$$\left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_0 = \left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right) + \left(\frac{^{27}\text{Al}}{^{24}\text{Mg}}\right) \times \left(\frac{^{26}\text{Al}}{^{27}\text{Al}}\right)_0 \quad (3)$$

In a plot of $^{26}\text{Mg}/^{24}\text{Mg}$ versus $^{27}\text{Al}/^{24}\text{Mg}$, cogenetic samples having the same initial Mg isotopic composition plot on an isochron whose slope corresponds to the initial $^{26}\text{Al}/^{27}\text{Al}$ of these samples. Figure 2 shows an example of an

^{26}Al - ^{26}Mg isochron for a Ca-Al-rich inclusion ([▶ CAIs](#)) from the carbonaceous [▶ chondrite](#) Allende. This isochron provided the first evidence that live ^{26}Al had existed in the Solar System and, since CAI are thought to be the first condensates of the solar nebula, shows that the initial $^{26}\text{Al}/^{27}\text{Al}$ of the Solar System was $\sim 5 \times 10^{-5}$ (Lee et al. 1977).

Since Eq. 2 does not contain the age t , short-lived nuclides cannot provide absolute ages. However, time differences Δt between any two samples 1 and 2 can be precisely determined from their initial abundance ratios P_0^{ij} . In case of the ^{26}Al - ^{26}Mg system, ages are usually given as the time elapsed since the formation of CAI and can be calculated as follows:

$$\Delta t = \frac{1}{\lambda} \times \ln \left[\frac{\left(\frac{^{26}\text{Al}}{^{27}\text{Al}}\right)_{\text{CAI}}}{\left(\frac{^{26}\text{Al}}{^{27}\text{Al}}\right)_{\text{sample}}} \right] \quad (4)$$

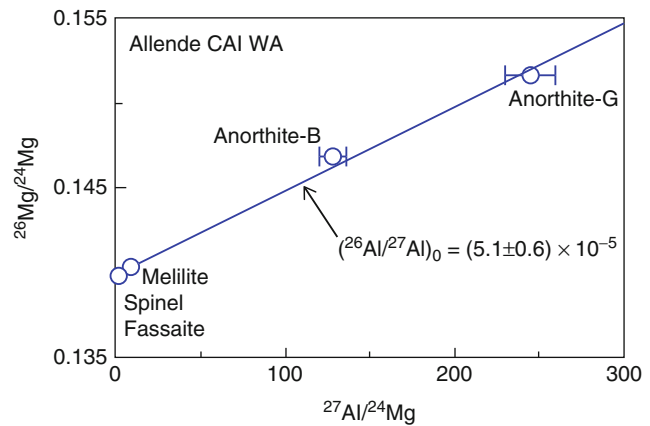
Similar equations apply to other short-lived systems and can be used to calculate time differences between any two samples or events.

Model Ages

A different type of age can be obtained from a single measurement of R and $R^{P/D}$ (for long-lived systems) or R and $R_s^{P/D}$ (for short-lived systems) combined with an assumption regarding the initial isotopic composition of the daughter, R_0 . This approach requires a model of the isotopic evolution of the reservoir a sample is derived from, such

Radiogenic Isotopes,

Fig. 2 $^{26}\text{Mg}/^{24}\text{Mg}$ versus $^{27}\text{Al}/^{24}\text{Mg}$ isochron for the Allende CAI WA as determined by Lee et al. (1977). Anorthites from this CAI contain highly radiogenic Mg, providing the first evidence for live ^{26}Al in the early solar system



that these ages are referred to as model ages. A prominent example is model ages calculated relative to a Chondritic Uniform Reservoir (CHUR), a term introduced by DePaolo and Wasserburg (1976) to investigate mantle-crust differentiation in the Earth using the ^{147}Sm - ^{143}Nd chronometer. The underlying assumption of the CHUR model is that the parent-to-daughter ratio of an isotope system in the bulk Earth is chondritic. Since both Sm and Nd are refractory elements, this is a reasonable assumption. This assumption also holds for the Lu-Hf and Hf-W systems, as all these elements are refractory.

Figure 3 illustrates the concept of CHUR model ages for the ^{176}Lu - ^{176}Hf system. The Earth's crust is thought to have formed by partial melting of the ► mantle. During melting, Hf enters the melt more readily than Lu, such that the crust will evolve with lower Lu/Hf than the bulk Earth, whereas the Lu/Hf of the depleted mantle will be higher. Over time, the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of crust and mantle diverge to lower and higher values compared to the evolution of CHUR, respectively. By convention, Hf isotope ratios are expressed in $\varepsilon_{\text{Hf}}(t)$ as deviations in parts per 10^4 from the Hf isotopic composition of CHUR. Mantle-derived rocks are thus characterized by positive $\varepsilon_{\text{Hf}}(t)$ and crustal rocks by negative $\varepsilon_{\text{Hf}}(t)$ values.

Assuming that the mantle has the same Lu-Hf isotopic history as CHUR, the model time of crust formation can be determined from Lu-Hf data by calculating the time at which the crust had the same Hf isotopic composition as CHUR. In case

of the ^{176}Lu - ^{176}Hf system, such a model age is calculated as follows:

$$\tau_{\text{CHUR}} = \frac{1}{\lambda} \ln \left(\frac{\left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}} \right)_{\text{sample}} - \left(\frac{^{176}\text{Hf}}{^{177}\text{Hf}} \right)_{\text{CHUR}}}{\left(\frac{^{176}\text{Lu}}{^{177}\text{Hf}} \right)_{\text{sample}} - \left(\frac{^{176}\text{Lu}}{^{177}\text{Hf}} \right)_{\text{CHUR}}} + 1 \right) \quad (5)$$

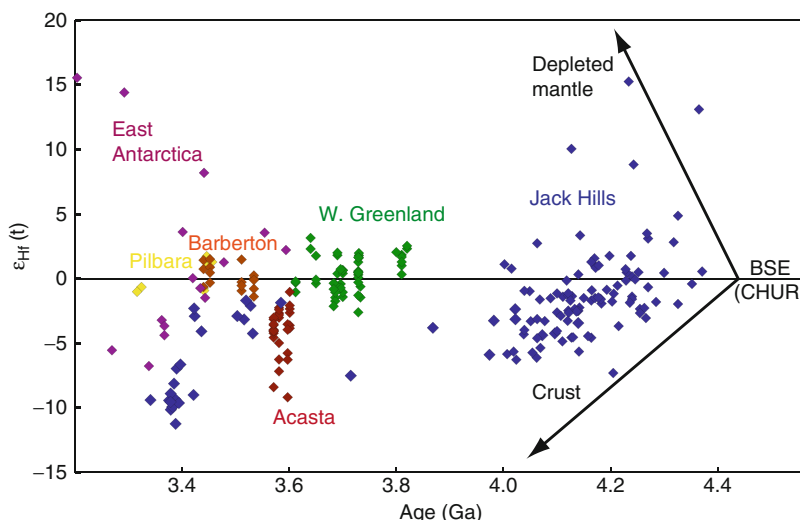
CHUR model ages are mostly used in studies investigating the large-scale geological evolution of planetary bodies, such as mantle-crust differentiation (^{147}Sm - ^{143}Nd , ^{176}Lu - ^{176}Hf) and core formation (^{182}Hf - ^{182}W).

Key Research Findings

Dating Meteorites and the Beginning of Planet Formation

Chondrites are a group of meteorites that never melted and preserved information on processes operating in the solar nebula, i.e., in the protoplanetary disk orbiting the young Sun. Many chondrites contain Ca-Al-rich inclusions (CAI), which consist of those minerals predicted to be the first condensates from a solar gas. Owing to their high U/Pb ratios, the age of CAI can be determined precisely by U-Pb chronometry and is ~ 4.567 Ga. Since CAI are the oldest objects known to have formed in the Solar System, their age is commonly used to define the age of the Solar System (Amelin et al. 2002, 2010).

^{26}Al - ^{26}Mg data for ► chondrules, the major component of most chondrites, show that they



Radiogenic Isotopes, Fig. 3 Hf isotopic composition of Archean and Hadean zircons. Zircons have high Hf contents but contain almost no Lu, such that they can be used to measure the Hf isotopic composition at the time of their crystallization. The latter can readily be determined using

the U-Pb system. This makes zircons both a powerful dating tool and a powerful monitor of crustal growth. Measurable Hf isotopic variations already existed at ~ 4.3 Ga, implying that substantial crust had already formed by this time. (Redrawn from Scherer et al. 2007)

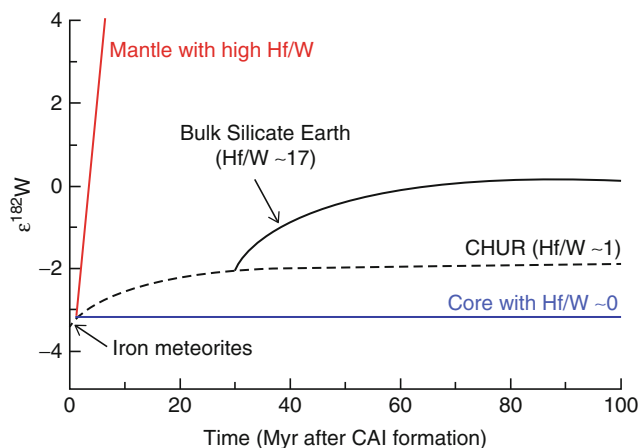
have much lower initial $^{26}\text{Al}/^{27}\text{Al}$ ratios than CAI. Provided that ^{26}Al was homogeneously distributed within the region where CAI and chondrules formed, the differences in initial $^{26}\text{Al}/^{27}\text{Al}$ ratios indicate that most chondrules formed ~ 2 Ma after CAI. Chondrules from some chondrites appear to have formed even later, some as late as 4–5 Ma after CAI formation. As chondrules formed by rapid melting of dust aggregates in the solar nebula, the chondrite parent bodies must thus have accreted several million years after Solar System formation (e.g., Krot et al. 2009).

Iron meteorites are thought to derive from the metal cores of differentiated protoplanets. The timing of their formation can be determined using the ^{182}Hf - ^{182}W chronometer (e.g., Kleine et al. 2009). Both Hf and W are refractory and thus assumed to occur in chondritic relative abundances in bulk planetary bodies (see above). During core formation, lithophile Hf remains in the mantle while siderophile W preferentially partitions into the core, resulting in high Hf/W ratios in the mantle and a low Hf/W ratio of ~ 0 in the core. Consequently, over time the mantle will evolve to higher-than-chondritic $^{182}\text{W}/^{184}\text{W}$ ratios, while the core maintains its W isotopic composition

acquired at the time of core formation (Fig. 4). The magnitude of the W isotopic effects in the mantle or core relative to chondrites can thus be used to determine an age of core formation in a way similar to that described above for Lu-Hf CHUR model ages (Fig. 4). The Hf-W data for magmatic iron meteorites show that these bodies underwent melting and core formation within less than ~ 1 Myr after CAI formation and, hence, well before the chondrite parent bodies accreted. Melting in the iron meteorite parent bodies most likely was triggered by energy release from ^{26}Al decay, while the chondrite parent bodies remained undifferentiated because they contained too little ^{26}Al to melt, probably because they accreted late (Kleine et al. 2009).

Accretion of the Earth and Segregation of Its Core

Accretion of the Earth involved highly energetic collisions with ► Moon- to Mars-sized planetary embryos, which raised the temperature of the Earth by thousands of degrees, causing the formation of magma oceans in which metal could separate from molten silicate and segregate toward to the center, forming a core (Stevenson 2008).



Radiogenic Isotopes, Fig. 4 W isotopic evolution in a planetary body undergoing core formation. By convention, the $^{182}\text{W}/^{184}\text{W}$ ratios are given in $\epsilon^{182}\text{W}$, which are the parts per 10^4 deviation of the $^{182}\text{W}/^{184}\text{W}$ of a sample from that of the terrestrial standard. Chondrites are characterized by an $\epsilon^{182}\text{W}$ value of -1.9 , whereas early formed metals (such as iron meteorites) have $\epsilon^{182}\text{W}$ values of around -3.3 . The W isotopic evolution of CHUR represents that of the bulk undifferentiated planet. During core formation,

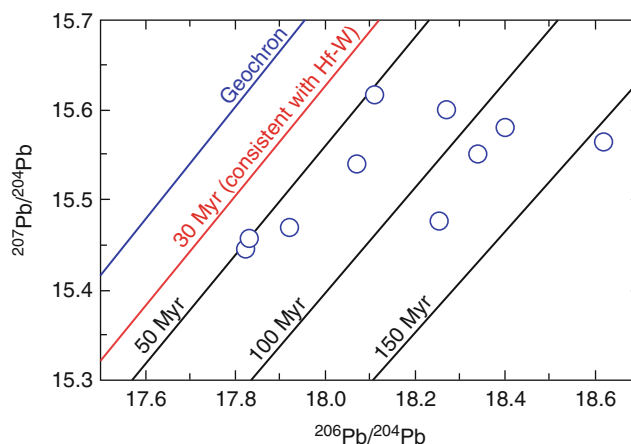
the chondritic Hf/W of the bulk planet is fractionated between mantle and core. The mantle has high Hf/W and evolves to radiogenic $\epsilon^{182}\text{W}$, while the core contains virtually no Hf such that its $\epsilon^{182}\text{W}$ remains constant over time. By comparing $\epsilon^{182}\text{W}$ and Hf/W of the mantle or core to that of chondrites, a model time of core formation can be calculated. The bulk silicate Earth has an $\epsilon^{182}\text{W}$ value of 0, corresponding to a two-stage model time of core formation of ~ 30 Myr after CAI formation

Thus, the rate of Earth's accretion can be determined by dating core formation. Such age constraints can be obtained from the U-Pb and Hf-W decay systems.

All estimates for the Pb isotopic composition of the **bulk silicate Earth** (BSE) plot to the right of the Geochron (i.e., the line of “zero” age for U/Pb fractionation) in a diagram of $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$, indicating an early loss of Pb from Earth's mantle (Fig. 5). Under the elevated pressure and temperature conditions of Earth's core formation, Pb is siderophile such that Pb loss most probably was to the Earth's core (Allègre et al. 1995; Wood and Halliday 2010). Estimates of the U-Pb model age of the Earth range between 56 and 130 Myr after Solar System formation (i.e., 4.52–4.44 Ga) and correspond to the time when Earth's core was fully formed and, hence, Earth entirely accreted (Rudge et al. 2010). The range in ages reflects uncertainties in the Pb isotopic composition of the BSE and bulk Earth as well as in the U/Pb ratio of the bulk Earth.

The BSE has a higher $^{182}\text{W}/^{184}\text{W}$ ratio ($\epsilon^{182}\text{W} = 0$) than the undifferentiated chondritic

meteorites ($\epsilon^{182}\text{W} = -1.9$), indicating that some fraction of Earth's core formed during the lifetime of ^{182}Hf . Assuming that core formation took place as a single event from a fully formed Earth, the W isotopic composition of Earth's mantle corresponds to a CHUR model age of ~ 30 Myr after CAI formation. However, Earth's core formed continuously during accretion over several millions of years, indicating that the W isotopic composition of Earth's mantle does not simply reflect one single event of core formation. Assuming that the Earth accreted at an exponentially decreasing rate (Wetherill 1986) and that the core formed in equilibrium with the mantle, the mean life of accretion τ of the Earth is ~ 11 Myr (corresponding to the time at which 63% of Earth's mass had accreted), while the end of accretion is given by the two-stage model age of ~ 30 Myr after Solar System formation (Jacobsen 2005). These timescales are faster than those obtained from U-Pb using the same model however (Halliday 2008; Kleine et al. 2009). The Hf-W and U-Pb timescales can be matched by assuming either disequilibrium during core formation or a rapid early accretion of the Earth



Radiogenic Isotopes, Fig. 5 Pb isotopic systematics of the bulk silicate Earth. Different estimates for the Pb isotopic composition of the BSE are shown as blue circles (for references see Rudge et al. 2010). The blue line labeled “Geochron” is the line of zero age U/Pb fractionation at the beginning of the Solar System. The red line represents the Pb isotopic compositions for which the timing of U/Pb fractionation would be consistent with that of Hf-W

fractionation in the exponential model. The black lines represent isochrons calculated with U/Pb fractionations during core formation at 50, 100, and 150 Myr after the beginning of the Solar System. The Pb isotopic composition of the BSE implies U/Pb fractionation due to core formation some time between ~50 and ~150 Myr after CAI formation

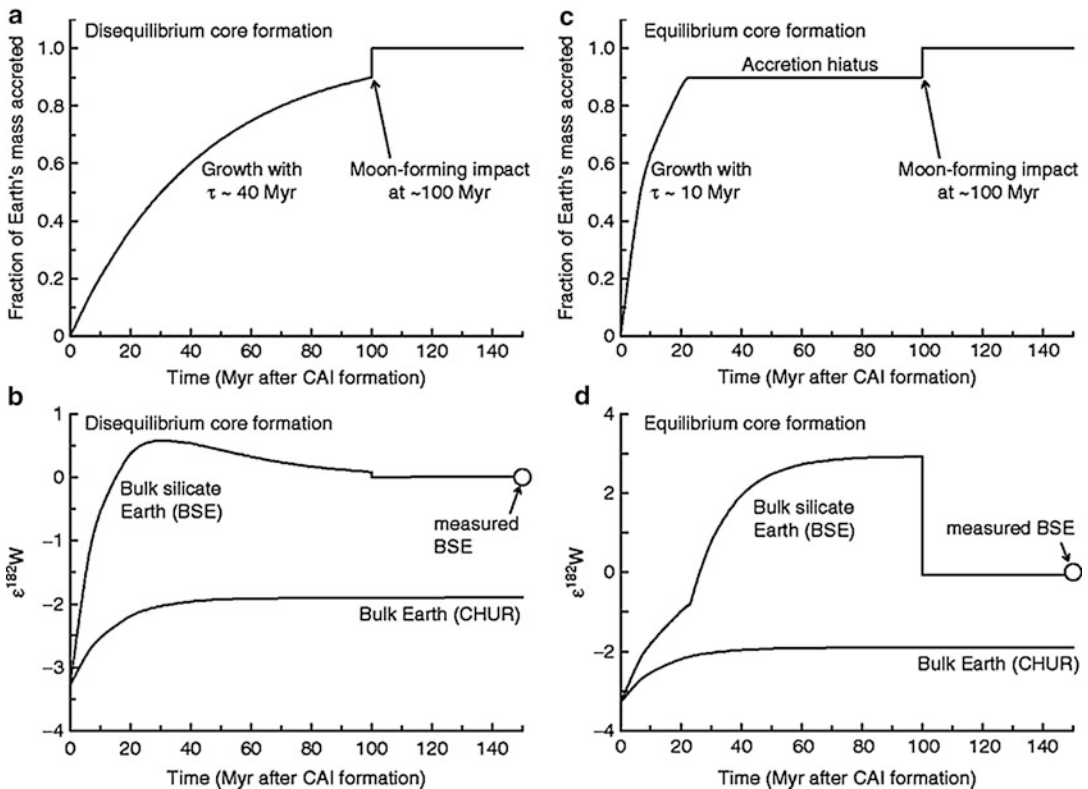
followed by a long accretion hiatus and a late Moon-forming impact (Halliday 2008; Rudge et al. 2010). Figure 6 illustrates these two end-member models for Earth’s accretion and differentiation.

Age and Origin of the Moon

The Moon formed at the very end of Earth’s accretion when a Mars-sized body (sometimes termed Theia) collided with the proto-Earth (Hartmann and Davis 1975; Canup and Asphaug 2001). As a result of the large amount of energy released during this collision, the Moon melted to form a magma ocean. The timescales for the formation of the Moon and solidification of its magma ocean can be quantified using the ^{182}Hf - ^{182}W , ^{146}Sm - ^{142}Nd , and ^{176}Lu - ^{176}Hf systems. Application of Hf-W chronometry to date, the Moon has been hampered by the cosmic-ray-induced production of ^{182}W by neutron capture of ^{181}Ta , resulting in apparent Hf-W ages of the Moon that are too old. However, the analyses of lunar metals that do not contain any Ta and hence Ta-derived ^{182}W show that in spite of large Hf/W fractionations within the silicate Moon, all lunar

samples have indistinguishable $^{182}\text{W}/^{184}\text{W}$ ratios, demonstrating that the lunar mantle must have solidified later than 60 Myr after Solar System formation (Touboul et al. 2007). The Lu-Hf and U-Pb systematics of KREEP, the residual liquid of the magma ocean, indicate that the magma ocean was completely solidified by ~4.4 Ga (Taylor et al. 2009; Nemchin et al. 2009), consistent with the Hf-W results but more difficult to reconcile with a ~4.3 Ga ^{146}Sm - ^{142}Nd model age of the lunar mantle.

The identical W isotopic compositions of the silicate Earth and Moon combined with their different Hf/W ratios provide evidence that the Earth and Moon separated late in accretion history, probably later than ~50 Ma after Solar System formation (Touboul et al. 2007). ^{147}Sm - ^{143}Nd chronometry indicates that the oldest lunar rocks, the ferroan anorthosites, crystallized no later than ~150 Ma following Solar System formation (Norman et al. 2003), such that the Moon most probably formed between 50 and 150 Ma after CAI formation, at about the same time than given by the U-Pb age of the Earth and the age of Pb loss from the Moon.



Radiogenic Isotopes, Fig. 6 Two end-member models of Earth's accretion and core formation based on Hf-W and U-Pb data. (a, b) Disequilibrium core formation: only 40% of the metal cores of newly accreted bodies are assumed to have first equilibrated with Earth's mantle before entering Earth's core. (c, d) Equilibrium core formation: for full equilibration during core formation, the main mass of the

Earth must have accreted rapidly, followed by a long accretion hiatus before a final Moon-forming impact at ~ 100 Myr. Both models can satisfy the Hf-W and U-Pb observations and indicate that Earth's accretion terminated late, some 100 Myr after Solar System formation (After Halliday 2008; Kleine et al. 2009; Rudge et al. 2010)

Origin of Earth's Water and the Late Veneer

Radiogenic isotopes can provide some information on the origin of Earth's water. The terrestrial mantle contains higher abundances of the platinum group elements (PGE) than expected from metal-silicate partitioning under equilibrium conditions. The overabundance of the PGEs has been interpreted to reflect the addition of a late chondritic veneer to Earth's mantle after formation of its core. Rhenium-187 decays to ^{187}Os such that the $^{187}\text{Os}/^{188}\text{Os}$ ratio of Earth's mantle precisely constrains the time-averaged Re/Os ratio of Earth's mantle. Osmium isotope data for terrestrial rocks and chondrites indicate that the Re/Os ratio of Earth's mantle is similar to ordinary chondrites but different from ► carbonaceous

chondrites. Consequently, the ► late veneer is thought to have had a composition similar to that of ordinary chondrites (Walker 2009), but these contain too little water to be the main source of Earth's water. This has led to the view that Earth received substantial quantities of water during its accretion (Drake and Righter 2002).

Early Differentiation and Mantle-Crust Evolution in the Earth

The decay products of long-lived radionuclides provide fundamental information regarding the composition, structure, and evolutionary history of the Earth's crust and mantle (Hofmann 1997). Among these, the ^{147}Sm - ^{143}Nd system has widely been used to investigate the early differentiation

of the Earth, but because Earth's oldest rocks postdate its accretion by several hundred of millions of years, the ^{147}Sm - ^{143}Nd constraints on Earth's earliest differentiation remain imprecise. Evidence for very early differentiation of Earth's mantle comes from Archean and Hadean zircons, some of which crystallized as early as 4.0–4.4 Ga ago. The ^{176}Lu - ^{176}Hf systematics of these zircons indicate that substantial crust on the Earth had already formed by ~ 4.3 Ga (Harrison et al. 2005; Scherer et al. 2007) (Fig. 3).

Short-lived nuclides can potentially provide more precise constraints on the timing of Earth's earliest differentiation because variation in their daughter products can only be produced during the first few hundred of millions of years of the Solar System. Relative to Earth's mantle, some Archean rocks from the Isua supercrustal belt have small ^{142}Nd excesses, indicating that an early proto-crust had already formed at 4.44 ± 0.08 Ga (Caro et al. 2003), that is, very soon after Earth had fully accreted.

The terrestrial mantle exhibits a small ^{142}Nd excess (from the decay of ^{146}Sm) relative to chondritic meteorites, which was interpreted to reflect depletion of the mantle within the first 30 Myr of the Solar System. A complementary early enriched reservoir may be hidden at the core-mantle boundary (Chase and Patchett 1988; Boyet and Carlson 2005). The preservation of a signature of such an early differentiation of the terrestrial mantle is difficult to reconcile with the age of the Earth's core and the age of the Moon however. The ^{142}Nd excess of the terrestrial mantle may thus reflect a slightly higher-than-chondritic Sm/Nd ratio of the Earth (Caro et al. 2008; Kleine et al. 2009).

Cross-References

- [Archean Mantle](#)
- [Bulk Silicate Earth](#)
- [CAIs](#)
- [Carbonaceous Chondrite](#)
- [Chondrite](#)
- [Chondrule](#)

- [Crust](#)
- [Earth, Age of](#)
- [Earth, Formation, and Early Evolution](#)
- [Geochronology](#)
- [Late Veneer](#)
- [Mantle](#)
- [Moon, The](#)
- [Nuclide](#)
- [Parent Body](#)
- [Siderophile Elements](#)

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Radiogenic Nuclides

- [Radiogenic Isotopes](#)

Radiolysis

Steven B. Charnley

Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Radiolysis refers to the dissociation of molecules by nuclear radiation (e.g., by alpha particles = helium nuclei).

In astrochemistry, radiolysis occurs in the gas phase by interaction with cosmic rays and in the solid phase through the impact of these cosmic rays with the grain materials, particularly the ice mantles.

Cross-References

- [Interstellar Ices](#)
- [Radiation Chemistry](#)

Radiometer

- [Bolometer](#)

Radiometric Dating

- [Absolute and Relative Ages](#)

Raman Scattering

Lisa Kaltenegger

Cornell University, Ithaca, NY, USA

Synonyms

- [Inelastic photon scattering](#)

Definition

Raman scattering is the inelastic scattering of a photon. Most photons are elastically scattered from atoms or molecules (► [Rayleigh scattering](#)), such that the scattered photons have the same energy and wavelength as the incident photons. However, a small fraction of scattered light is absorbed and subsequently emitted via an intermediate electronic state, with the scattered photons having a frequency different from the frequency of the incident photons. The energy differences are equal to the differences of the vibrational and rotational energy levels of the molecule. There are two types of Raman scattering: (1) Stokes scattering, when the molecule absorbs energy and the resulting photon has a lower energy and is shifted to the red side of the incident spectrum, and (2) anti-Stokes scattering, where the molecule loses energy and the resulting photons are more energetic and thus shifted to the blue side of the spectrum.

Cross-References

- [Mie Scattering](#)
- [Rayleigh Scattering](#)

Raman Spectroscopy

Francis McCubbin
Institute of Meteoritics, University of New Mexico, Albuquerque, NM, USA

Definition

Raman spectroscopy is a vibrational spectroscopic technique that depends on the inelastic scattering of photons. It is useful for identifying the presence of specific molecular groups within a solid, liquid, or gaseous sample. Raman spectroscopy is widely considered to be a complementary technique to infrared spectroscopy (although Raman spectroscopy can be carried out at infrared wavelengths), but Raman spectroscopy is typically preferred in

studies of inorganic carbon. Specifically, Raman spectroscopy can be used to detect double- and triple-bonded carbon groups, which are invisible to standard infrared spectroscopic techniques. The ability to detect carbon-bearing molecules, coupled with the submicron spatial resolution of modern Raman microspectroscopic imagers, makes Raman spectroscopy an important technique for studying microfossils. Furthermore, Raman spectroscopy is nondestructive, so it makes an excellent tool for classifying the mineralogy and microtextures of precious samples including meteorites and lunar samples returned from the Apollo and Luna missions to the Moon.

History

Raman spectroscopy is named after Sir Chandrasekhara Venkata Raman. Sir Raman discovered the phenomenon that bears his name in 1928 using sunlight (light source), a telescope (collector), and his eyes (detector). Today, Raman instruments are much more complex with lasers (light source), lenses, triple monochromators and holographic gratings (collector), and charge-coupled devices (detector).

Cross-References

- [CCD](#)
- [Infrared Spectroscopy](#)
- [Microfossils](#)

Rare Earth Elements

Daniele L. Pinti
Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

REE · Archean · Banded iron formation · Chert · Igneous rocks · Sedimentary rocks · Stromatolites

Synonyms

Lanthanides; Rare earth metals; Rare earth oxides

Acronyms

REE

Definition

The rare earth elements (or REE) comprise the family of lanthanides (atomic number $Z = 57$ –71), corresponding to the progressive filling of the 4f orbitals, together with the elements scandium (Sc, $Z = 21$) and yttrium (Y, $z = 39$) (Table 1). Their abundance in geological materials is usually less than 0.1 wt. %, that is, the term “rare” compared to abundances of rock-composing major oxides (SiO_2 , K_2O , CaCO_3 , etc.). They are an extremely consistent group in terms of chemical behavior, making them suitable tracers of numerous geological processes. Rare earth elements are considered particularly informative on the conditions prevailing during the

formation of rocks, and REE studies have important applications in petrology and in oceanography, where these elements are derived from the weathering of continental masses and ► [mid-ocean ridges](#) hydrothermalism.

Overview

The term “rare earth elements” derives from minerals from which they were first isolated, which were uncommon oxide-type minerals. However, this name is no longer accepted by the IUPAC (International Union of Pure and Applied Chemistry) because some of these elements are neither “rare” nor “earths” (an obsolete term for water-insoluble strong-basic oxides of electropositive metals). The low atomic number elements of the REE series are termed light rare earth elements (abbreviated LREE: from lanthanum (La) to neodymium (Nd); $Z = 57$ –60), and those with the higher atomic number are referred to as heavy rare earth elements (abbreviated HREE, from gadolinium (Gd) to lutetium (Lu); $Z = 64$ –71). Sometimes the term middle rare earth elements (abbreviated MREE), is loosely applied to the

Rare Earth Elements, Table 1 List of lanthanides + Sc and Y. Ionic radius is for trivalent ionic species (coordination number = 8) unless indicated (from Rollinson 1993 modified)

Atomic number	Name	Symbol	Group	Ionic radius (pm)*
57	Lanthanum	La	LREE	116
58	Cerium	Ce	LREE	114.3 (97, Ce^{3+})
59	Praseodymium	Pr	LREE	112.6
60	Neodymium	Nd	LREE	110.9
61	Promethium	Pm	MREE	Not naturally occurring
62	Samarium	Sm	MREE	107.9
63	Europium	Eu	MREE	106.6, 125 (Eu^{2+})
64	Gadolinium	Gd	MREE, HREE	105.3
65	Terbium	Tb	MREE, HREE	104.0
66	Dysprosium	Dy	MREE, HREE	102.7
67	Holmium	Ho	MREE, HREE	101.5
68	Erbium	Er	HREE	100.4
69	Thulium	Tm	HREE	99.4
70	Ytterbium	Yb	HREE	98.5
71	Lutetium	Lu	HREE	97.7
68	Erbium	Er	HREE	100.4
21	Scandium	Sc	–	114
39	Yttrium	Y	–	101.9

elements from about promethium (Pm) to about holmium (Ho) ($Z = 61\text{--}63$). Promethium ($Z = 61$) is a short-lived nuclide and is not observed in nature.

Due to similar outer electron shells, REE have very similar chemical and physical properties. Yttrium (Y) mimics the heavy lanthanides, particularly Ho, because having a similar the ionic radii. However, scandium (Sc) is a substantially smaller cation with geochemical behavior that differs from other rare earths. In most literature, REE include only lanthanides and Y, and Sc is treated separately (Nozaki 2001). They behave generally as incompatible elements (elements that prefer to stay in residual melt liquid during fractional crystallization) and thus they tend to be “concentrated” in the terrestrial crusts. They all form stable valences of 3^+ ions with similar ionic radii, with exception of cerium (Ce) (which has valence 3^+ and 4^+) and europium (Eu) (which has valence 2^+ and 3^+). The chemical behavior of trivalent REE varies with decreasing ionic radius and increasing atomic number (*lanthanide contraction* effect). These smooth changes cause fractionation of REE during igneous and sedimentary processes. Rare earth elements are also quite insoluble and therefore relatively immobile during low-grade [▶ metamorphism](#), [▶ weathering](#), and [▶ hydrothermal alteration](#). This is a very important feature giving insight into the origin of [▶ igneous rocks](#) and [▶ sedimentary rocks](#) through the low-temperature processes that commonly affected the Archean crust. Eu^{2+} is more soluble than trivalent elements and Eu excess may indicate hydrothermal alteration. Cerium becomes tetravalent under marine oxidative conditions: Modern manganese (Mn) nodules show Ce excesses that are mirrored by the striking negative Ce anomaly of seawater (e.g., Nozaki 2001).

Basic Methodology

Rare earth elements are present in any geological material, rocks, minerals, and in aqueous fluids (Henderson 1984; Rollinson 1993; Nozaki 2001) and thus they can be used for tracing numerous

processes, from mantle differentiation (e.g., Weyer et al. 2003) to metasomatism (i.e., the chemical alteration of a rock by hydrothermal or metamorphic-related fluids) (e.g., Whitney and Olmsted 1998), from identifying redox reactions to trace sources of continental inputs in oceans (e.g., Nozaki 2001).

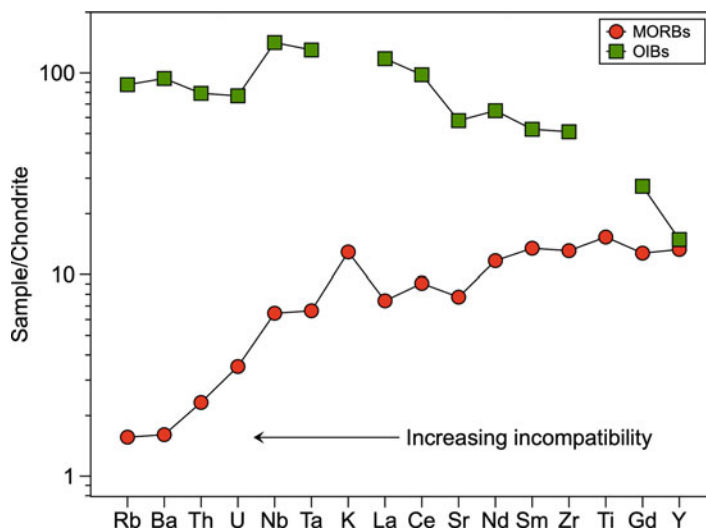
REE were initially measured by neutron-activation techniques, which have been progressively abandoned with the development of the thermal ionization mass spectrometry (TIMS) or inductively coupled plasma mass spectrometry (ICP-MS). Now this instrumentation is usually employed by laboratories worldwide to measure REE in rocks, minerals, or aqueous fluids at parts per million (ppm) to parts per billion (ppb) levels.

In order to smooth the natural variations inherited from nucleosynthesis, the abundances of REE are usually represented in the Coryell-Masuda diagram, often nicknamed “spider diagrams” (a term still popular but which is progressively changed into “multielement diagrams”), where REE are plotted alone or in combination with major and minor elements, along the x -axis (i.e., Fig. 1). The element abundances are first normalized to their concentrations in a specific reference material or in a particular geochemical reservoir and the normalized abundance plotted in the y -axis at log scale.

For igneous rocks, typical references include the composition estimated for the primitive mantle (i.e., the mantle prior to the extraction of the [▶ continental crust](#); Wood et al. 1979) or CI-chondrites, both synonymous of the Bulk Silicate Earth composition for most elements. Normalizing the rocks’ REE compositions to these references allows identifying anomalies in REE that can be related to processes of partial melting, differentiation, and fractional crystallization. For sediments, the references are the NASC (North American Shale Composite; Gromet et al. 1984) and the Post-Archean Average Australian Shale (PAAS; Taylor and McLennan 1985; McLennan 2001). The use of Precambrian shales as a reference allows to observe changes in REE composition with progressive continental growth, weathering, and recycling during eons.

Rare Earth Elements,

Fig. 1 Multielement diagram depicting major, trace, and REE elements in a typical ocean island basalt (OIB) and a mid-ocean ridge basalt (MORB) (from Winter 2001; redrawn). Concentrations are normalized against the chondritic values of Nakamura (1974). MORBs show strong depletion of most incompatible elements against an enrichment of the same elements for OIBs



Key Research Findings

Rare earth elements are used in a multitude of studies involving the evolution of the geosphere and hydrosphere and enumerating them are well beyond the scope of this entry. A few examples of applications related to the understanding of the Earth's origin are described below.

Applications

Igneous Petrology and the Archean Mantle

The REE concentration in igneous rocks is controlled by crystal-melt equilibria during magmatic evolution (=differentiation). During magmatic differentiation, elements termed *compatible* remain in minerals, while the residual liquid phase is enriched in *incompatible* elements. The LREE are very incompatible, whereas the HREE are only weakly incompatible, leading to the fractionation of the LREE/HREE ratio of rocks. In addition to the magmatic effects, depletion or enrichment of LREE is controlled by the REE chemistry of the source of the magmas. The upper mantle from which the continental crust has been extracted over the Earth's history is depleted in incompatible elements and thus in REE. Figure 1 shows the concentrations of sixteen REE normalized to the composition of chondrites and arranged in the order of increasing

compatibility for ocean island basalts (OIBs) and mid-ocean ridge basalts (MORBs). OIBs and MORBs show two distinct patterns (Fig. 1). MORBs are the product of large degrees of partial melting of the upper mantle, and thus MORB have comparable relative REE abundances to their mantle source (Gast 1968). In contrast, oceanic island basalts (OIBs) show extreme degrees of incompatible element enrichment. This has been attributed to lower degrees of partial melting of a less depleted source in incompatible elements than the MORB source.

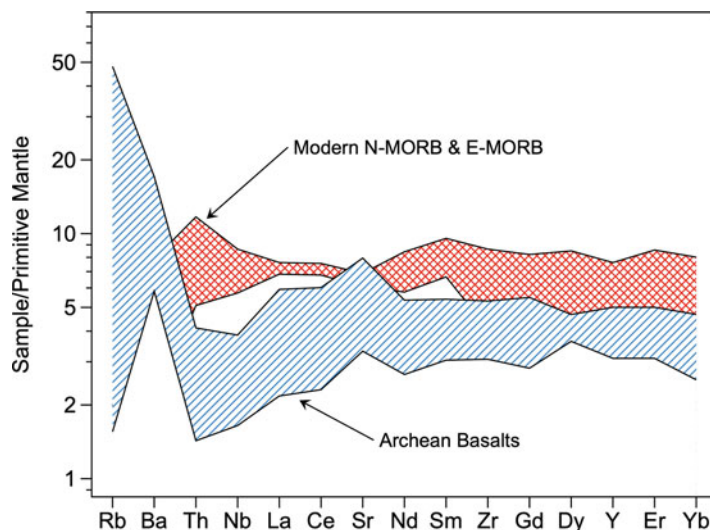
Comparing modern and Archean REE patterns of igneous rocks can be useful for explaining the thermal evolution of the mantle. Arndt et al. (1997) compared Archean basalts and modern MORBs. Archean basalts show a stronger depletion in incompatible elements with respect to modern MORBs, which cannot be explained by variations in the composition of the mantle source (Fig. 2). As incompatible elements are diluted upon progressing melting, the weak enrichment of incompatible element in Archean basalts reveals extensive melting of the hotter Archean mantle.

Sedimentary Petrology and Archean Sediments

Different factors control the distribution of the REE in sedimentary rocks, depending on their origin as "clastic" sediments (which means derived

Rare Earth Elements,

Fig. 2 Multielement diagram showing major, trace, and REE elements in Archean tholeiitic basalts and in modern MORB, normalized against primitive mantle. The relative depletion of elements in Archean counterparts of modern basalts can be explained by a larger degree of partial melting produced in a hotter Archean mantle (After Arndt et al. 1997; redrawn)

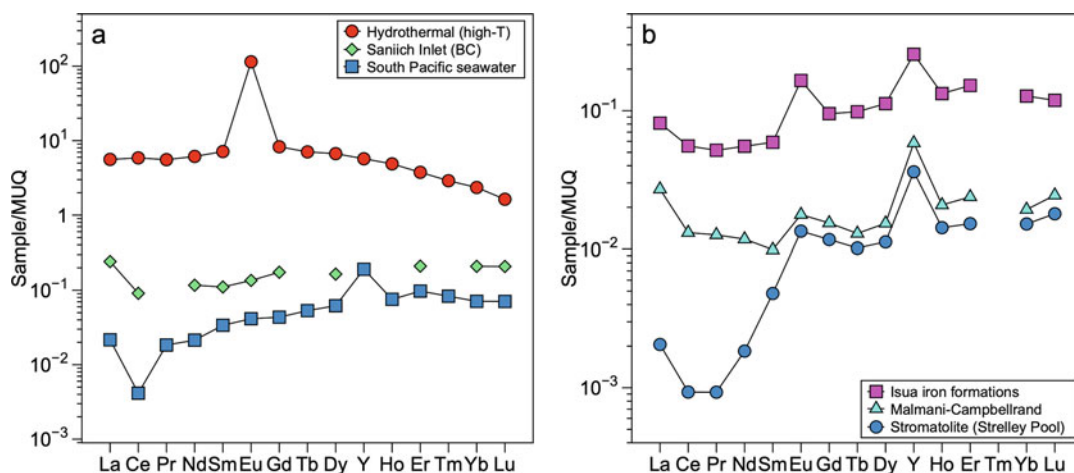


from erosion of igneous, metamorphic, or sedimentary rocks) or “chemical” sediments, that is, sediments formed by the precipitation of minerals from seawater or hydrothermal fluids. The most important factor contributing to the REE content in clastic sediments is their provenance (igneous, metamorphic, or sedimentary source). This is because REE are essentially insoluble and present in very low concentrations in seawater (Fig. 3a). The REE present in clastic sediments are therefore chiefly transported as particulate matter and reflect the chemistry of their source.

The REE amount in aqueous fluids is a function of the type of complexes that the REE may form, their residence time in the ocean, and the oxidizing potential of the water. In shale-normalized REE + Y diagrams, modern seawater is characterized by depleted LREE relative to mid and HREE resulting in positively sloped patterns, with a characteristic positive anomaly for yttrium (Y) and a negative anomaly for cerium (Ce) (Fig. 3a) (Alibo and Nozaki 1998). The Ce anomaly is expressed as Ce/Ce^* , where Ce^* is interpolated between the neighbouring elements La and Nd. Likewise, the Eu anomaly is expressed as Eu/Eu^* , where Eu^* is interpolated between the neighboring elements Sm and Gd. The Y anomalies are related to its higher capability to make soluble complexes with respect to the neighboring REE. The Ce anomaly reveals the oxidation of Ce^{3+} into Ce^{4+} , which is rapidly

scavenged by Mn-Fe oxides. Cerium anomalies in sediments and sedimentary rocks are thus useful proxies for the state of oxidation in the ocean and the atmosphere in the past. The progressive enrichment from the lighter to the heavier REE is believed to result from the increasing capacity to form soluble complexes with increasing atomic mass. Hydrothermal fluids originate in convection cells along mid-ocean ridges and back-arc spreading centers. Chondrite-normalized or shales-normalized REE + Y patterns show enrichment of LREE compared to mid- and heavy REE and a pronounced positive Eu anomaly (Fig. 3a) (Michard et al. 1983; Douville et al. 1999; Bau and Dulski 1999). The Eu and LREE enrichment seem to be controlled by fluid-solid exchange with plagioclase (a reservoir of Eu).

These characteristics have been applied to interpret the REE patterns in Archean chemical sediments, mainly cherts (e.g., Bolhar et al. 2005; Orberger et al. 2006), banded iron formations (Bolhar et al. 2004, 2005), and stromatolitic carbonates (Kamber and Webb 2001; Van Kranendonk et al. 2003). Figure 3b shows the REE + Y pattern, in 3.5-Ga-old stromatolites from Strelley Pool, Pilbara Craton, in 2.5-Ga-old microbialites (a generic term referring to organo-sedimentary structures such as stromatolites) from the ► [Campbellrand-Malmani platform](#), South Africa, and in the 3.7 Ga-iron formations from ► [Isua](#), West Greenland. These



Rare Earth Elements, Fig. 3 Multielement diagram showing: (a) REE measured in seawater (data from Alibo and Nozaki 1998); anoxic water of the Saanich Inlet, BC, Canada, as analogue of anoxic Archean seawater (data from German and Elderfield 1989); and high-temperature hydrothermal vents (data from Bau and Dulski 1999). (b) Multielement diagram showing REE measured in chemical sediments: stromatolites from Strelley Pool, Pilbara Craton, Western Australia (data from Van

Kranendonk et al. 2003); iron formations from Isua Supracrustal Belt, West Greenland (data from Bolhar et al. 2004); and carbonate microbialites from the Campbellrand-Malmani platform, South Africa (data from Kamber and Webb 2001). REE concentrations are normalized against the new reference material Mud of Queensland of Kamber et al. (2005) based on analyses of 30 alluvial sediments collected from 25 rivers in Queensland, Eastern Australia

patterns differ from both modern seawater and hydrothermal solutions. Figure 3a suggests that these organisms may have grown in anoxic waters, such as those from the modern Saanich fjord behind the Vancouver Island, and attests to the prevailing low levels of free oxygen in the mid-Archean atmosphere.

In contrast, the direct influence of hydrothermal fluids can be observed in some Archean cherts (Fig. 4), which show REE patterns very similar to those measured in black-smoker hydrothermal fluids. This reflects the common interpretation of Archean cherts as a product of secondary silicification of meta- or volcanoclastic sediments by silica-rich hot fluids (e.g., Weis and Wasserburg 1987; Orberger et al. 2006).

Element/element diagrams can also be useful to determine the depositional environment of the Archean sediments, both in terms of source(s) and redox conditions, particularly looking at the Ce and Eu anomalies. This is particularly useful in sediments where isotopic biosignatures are measured, such as carbon or nitrogen isotopes (e.g., Pinti et al. 2009a) in order to determine if the

depositional environment is compatible with the habitats where past organisms lived and left isotopic traces of their metabolic activity.

Figure 5 illustrates the redox-sensitive Eu anomalies plotted against the Y/Ho ratios for Archean cherts sampled in 3.5 Ga formations of the North Pole dome (Pi-47-00, Pi-85-00, and Pano D136-0), famous Apex chert microfossil locality (sample Pi-02-07), stromatolite (Pi-02-47), and 3.2 Ga formations of Dixon Island (Pi-01-45), all located within the Archean Pilbara Greenstone Belt, Western Australia. Three fields are reported which correspond to the REE signatures of the three types of cherts which eventually existed during Precambrian (van den Boorn et al. 2007): (1) silicification of volcanoclastic debris by silica-saturated seawater and relatively weak or no hydrothermal input (S-cherts); and (2 and 3) in sediment-starved shallow or deep environments, interaction between hot Si-rich fluid and seawater in different proportions promoting orthochemical deposition of silica (C-cherts). These fields fall close to three possible sources of REE, corresponding to three distinct geological

Rare Earth Elements,

Fig. 4 Multielement diagram showing REE measured in high-temperature hydrothermal vents (data from Bau and Dulski 1999) and a 3.5 Ga Archean chert from radiating swarm dykes of the Dresser Formation, North Pole Dome, Western Australia (data from Orberger et al. 2006). Similarities between the fractionation of REE suggest the precipitation of chert (silicification) from hydrothermal fluids

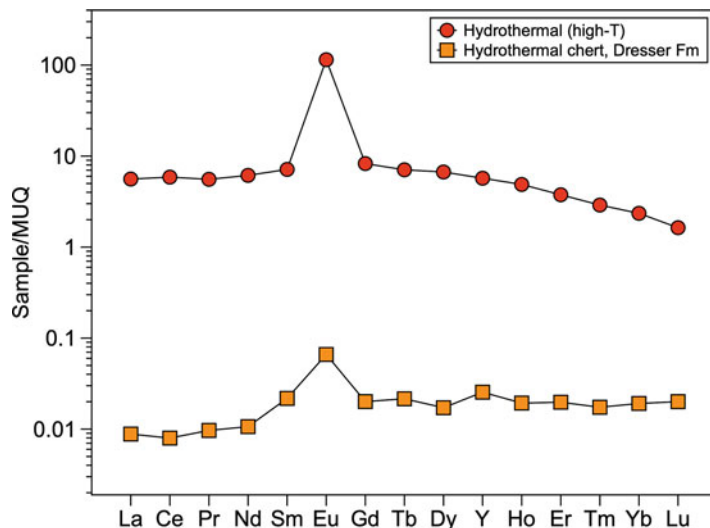
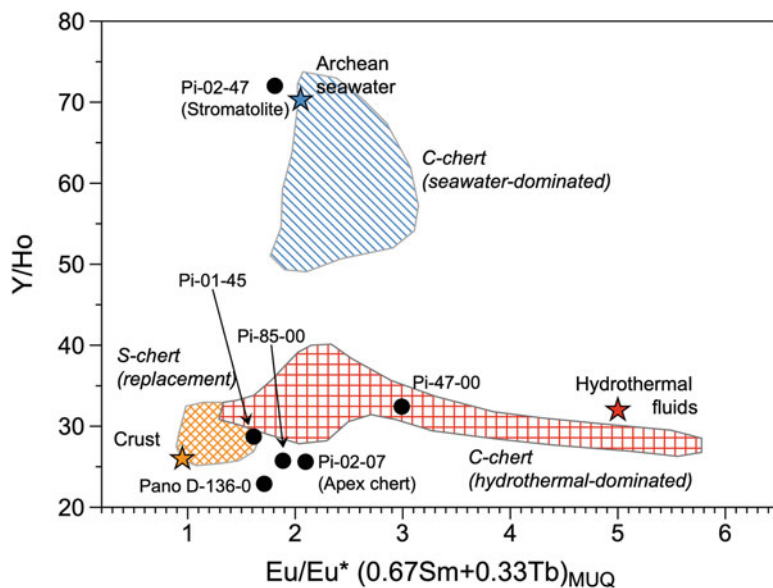
**Rare Earth Elements,**

Fig. 5 Eu/Eu^* ratio calculated as $\text{Eu}/[(0.67\text{Sm} + 0.33\text{Tb})]_{\text{MUQ}}$ against the raw Y/Ho ratio. The three shaded areas labeled “S-chert” and “C-chert” have been obtained by plotting REE data from van den Boorn et al. (2007). Black dots are 3.5–3.2 Ga-chert samples from Pinti et al. (2009a)



environments: (1) hydrothermal fluids ($\text{Eu}/\text{Eu}^* \gg 5$ and $\text{Y}/\text{Ho} = 32$; Mills and Elderfield 1995); (2) upper-crust rocks ($\text{Eu}/\text{Eu}^* = 0.95$ and chondritic $\text{Y}/\text{Ho} = 26$; Taylor and McLennan 1981); and (3) Archean seawater represented by Strelley Pool stromatolites ($\text{Eu}/\text{Eu}^* = 2.05$ and superchondritic $\text{Y}/\text{Ho} = 70.3$; Van Kranendonk et al. 2003).

The diagram below shows that the silicified stromatolite (sample Pi-02-47) has typical REE values from the Archean seawater, well distinguished from other chert samples. Apex chert

REE signatures indicate an influence from hydrothermal fluids, as suggested by Brasier et al. (2002) and Pinti et al. (2009b). More interestingly, cherts (Pi-47-00, Pano D-136-0) which contain nitrogen with a light isotopic composition ($\delta^{15}\text{N}$ of -5%) were interpreted by Pinti et al. (2001) to derive from the metabolic activity of chemolithoautotrophs organisms living in hydrothermal environments have REE composition closer to that of C-cherts formed under a stronger influence of hydrothermal effluents with contribution of crustal material (Fig. 5).

Future Directions

Numerous studies on meteorites and lunar samples used REE to trace and quantify secondary processes such as hydrothermal alteration or the rate of mantle melting and crustal evolution. The study of REE on Martian meteorites is important to understand the dynamics of crust formation on this planet (e.g., Nyquist et al. 2016). When samples from Mars can be returned to Earth, REE measurements will be fundamental to shed light on the igneous and sedimentary history of the Red Planet. REE measurements were also performed on the asteroidal material brought to Earth from Itokawa (Hayabusa 1 mission) (Ebihara et al. 2015) and similar studies will be performed on grains from Ryugu (Hayabusa 2 mission) actually under examination and Bennu (OSIRIS-REx mission) which will return on Earth in 2023, to decipher the geological history of these asteroids representing planetesimals.

Cross-References

- [Archean Mantle](#)
- [Banded Iron Formation](#)
- [Bulk Silicate Earth](#)
- [Campbellrand-Malmani Platform, South Africa](#)
- [Cerium, Anomalies of](#)
- [Chert](#)
- [Hydrothermal Environments](#)
- [Igneous Rock](#)
- [Isua Supracrustal Belt](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)
- [Pilbara Craton](#)
- [Sedimentary Rock](#)
- [Stromatolites](#)

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Rare Earth Metals

► Rare Earth Elements

Rare Earth Oxides

► Rare Earth Elements

Rare Gases

► Noble Gases

Rate Equation Models

Eric Herbst

University of Virginia, Charlottesville, VA, USA

Definition

Rate equation models are chemical simulations in which the rate of change of the concentration of each molecule in the simulation is written in terms of the rates of formation and depletion. The integration of the coupled differential equations leads to the concentration of each species as a function

of time. Large numbers of chemical reactions, typically greater than 1000, are needed to simulate the chemistry of interstellar clouds in the gas and on the surfaces of dust particles.

Overview

Rate equation models consist of kinetic differential equations, which equate the time derivative of the concentration of each molecule in the model with the sum of their rates of gain and loss (Wakelam et al. 2010). The gain and loss terms can involve bimolecular collisions between species or can involve bombardment by photons and external cosmic rays leading to ionization and dissociation. As an example, consider a gas-phase process in which a molecule C is formed by a reaction between species A and B and destroyed by collision with species D and by photon bombardment. The kinetic differential equation for species C is then

$$d[C]/dt = k_{AB}[A][B] - k_{CD}[C][D] - k_{\text{phot}}[C],$$

where the brackets refer to concentration and each k is a rate coefficient (sometimes referred to as a rate constant in the chemical literature). If the model includes grain chemistry, an additional loss term involves accretion of species C onto the dust grains, while an additional gain involves desorption of C from the grain, both thermal and non-thermal. Rate coefficients, if measured or calculated, are often fit to expressions of the type $\alpha(T/300 \text{ K})^\beta \exp(-\gamma/T)$.

Rate equation models normally contain a large number of these differential equations, which can be integrated to obtain concentrations as functions of time despite the fact that they are strongly coupled with each other and are “stiff,” a term that refers to strongly differing reaction times. In the interstellar medium, the granular chemistry can include reactions that occur on the surface of bare silicate or carbonaceous grains, as well as reactions on and in ice mantles, which build up in cold clouds. In the simplest treatments, all ice molecules are treated in the same manner, whether or not they lie on the surface or in the bulk of the

mantle. More complex models differentiate between these two phases. Reactions on grain surfaces can occur via a variety of different mechanisms, including thermal diffusion of reactants on grain surfaces leading to collisions (Langmuir-Hinshelwood mechanism), collisions of a gas-phase species with a species adsorbed on a grain (Eley-Rideal mechanism), and nonthermal motion of a reactant often newly landing on a grain and leading to an enhanced collision rate with a surface species (hot-atom mechanism). Additional processes include adsorption, thermal desorption, and nonthermal desorption via photons, cosmic rays, and the exothermicity of surface reactions. Chemical processes in the bulk mantle are poorly understood.

Concentrations of species both in the gas and on grains are typically expressed with respect to the total amount of gaseous hydrogen, both atomic and molecular, and known as fractional abundances. Rate equations involving surface species can be poor representations of surface chemistry in the limit of small numbers of selected important molecules per grain, where stochastic methods involving the treatment of individual species are more accurate if more computationally expensive. Rate equations can be modified to be more accurate in this limit (Garrod et al. 2009).

Cross-References

- [Interstellar Chemical Processes](#)
- [Interstellar Cloud](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)

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Rayleigh Scattering

Emmanuel Marcq

LATMOS/IPSL, UVSQ Université Paris-Saclay,
Sorbonne Université, CNRS, Guyancourt, France

Keywords

Scattering (conservative, elastic) · Far field · Polarizing

Definition

Rayleigh scattering is an exact, analytical solution to the problem of radiation scattering in the limit of a vanishingly small scattering particle compared to the radiation wavelength. As such, it is valid for gaseous molecules at wavelengths used in planetary atmospheric studies, resulting in a polarized, conservative scattering increasing toward shorter wavelengths. It gives a characteristic bluish hue to the upper layers of clear atmospheres, has a major influence on planetary albedos (and thus radiative balance), and provides a lower bound on the probed altitude for transit spectroscopy.

Overview

Hypotheses

In Rayleigh scattering, the scattering particle is assumed to be a point-like, *induced* electrical dipole such as:

$$\vec{p} = \alpha(\omega)\varepsilon_0\vec{E} \quad (1)$$

where $\vec{E}$ is the oscillating electrical field (angular frequency ω) from the incident radiation, $\vec{p}$ the induced electrical dipole, ε_0 the vacuum permittivity, and $\alpha(\omega)$ the scalar *polarizability* of the induced dipole (dimensionnally homogeneous to a volume in SI units).

Since $\vec{E}$ oscillates at a frequency $\nu = \omega/2\pi$, then so does $\vec{p}$. Thus, like any variable electrical

dipole, the induced dipole will radiate its own electromagnetic radiation in all directions at the same frequency – as such, Rayleigh scattering is a typical example of *elastic scattering*.

The simplest model for the induced dipole is an electronic cloud subject to a harmonic potential around a positive nucleus. In such a case, there will be a phase shift between the electronic oscillation and the incident field, leading to partial absorption of the incident radiation. The absorbed power is exactly equal to that of the scattered radiation, so that no energy leaves the electromagnetic field. In other words, Rayleigh scattering is an example of *conservative scattering*: $\varpi_0 = 1$ at all frequencies.

Finally, three last hypotheses are assumed:

- Only *far field* scattered electromagnetic radiation is considered, that is, neglecting terms which vanish faster than r^{-2} , r being the distance between the observer and the scattering dipole.
- The incident radiation frequency ν is assumed to be much smaller than the resonant frequency ν_0 associated with the harmonic potential of the dipole: $\nu \ll \nu_0$.
- The medium is dilute, that is inter-dipoles interactions are negligible, which is the case in an ideal gaseous phase.

Cross Section

The scattering cross section in Rayleigh regime is given by:

$$\sigma_\lambda = \frac{128\pi^5\alpha_0^2}{3\lambda^4} \quad (2)$$

or, using macroscopic quantities such as (real) refractive index n and scatterers number density N instead of the microscopic static polarizability α_0 :

$$\sigma_\lambda = \frac{8\pi^3(n^2 - 1)^2}{3N^2\lambda^4}f(\delta) \quad (3)$$

The weak dependency of n with wavelength yields the characteristic spectral exponent $\sigma_\lambda \propto \lambda^{-4}$ of Rayleigh scattering, sometimes corrected as

$\sigma_\lambda \propto \lambda^{-4+\varepsilon}$ with $\varepsilon \ll 1$. Also, a corrective multiplicative factor $f(\delta) = \frac{6+3\delta}{6-7\delta} \approx 1$ for $\delta \ll 1$ is included in order to account for the anisotropy of molecular polarizability.

Phase Function

The scalar phase function of Rayleigh scattering only depends on the scattering angle Θ and is given by:

$$P(\Theta) = \frac{3}{4}(1 + \cos^2 \Theta) \quad (4)$$

yielding an asymmetry parameter $g = 0$, although Rayleigh scattering is *not* isotropic.

Polarization

In the single scattering limit, Rayleigh scattering is strongly polarizing, as can be seen in its phase matrix in the Stokes formalism (with the Q direction along the scattering plane):

$$\vec{P}(\Theta) = \frac{3}{4} \begin{pmatrix} \cos^2 \Theta + 1 & \cos^2 \Theta - 1 & 0 & 0 \\ \cos^2 \Theta - 1 & \cos^2 \Theta + 1 & 0 & 0 \\ 0 & 0 & 2 \cos \Theta & 0 \\ 0 & 0 & 0 & 2 \cos \Theta \end{pmatrix} \quad (5)$$

which yields the degree of linear polarization $P_l(\Theta)$ of (single) Rayleigh scattering for unpolarized incident radiation:

$$p_l(\Theta) = \frac{\sin^2 \Theta}{1 + \cos^2 \Theta} \quad (6)$$

P_l therefore ranges from 0 when source-scatterer-observer are aligned ($\Theta = 0^\circ$ or 180°), to 100% for $\Theta = 90^\circ$.

Importance in Planetary Atmospheres

Clear Sky

Out of gaseous absorption bands, radiative transfer within a purely gaseous atmosphere (with no aerosols) is well approximated by Rayleigh scattering in a gas layer of total optical depth $\tau \propto P$, yielding:

- A weakly attenuated direct beam, superimposed to a faint, blue, strongly polarized diffuse component for $\tau \ll 1$ (P less than ~ 0.1 bar, dominated by single scattering).

- A strongly attenuated reddened direct beam, superimposed to a bright, almost white, weakly polarized diffuse component for $\tau \gg 1$ (P larger than a few bars), due to the prevalence of multiple scattering in this case.

Transit Spectroscopy

Even in absence of clouds (or other aerosols) and gaseous absorption, Rayleigh scattering by clear atmospheres leads to the existence of a lower “transit floor,” limiting the atmospheric depth that can be probed using transit spectroscopy.

Due to the λ^{-4} dependency of Rayleigh scattering, this Rayleigh floor is more noticeable at shorter wavelengths and displays a characteristic spectral slope. It can be shown that:

$$\frac{d \ln \delta(\lambda)}{d \ln \lambda} \approx \frac{-8H}{R} \quad (7)$$

where $\delta(\lambda)$ is the transit depth for the considered wavelength, R the planetary radius, and H the atmospheric scale height. This provides a direct measurement of $H = kT/\mu g$, which can be used in turn to derive the atmospheric temperature T , local gravity acceleration g , or the mean molecular mass μ .

Albedo

Since Rayleigh scattering is conservative, it will always increase the albedo of a planet compared to the albedo of the underlying cloud ceiling or planetary surface. This effect is particularly dramatic:

- For thicker atmospheres ($P > 1$ bar)
- Around hotter stars, whose emission peak is shifted to shorter wavelengths
- For highly polarizable species, such as CO_2 , which exhibit a comparatively larger Rayleigh cross section

The case of CO_2 is of particular interest for planetary habitability, since it yields the classical definition of the *outer edge* of the habitable zone for typical telluric atmospheres (major species $\text{CO}_2\text{--H}_2\text{O--N}_2$). The amount of CO_2 greenhouse required to sustain surface temperatures above the freezing point of water increases with increasing

stellar distances. This leads to a higher albedo due the strong Rayleigh scattering by increasing CO₂, and therefore to a decrease of the equilibrium temperature that more than offsets the increase in greenhouse effect, hence the existence of an optimal distance that defines the outer edge of the habitable zone (Kasting et al. 1993; Neubauer et al. 2013).

Cross-References

- [Atmospheric Retrieval for Exoplanets](#)
- [Greenhouse Effect](#)
- [Mie Scattering](#)
- [Radiative Transfer \(Atmospheres\)](#)

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Reaction Network

- [Artificial Chemistries](#)
- [Chemical Reaction Network](#)

Reaction Rate Coefficient

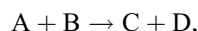
Steven B. Charnley
Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Definition

Reaction rate coefficients are the phenomenological coefficients occurring in rate expressions for

elementary chemical reactions. They can be determined either experimentally or theoretically. Bimolecular rate coefficients are expressed in units of cm³ s^{−1} and unimolecular ones in units of mol. s^{−1}. Typical values for interstellar chemistry are 10^{−9} cm³ s^{−1} for ion-neutral reactions and 10^{−11} cm³ s^{−1} for neutral-neutral reactions.

For example, for the reaction



where the letters represent either neutral or charged atoms or molecules, the rate at which the reaction occurs is $kn(A)n(B)$, with n the number density of a species in units of cm³ when the reaction rate coefficient k is expressed in cm³ s^{−1}.

Cross-References

- [Bimolecular Reaction](#)
- [Interstellar Chemical Processes](#)
- [Unimolecular Reaction](#)

Reaction Vessels

- [Simulation Chambers](#)

Recombination

Enrique Viguera
Genetics Department Sciences Faculty,
University of Malaga, Malaga, Spain

Synonyms

[Crossing over](#); [DNA recombination](#)

Definition

Recombination is the process by which a new nucleic acid molecule formed by the combination (through covalent joining) of different sequences is obtained. It may involve (1) physical exchange between two duplex DNA homologous molecules

(homologous recombination) occurring at any point along their sequence, (2) the covalent joining of two molecules at specific sequences (site-specific recombination) or at unrelated sequences (nonhomologous end joining), and (3) the joining of two different parental sequences by short repeats during replication (copy-choice recombination). Recombination is a major source of genetic variation during meiosis (the process of reductional cellular division in which a diploid cell generates four haploid cells that results in the formation of gametes or spores) in eukaryotes, as well as in the reshuffling (process by which DNA or RNA chimeric forms are generated by a breakage-and-join or template-switching mechanisms) of immunoglobulin genes and viral genes. Recombination enzymes are implicated in ► [DNA repair](#).

Cross-References

- [DNA Damage](#)
- [DNA Repair](#)
- [Gene](#)
- [Genetic Map](#)
- [Genetics](#)
- [Genome](#)
- [Genomics](#)
- [Genotype](#)
- [Lateral Gene Transfer](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Replication \(Genetics\)](#)

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Recurring Slope Lineae

- [Slope Lineae, Recurrent](#)

Red Beds

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Primary red beds are non-marine sedimentary sequences composed of sandstone, siltstone, or shale, covered by a red coating from the dehydration of goethite to hematite, the former being unstable at high temperatures and in the absence of water. These sedimentary rocks are deposited in hot arid climates (deserts) under oxidizing conditions. Red beds can form also during diagenesis (the processes after burial bringing to the lithification of sediments) by alteration of Mg-Fe-rich silicates by oxygenated groundwater. Red beds are common in the Proterozoic and Phanerozoic and mark particularly oxidizing periods such as during the Permian and the Triassic. Their absence in sedimentary sequences older than 2.65 Ga is often interpreted as an evidence of a poorly oxygenated atmosphere during the Archean.

Cross-References

- [Goethite](#)
- [Great Oxidation Event](#)
- [Hematite](#)
- [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Siderite](#)
- [Weathering Profile](#)

Red Dwarf

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

The smallest ($M \sim 0.75\text{--}0.1\ M_{\odot}$), coolest ($T < 3,500\ \text{K}$), and least luminous ($L \sim 10^{-3}\text{--}0.1\ L_{\odot}$) fusion-powered stars, of spectral type M or late K, are called red dwarfs. They are the most numerous stars in the galaxy: 20 out of 30 stars in the solar neighborhood (including our nearest neighbor, Proxima Centauri) belong to this class. The less massive of them live up to 10^{13} years and all of them are still on the early main sequence phase. In many cases, planets have been found orbiting red dwarf stars.

Cross-References

- [Spectral Type](#)
- [Stars](#)

Red Giant

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

A low or intermediate mass star ($0.4\text{--}8\ M$) in the late phase in its evolution becomes a red giant. After exhaustion of the central hydrogen fuel, the stellar core contracts, and the envelope expands (to tens or hundreds of times its size on the main sequence) and cools. Hydrogen fuses to helium in a shell surrounding the core, releasing more power (energy per unit time) than on the main sequence, and the point representing the star ascends the red giant branch of the ► [Hertzsprung-Russell diagram](#). The ascent stops when core temperature allows helium fusion, which takes place in the red clump (for metal-rich

stars) or in the ► [horizontal branch](#) (for metal-poor stars). More massive stars become red supergiants, which are substantially more luminous, while *red dwarfs* are fully convective and never evolve to red giants (no differentiation occurs between core and envelope).

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Horizontal Branch](#)
- [Main Sequence, Star](#)
- [Stellar Evolution](#)

Red Rectangle

Sun Kwok

Faculty of Science, The University of Hong Kong, Hong Kong, China

Keywords

Reflection nebulae · Extended red emission · Molecular synthesis – photoluminescence · Unidentified infrared emission bands

Synonyms

[AFGL 915](#), [IRAS 06176-1036](#); [HD 44179](#)

Definition

The Red Rectangle (astronomical coordinates J2000 RA = 06 19 58.2, DEC = $-10\ 38\ 14.7$) in the constellation Monoceros is the common name given to the infrared source CRL 915 (=AFGL 915). The central star of the nebula is HD 44179 = BD $-10^{\circ}1476$.

History

The Red Rectangle was discovered as the result of ground-based identification of infrared sources

observed in the Air Force Cambridge Research Laboratory (AFCRL) rocket sky survey. The infrared object AFCRL 915 coincides in position with a nebulous object on the National Geographic Society-Palomar Sky Survey red print. Because of the peculiar shape of the nebula, the object was given the name “the Red Rectangle” by Martin Cohen and Mike Merrill. In November 1973, Cohen and Merrill took a picture of the object with the 4-m telescope of the *Kitt Peak National Observatory* and found it to have a set of spikes in the form of an “X.” Nebular emission can be detected as far as 56 arc s from the star, giving a total angular extent of ~ 2 arc min in the sky. Recent *Hubble Space Telescope* imaging reveals a biconical structure, with the edges of the cone connected by straight “ladders” (see Fig. 1). These structures have been interpreted as the result of projection effects of concentric arcs due to spherical episodic outflows (Koning et al. 2011).

Overview

The central star HD 44179 is of ► [spectral type B9-A0](#) and has been identified as a spectroscopic binary system of period 319 ± 3 days (Van Winckel et al. 1995). It is deficient in iron ($[\text{Fe}/\text{H}] = -3.3$) and other refractory elements

(Mg, Si, Ca) but has normal solar C, N, O, S, abundances.

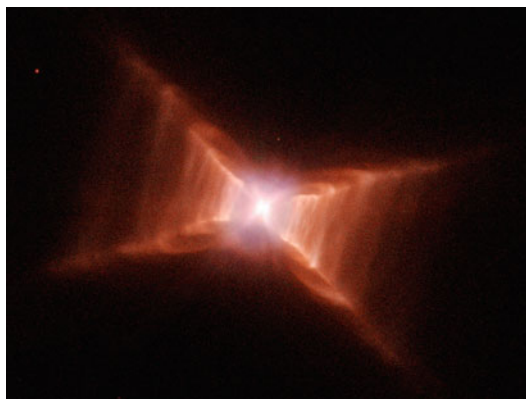
In the infrared, the Red Rectangle shows strong ► [unidentified infrared emission \(UIE\) bands](#) (Russell et al. 1978), suggesting that it is carbon rich. However, infrared emission features attributed to crystalline silicates (olivines) are also seen (Waters et al. 1998).

The astronomical extended red emission (ERE) was first discovered in the Red Rectangle (Schmidt et al. 1980). The ERE is likely to be due to photoluminescence of a carbonaceous semiconductor, but the exact chemical nature of the carrier is not known. Narrow emission features resembling those of the diffuse interstellar bands (DIB) can be seen on top of the continuum emission (Van Winckel et al. 2002).

Although the Red Rectangle is widely believed to be an object in the late stages of stellar evolution, its exact evolutionary status is not certain. The most interesting aspect is that the Red Rectangle is an active site of molecular synthesis. The fact that the DIB, ERE, and UIE unidentified emission phenomena all manifest themselves in this nebula raises the question of whether the carriers responsible for these three spectral mysteries are chemically related.

Cross-References

- [Diffuse Interstellar Bands](#)
- [Extended Red Emission](#)
- [Stellar Evolution](#)
- [Unidentified Infrared Emission Bands](#)



Red Rectangle, Fig. 1 HST wide field planetary camera 2 image of the Red Rectangle. (Photo credit: NASA/ESA Hans Van Winckel and Martin Cohen)

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sometimes useful to define R_V , the *ratio of total visual to selective extinction*, as

$$R_V = A_V / E_{B-V}. \quad (2)$$

where A_V is the extinction in the visual band. Although theoretically it might be expected that A_V would depend on the size and composition of the interstellar dust particles, in the low-density portion of the ► [interstellar medium](#), R_V is nearly constant and approximately equal to 3.

Cross-References

- [Extinction, Interstellar or Atmospheric](#)
- [Interstellar Dust](#)
- [Johnson UBV Bandpasses](#)
- [Magnitude](#)

Reddening, Interstellar

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Because the extinction by ► [interstellar dust](#) grains depends upon wavelength, with greater extinction at shorter wavelengths, starlight passing through the interstellar medium is reddened with respect to the light emitted by the source star. The reddening of a star is customarily quantified by astronomers through “selective extinction,” defined as

$$E_{B-V} = (B - V) - (B - V)_0 \quad (1)$$

where B (blue) and V (visual) are the stellar ► [magnitudes](#) on the Johnson photometric system (observed values minus intrinsic values [subzero] for the star, where the intrinsic values are estimated from the values for stars near the Sun of the same spectral type as the star in question). The central wavelengths of these photometric bands are 0.44 μm for B and 0.55 μm for V . It is

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REDESPA

Jesús Martínez-Frías
Instituto de Geociencias, IGEO (CSIC-
Universidad Complutense de Madrid), Madrid,
Spain

Definition

REDESPA is the Spanish Planetology and Astrobiology Network (Red Española de Planetología y Astrobiología - REDESPA). It was founded and established by Dr. Jesús Martínez-Frías in 2013 under the umbrella of the Official Spanish Association of Geologists (ICOG). It is coordinated by a Board of more than 50 experts from different disciplines and from more than a dozen Spanish organizations including the Spanish National Research Council (CSIC), National Institute of Aerospace Technology (INTA), Centro de

Astrobiología (CAB), National Astronomic Observatory, and Science Museum of Castilla-La Mancha. REDESPA's mission is to promote planetary sciences and astrobiology as an open and versatile platform about different scientific subjects in a transdisciplinary approach, as well as educational, ethical, and societal issues. In the context of REDESPA, there is a special and specific chapter for young researchers (JIPA: Jóvenes Investigadores en Planetología y Astrobiología). The Membership registration in REDESPA is free and open to all interested people. REDESPA has developed different Courses, in collaboration with the ICOG's Professional School of Geology for Spain and LatinAmerica, about Planetology and Astrobiology (two editions), Mars and Catastrophes and Extinction Events and with the Ministry of Defense (Cátedra Juan de Borbón), Complutense University of Madrid and Institute of Geosciences (IGEO) about "Challenges in Astrobiology for the future of Humankind." REDESPA is one of the founding institutions of the Red Iberoamericana de Astrobiología (Latin American Astrobiology Network).

Redox Potential

Tori M. Hoehler
Exobiology Branch, NASA Ames Research
Center, Moffett Field, Mountain View, CA, USA

Keywords

Oxidation · Reduction · Electrochemical potential

Synonyms

E ; E_H ; Reduction potential

Definition

The redox potential is a measure of the thermodynamic driving force for a species to either donate

electrons (be oxidized) or accept electrons (be reduced) in aqueous chemical reactions.

Overview

With origins in electrochemistry, the concept of redox potential is also widely employed in describing and understanding the energetics of electron transfer chemistry in biological and geochemical systems. While defined in the strict chemical sense in reference to a single species or reaction, redox potential is also sometimes considered in both biology and geochemistry as a property of an overall system (e.g., an assemblage of microorganisms or minerals) that influences reactions and processes occurring within the system. Significant differences exist in the terminology and measures used to describe redox potential in the geochemical and biological sciences, but all relate fundamentally to the direction of, and thermodynamic driving force for, electron transfer in chemical reactions.

Electrochemistry

► **Reduction** or oxidation potentials came into use to describe, and are measured in, electrochemical cells. A chemically complete cell represents an oxidation half reaction (e.g., $X_{\text{red}} \rightarrow X_{\text{ox}} + ne^-$) coupled to a reduction half reaction (e.g., $Y_{\text{ox}} + ne^- \rightarrow Y_{\text{red}}$). The zero-current potential (in volts) is, in practice, measured for the entire cell ($X_{\text{red}} + Y_{\text{ox}} \rightarrow X_{\text{ox}} + Y_{\text{red}}$) but, in principle, constitutes a characteristic contribution from each half reaction. Reduction potentials can thus be measured (and are reported) relative to a reference standard half reaction, the standard hydrogen electrode (SHE), which is assigned a reduction potential of zero for all temperatures. The SHE consists of $\text{H}_2(\text{g})$ and $\text{H}^+(\text{aq})$ at unit fugacity (1 bar) and activity (1 M), respectively, with a platinum electrode. Tabulated data are typically presented for individual half reactions, as *standard* reduction potentials, E° (representing the characteristic contribution of that half reaction to an electrochemical cell with products and reactants in their standard state), at a specified temperature. A positive reduction potential implies that a given half reaction will proceed spontaneously

in the reductive direction when coupled to a half reaction having a less positive, or negative, reduction potential (in which case the second half reaction will proceed in the reverse direction, as an oxidation).

Electrochemical potential, E (or E_H , where the subscript H denotes reference to the SHE), is directly related to Gibbs energy change, ΔG , via the Nernst equation:

$$\Delta G = -nFE \quad (1)$$

where n is the stoichiometry of electron transfer in the reaction and F is the Faraday constant ($96,485 \text{ Coulombs} \cdot \text{mol}^{-1}$). Accordingly, E is sensitive to activities of products and reactants, as well as temperature and (to a significantly smaller degree, for aqueous reactions) pressure. The redox potential under nonstandard conditions is related to the standard reduction potential via

$$E = E^\circ - (RT/nF) \ln Q \quad (2)$$

where T is Kelvin temperature, R is the universal gas constant ($R = 8.314 \text{ J} \cdot \text{mol}^{-1} \text{ K}^{-1}$), and Q is the reaction quotient (the mathematical product of the activities of products raised to their respective stoichiometric coefficients divided by the mathematical product of the activities of reactants raised to their respective stoichiometric coefficients).

Biology

Virtually all reactions employed in catabolism, and many reactions employed in metabolism more generally, involve transfer of electrons. Extensive use is made of redox potentials in characterizing such processes. Because reactions in cell cytoplasm typically occur at near-neutral pH, a convention in biology is to work with a modified standard reduction potential, $E^{\circ'}$ (or E_o'), that specifies the zero-current potential for a given half reaction at pH = 7 (where standard reduction potential is expressed for unit H^+ activity, or pH = 0). For reactions that include protons as products or reactants, $E^{\circ'}$ differs from E° , but the two can be related through Eq. 2 above (by setting $\{\text{H}^+\} = 10^{-7}$ in the Q term). In both biology and geochemistry, the quantity $p\varepsilon$ is sometimes also used as a measure of redox

potential. In analogy to pH ($= -\log\{\text{H}^+\}$), $p\varepsilon$ is a measure of the solution activity of hypothetical free electrons, $p\varepsilon = -\log\{e^-\}$, and is related to E via

$$p\varepsilon = (F/2.3RT)E \quad (3)$$

Geochemistry

Geochemical systems are frequently also characterized with reference to redox potential. In addition to the measures above, the overall redox potential of a system may be described in terms of hypothetical activities or fugacities of H_2 or O_2 (e.g., a_{H_2} or f_{H_2}). Such expressions can be related to E via Eq. 2 above (by specifying the non-unit activity or fugacity of H_2 or O_2 in the reaction quotient (“ Q ”) term). Oxygen fugacity, f_{O_2} (and, therefore, redox potential), is sometimes also specified by reference to mineral “redox buffers.” These buffers, constituting the reduced and oxidized mineral species in a reaction involving oxygen, specify a unique f_{O_2} for a given set of physicochemical conditions. Thus, for example, “QFM” specifies f_{O_2} (for a given temperature) at equilibrium in the oxidation of fayalite (F) to magnetite (M) and quartz (Q), $3 \text{ Fe}_2\text{SiO}_4(\text{F}) + \text{O}_2 \rightarrow 2\text{Fe}_3\text{O}_4(\text{M}) + 3\text{SiO}_2(\text{Q})$, when all three mineral species are present. Mineral redox buffers are a convenient way to describe changing redox conditions over wide-ranging temperatures and to understand real-world effects on redox chemistry within the solid Earth.

Cross-References

- [Bioenergetics](#)
- [Electron Acceptor](#)
- [Electron Donor](#)
- [Energy Sources](#)
- [Redox Zonation](#)
- [Reducing Agent](#)
- [Reduction](#)

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Redox Zonation

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Anoxic · Hypoxic · Oxic · Oxygen levels · Redox potential · Suboxic

Synonyms

Chemical zone; Metabolic zone; Redox zone

Definition

Redox zonation is the subdivision of natural environments based on the availability of O_2 to be consumed by biological respiration and inorganic chemical reactions. Traditional classification scheme for sedimentary environments in *oxic* and *anoxic* (with *anoxic*' sub-terms *sulfidic* and *nonsulfidic*) was based on the amount of measurable dissolved O_2 and dissolved sulfide in sediments at the time of precipitation of authigenic minerals (i.e., minerals grown in situ) (Berner 1981).

Overview

Redox zonation is common in natural systems, especially where mixing is limited, and oxygen is consumed by biological respiration and inorganic chemical reactions (Canfield and Thamdrup 2009).

Geochemical environments where sedimentary rocks formed are characterized in terms of hydrogen ion activity (pH) and the oxidation-reduction potential (Eh). But these parameters are not useful in a practical sense, pH being quite uniform for marine and nonmarine subaqueous sediments (pH = 6–8) and Eh not practically measurable (Berner 1981). Indeed, many of the species involved in sedimentary oxidation-reduction reactions, such as SO_4^{2-} or NH_4^+ , are not electroactive, that is, they do not readily accept or release electrons from the gold and platinum electrodes used for measuring the Eh. The common classification defined by Berner (1981) was based on the amount of dissolved O_2 and total sulfide (H_2S plus HS^-) measurable in a specific environment and the presence or absence of characteristic mineral phases sensitive to the occurrence of O_2 and H_2S in the environment.

The classification of redox zones in the sedimentary environment proposed by Berner in 1981 was subdivided into *oxic* and *anoxic* main zones depending upon the presence or absence of measurable dissolved oxygen. The *anoxic* zone was then further subdivided into *sulfidic* and *nonsulfidic* depending upon the presence or absence of measurable dissolved sulfide. Finally, *nonsulfidic* subzone was classified as post-oxic and methanic. Each zone and subzone was characterized by specific mineral phases stables at the O_2 and/or H_2S amount available in the environment.

In the classification of Berner (1981), the term *oxic* was then identified as a zone containing O_2 with concentrations higher than 1 $\mu\text{mol/L}$ and occurrence of ► [hematite](#), ► [goethite](#), manganese-bearing oxides but not of organic matter. The term *anoxic* was then assigned to a zone where O_2 concentration is less than 1 $\mu\text{mol/L}$. This *anoxic* zone was then subdivided into “sulfidic” (H_2S concentration higher than 1 $\mu\text{mol/L}$ and occurrence of pyrite, marcasite, and organic matter) and “non-sulfidic” (H_2S concentration less than 1 $\mu\text{mol/L}$). The “non-sulfidic” zone is in turn divided into two subzones. The first is termed *post-oxic* with presence of glauconite and iron silicates; no sulfide minerals and minor organic matter. The amount of organic matter is so small that decomposition cannot be run by sulfate

reduction but nitrate, manganese, and iron reduction (Berner 1981). The other subzone is *methanic*, a highly reducing anoxic-nonsulfidic environment with presence of siderite, sulfide minerals, and organic matter which decomposes to produce dissolved methane, hence the name *methanic*.

The most important addition to this simple scheme was the addition of the so-called *suboxic* zone at the oxic-anoxic interface, which is defined as the region where concentrations of oxygen and sulfide are both extremely low and have no perceptible gradients (Murray et al. 1989).

The redox zonations, translated to the open ocean, are based on the sequential thermodynamic availability of electron acceptors to oxidize organic matter during respiration processes. These so-called metabolic zones have names depending on the electron acceptor available and are subdivided into “oxic/► [aerobic respiration](#)” (electron acceptor being O_2), nitrate reduction (NO_2^- , NO_3^-), manganese reduction (MnO_2), iron reduction ($FeOOH$), sulfate reduction (SO_4^{2-}), and methanogenesis (CO_2) (Canfield and Thamdrup 2009).

Cross-References

- [Aerobic Respiration](#)
- [Anoxic](#)
- [Goethite](#)
- [Hematite](#)
- [Methanogens](#)
- [Oxic](#)
- [Oxic Sediments](#)
- [Redox Potential](#)
- [Siderite](#)

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Redox Zone

- [Redox Zonation](#)

Redshift

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

The redshift is a quantity, generally noted z , that measures the Doppler effect of a celestial object which is going away from the observer, thus whose light exhibits an apparent shift toward a longer wavelength. The term is especially suited for distant objects in the expanding universe (galaxies, quasars, clusters of galaxies), since it supposes that the change of wavelength is positive (the apparent longer wavelength makes the object redder than it is in its restframe). The term *blue-shift* is sometimes used for the reverse situation of an object which is approaching the observer. The redshift gives a direct information on the recession velocity v of the object. For a velocity which is much lower than the speed of light c , the Galilean approximation $z = v/c$ is valid. For velocity approaching the speed of light, a relativistic formulation must be used. Note that there is also a redshift, i.e., a positive change in wavelength, that could be due to a very strong gravitational field; in that case, one speaks of gravitational redshift.

Cross-References

- [Doppler Shift](#)
- [Galaxy](#)
- [Spectroscopy](#)

Reducing Agent

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Definition

A reducing agent is a compound that facilitates the ► [reduction](#) of an oxidized compound by a coupled electron transport in an oxidation-reduction process, known as a redox reaction. The reducing agent loses the electron which is transferred to the oxidized compound. Redox reactions are fundamental in biological systems and are involved in all metabolic processes, especially in energy conservation reactions.

Cross-References

- [Bioenergetics](#)
- [Carbon Dioxide](#)
- [Electron Donor](#)
- [Oxidation](#)
- [Reduction](#)

Reductant

- [Electron Donor](#)

Reduction

Concepción Alonso

Universidad Autonoma de Madrid, Madrid, Spain

Keywords

Electron acceptor · Oxidative · Oxidizing agent

Definition

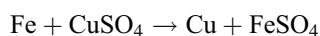
Reduction can be defined in different terms: as a gain of electrons or hydrogen or the loss of oxygen by an atom or a molecule

Overview

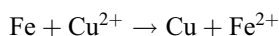
Reduction in Terms of Electron Transfer

Reduction is the gain of electrons.

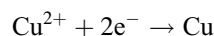
For example, in the reaction between iron and copper sulfate solution,



Copper sulfate and iron sulfate are both ionic compounds. If rewritten as an ionic equation, it turns out that sulfate ions are spectator ions, and the equation can be written as:



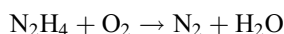
It can be seen that copper is *reduced* from copper (II) ions to metal copper (Cu^0) by gaining two electrons



Reduction in Terms of Hydrogen Transfer

Reduction is the gain of hydrogen.

- Hydrogen atoms are transferred from hydrazine (N_2H_4) to oxygen in the following reaction:

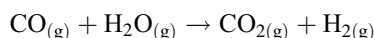


Oxygen gains hydrogen and is *reduced* to water.

Reduction in Terms of Oxygen Transfer

Reduction is the loss of oxygen.

- In the following reaction,



Water is *reduced* to hydrogen by the loss of an oxygen atom.

In general terms, reduction implies a decrease in an atom's oxidation state. However, it is only correct to speak about the oxidation state of a metal atom when the compound is purely ionic. Molecules, atoms, or ions that have the ability to oxidize other substances are said to be *oxidative* and are known as oxidizing agents, *oxidants*, or oxidizers. In other words, the oxidant removes electrons from another substance and as a consequence is itself reduced. And, because it "accepts" electrons, it is also called an ► [electron acceptor](#). The electronic transfer reactions known as redox reactions are especially important in biology because most of the biochemical reactions imply reduction or oxidation reactions.

Oxidants are usually chemical substances with elements in high oxidation numbers (e.g., H_2O_2 , MnO_4^- , CrO_3 , $\text{Cr}_2\text{O}_7^{2-}$, OsO_4) or highly electro-negative substances that can gain one or two extra electrons by oxidizing a substance (O, F, Cl, Br).

Cross-References

- [Electron Acceptor](#)
- [Electron Donor](#)

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Reduction Potential

- [Redox Potential](#)

Reductionism

Christophe Malaterre
Institut d'Histoire et Philosophie des Sciences et Techniques (IHPST), Université Paris I-Panthéon Sorbonne, Paris, France

Keywords

Explanatory reduction · Inter-theoretic reduction · Methodological reduction · Ontological reduction

Definition

Reductionism is a philosophical notion that encompasses a set of ontological, methodological, and epistemological claims about how entities, processes, methods, and knowledge relate to one another across levels of organization and/or scientific domains. Typically, the question is whether such elements at higher levels of organization (i.e., biological) can be deduced from elements at lower levels (i.e., chemical).

Overview

Reductionism encompasses several related claims that revolve around three major types of objects a reduction might concern: the "furniture of the world" (ontological claims), the methods and heuristics of science (methodological claims), theories, explanations, and, more generally, knowledge (epistemological claims) (e.g., Ayala 1974; Sarkar 1992; Nagel 1998).

Ontological reductionism is typically a claim about how entities and processes belonging to a given level of organization can be shown to be entities and processes belonging to a lower level

of organization. For instance, biological entities might be claimed to be constituted by molecules and nothing but molecules in interaction. Such a claim generally entails a metaphysical claim of physicalism. Claims about whether properties (e.g., biological, mental) can be reduced to physical properties remain controversial (so-called type-type reductionism) and are met with opposition by ontological emergentism and non-reductive physicalism (e.g., Kim 1999).

Methodological reductionism asserts that systems at a given level of organization are most fruitfully investigated by decomposition and analysis at lower levels of organization. Even though it is generally accepted that such heuristics can yield scientific knowledge, methodological reductionism remains controversial in that it might lead to overlook interesting generalizations within any given level of organization (e.g., Wimsatt 2006).

Epistemic reductionism concerns claims about how knowledge (e.g., theories, explanations) about entities and processes belonging to a given level of organization (or to a specific scientific domain) might be related to knowledge pertaining to a lower level of organization (or to a different scientific domain). In particular, inter-theoretic reduction encompasses claims about how theories are related to one another, for instance, through relations of logical deduction aided with bridge principles or through relations of successive replacement (e.g., Nagel 1961; Schaffner 1967).

Cross-References

- [Chance and Randomness](#)
- [Materialism](#)
- [Physicalism](#)

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Reductive Pentose Phosphate Cycle

- [Calvin-Benson Cycle](#)

Reference Frame

- [Coordinate Systems](#)

Reflection Nebula

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A reflection nebula is that part of an interstellar ► [molecular cloud](#) that is close enough to a star to be visible through the starlight reflected off the cloud's dust. Since the dust scatters light more strongly at shorter wavelengths, the reflection nebula is bluish, and the spectrum is typically continuous. The appearance of a reflection nebula may be contrasted with that of an ► [emission nebula](#), where the spectrum consists of individual emission lines.

Cross-References

- [Emission Nebula](#)
- [Interstellar Dust](#)
- [Interstellar Medium](#)

Reflectivity

- ▶ [Albedo](#)

Refractory Molecule

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

A molecule with a very high ▶ [sublimation](#) temperature is termed refractory. Such molecules condense at high temperature in the ▶ [solar nebula](#) or in stellar envelopes; they include silicon carbide and iron and magnesium silicates that are thought to form the cores of many ▶ [interstellar dust](#) particles.

Cross-References

- ▶ [Interstellar Dust](#)
- ▶ [Solar Nebula](#)
- ▶ [Sublimation](#)

Refractory Organic Polymer

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In geochemistry, a refractory organic polymer refers to an often poorly structurally defined

polymer formed through chemical transformation, for example, during ▶ [diagenesis](#). Biological materials, such as the residues of dead organisms or the waste products of living organisms, may accumulate in sediments and form an amorphous “polymer” which may shed some easily hydrolyzed moieties and volatile elements during aging. Some examples of refractory biological organic polymers include ▶ [kerogen](#) and the humic and fulvic acids. As aging continues, less and less of the polymer is easily hydrolyzed, and the material is said to be refractory. Such polymers may also be derived from abiotically synthesized organic materials, for example, the insoluble organic material found in carbonaceous chondrite meteorites.

Cross-References

- ▶ [Chondrite](#)
- ▶ [Diagenesis](#)
- ▶ [Kerogen](#)
- ▶ [Tholins](#)

Regio

Roland J. Wagner

German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Definition

Regio is an area characterized by an ▶ [albedo](#) (including radar albedo) or color difference from adjacent areas on a ▶ [planet](#), a ▶ [satellite](#), or on a minor planet (▶ [asteroid](#)). On planets or satellites, surface areas termed regio are generally several millions of square kilometers across.

Cross-References

- ▶ [Albedo Feature](#)
- ▶ [Asteroid](#)

- [Mars](#)
- [Planet](#)
- [Satellite or Moon](#)
- [Venus](#)

Regolith, Planetary

Harald Hoffmann

DLR, Institute of Planetary Research, Berlin,
Germany

Keywords

Megaregolith · Lunar soil · Regolith

Definition

Regolith is the cover of loose material overlying the bedrock of a ► [planet](#), satellite, or ► [asteroid](#) and includes fragmented and weathered rocks, soil, and sediments.

Overview

A regolith is the cover or mantle of loose material overlying the bedrock of a planet or other solid solar system body. It includes fragmented and weathered rock debris, soil, and sediments. If present, atmospheres, hydrospheres, or biospheres, as in the case of the ► [Earth](#), play a dominant role in regolith formation. More common, however, are planetary bodies without a dense atmosphere. Here, the regolith is formed and modified by impact processes, mass wasting, and ► [space weathering](#), as on the surfaces of ► [Mercury](#), most of the satellites, and the asteroids. The processes involved, however, vary over time (cratering rate and impactor size), with gravity and the heliocentric distance (kinetic energy and space weathering).

The best-studied example of a planetary regolith is the lunar case. During the period of Heavy Bombardment, the lunar ► [crust](#) was deeply fractured and fragmented by large impacts, generating a global layer of impact debris that may reach a

cumulative thickness of several kilometers. On the Moon, this chaotically mixed layer is termed the “megaregolith.” After the Heavy Bombardment, smaller-sized impacts resulted in a finer-grained surface layer that is only a few meters to some 10 m thick. It is continuously turned over and tends to be homogenized. The overall growth rate in thickness decreases over time because the regolith itself protects the underlying material. Only rare larger impact events are able to excavate fresh material, and the superposition of ejecta blankets creates a layered regolith structure. This uppermost pulverized surface layer is normally referred to as “the lunar regolith.” Typically, it has an average grain size of 60–80 μm and constitutes a poorly sorted pebble- or cobble-bearing silty sand. The term “lunar soil” refers to the <1 mm grain size fraction of the lunar regolith.

In analogy to the lunar case, the term regolith as used in astronomy is often used to refer only to the uppermost finer-grained layer of a planetary surface that is not protected by a dense atmosphere.

Cross-References

- [Asteroid](#)
- [Biosphere](#)
- [Crater, Impact](#)
- [Crust](#)
- [Earth](#)
- [Hydrosphere](#)
- [Late Heavy Bombardment](#)
- [Mercury](#)
- [Moon, The](#)
- [Planet](#)
- [Rock](#)
- [Satellite or Moon](#)
- [Space Weathering](#)

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Regolith, Terrestrial

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Synonyms

[Laterites](#); [Soil](#)

Definition

The terrestrial regolith (ῥήγος = *rhegos* = blanket; λίθος = *lithos* = rock) is a layer of unconsolidated material overlying solid rock. It forms as a result of mechanical and chemical ► [weathering](#), biological processes, deposition of loose material, or brecciation of rock. It may consist of soil, alluvium, and other sedimentary deposits; fractured and oxidized rock; and volcanic ash or scoria. Its thickness varies from negligible to several hundred meters. Regoliths have been observed on Earth, Moon, some asteroids, and other planets.

Cross-References

- [Breccia](#)
- [Moon, The](#)
- [Regolith, Planetary](#)
- [Weathering](#)
- [Weathering Profile](#)

Relative Age Dating

- [Absolute and Relative Ages](#)

Relative Ages of Rocks

- [Absolute and Relative Ages](#)

Replication (Genetics)

Enrique Viguera
Genetics Department, Sciences Faculty,
University of Malaga, Malaga, Spain

Keywords

Cell cycle · DNA polymerase · Fidelity ·
Nucleotides · RNA polymerase · Template

Synonyms

[Nucleic acid duplication](#)

Definition

Replication is the process by which a nucleic acid molecule is duplicated. DNA replication is required before cell division, ensuring that each daughter cell contains a copy of the ► [genome](#). In eukaryotes, chromosomal replication occurs in the cell nucleus, during the S phase of the cell cycle. DNA replication proceeds in a semiconservative manner in which each of the parental strands of the DNA double helix acts as a template for the nascent strand. A DNA polymerase enzyme catalyzes the formation of a phosphodiester bond between a free 3'-hydroxyl radical of a ► [primer](#) DNA chain and an incoming deoxyribonucleotide, so that replication proceeds in the 5–3' direction. RNA replication occurs during the infective cycle of viruses with RNA genome (with some exceptions including retroviruses which retro-transcribe their genomic RNA into DNA).

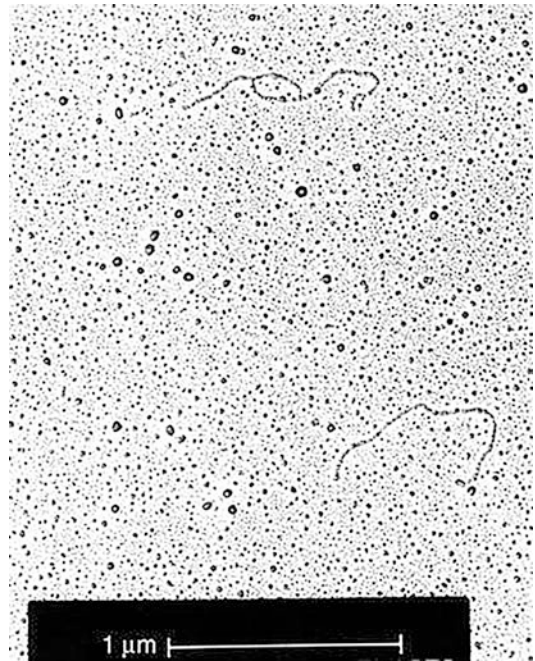
Overview

DNA replication in vivo requires three steps: (1) initiation of the polymerization of a DNA

chain, (2) elongation, and (3) termination. DNA replication initiates at a specific site, the origin of replication, that controls the replication of a unit of DNA called a replicon. Most bacteria and viral chromosomes contain a unique replication origin, whereas eukaryotes contain multiple replication origins. Replication of chromosomes can proceed in a unidirectional or bidirectional mode, whereas a rolling circle mechanism has been described for the replication of some viral chromosomes. Origins of replication are recognized by initiator proteins that induce the opening of the DNA double helix and recruit other proteins to constitute the replication fork (a Y-shaped region of DNA that results from the separation of the DNA strands at which replication of new strands takes place; Fig. 1). Because of the 5–3' polarity of replication, one strand is synthesized in a continuous manner (leading strand) and the other in a discontinuous manner (lagging strand). The leading strand is primed at the origin, whereas the lagging strand is primed by a primase enzyme which synthesizes an RNA primer that is later elongated by the DNA polymerase (generating the so-called Okazaki fragment). The replication machinery that moves along the DNA during the elongation step is called the replisome. Termination occurs when two oppositely migrating replication forks meet each other. Accidental termination of a replication fork might be lethal unless the replication machinery is reassembled by the action of ► [recombination](#) proteins or the DNA region is replicated by a convergent replicating fork.

RNA ► [virus](#) replication depends on RNA-directed RNA polymerases that catalyze replication of RNA from an RNA template. These polymerases lack an error correction mechanism, which explains partly the high ► [mutation](#) rates of RNA viruses.

DNA can be replicated in vitro by a DNA polymerase, using a DNA template, a primer that pairs with the template and provides a 3'-OH end to be extended, the four deoxyribonucleotides triphosphate (dATP, dTTP, dCTP, and dGTP), and metal ions. The sequence of the DNA template dictates the complementary ► [nucleotides](#) to be inserted into the nascent strand. DNA replication fidelity relies on the high ► [nucleotide](#)



Replication (Genetics), Fig. 1 Electron micrograph of a plasmid DNA restriction fragment from the bacterium *Escherichia coli* containing an internal replication bubble (upper). Plasmid replication intermediates were isolated and digested with a specific restriction enzyme. The DNA samples were extracted with phenol, filtered by passage through Sephadex LH60, and prepared for electron microscopy by cytochrome c spreading in 50% formamide and carbonate buffer on a water hypophase. The spreading film was picked up with Parlodion-coated cooper grids, the DNA was shadowed with platinum/iridium (80:20), and micrographs were recorded using a Phillips EM400 electron microscope. The bar corresponds to 1 μ m. (Authors: Enrique Viguera, Bernardo Schwartzman and Rudy Lurz)

selectivity of the DNA polymerase and the editing of the misinserted nucleotides (thanks to the proofreading activity of the DNA polymerase). DNA polymerases lacking this 3–5' exonuclease activity (as well as RNA-directed RNA polymerases) have reduced fidelity. Amplification of a DNA template may be carried out by ► [polymerase chain reaction](#) using thermostable DNA polymerases or by isothermal amplification using a DNA polymerase endowed with high strand displacement activity (the DNA polymerase of the virus Phi29). DNA replication blockage in a repeated sequence can lead to the generation of deletions or expansions in the DNA ("indel" mutation) by a replication slippage mechanism.

Cross-References

- [Amplification \(Genetics\)](#)
- [Base Pair](#)
- [Chromosome](#)
- [DNA](#)
- [DNA Damage](#)
- [DNA Sequencing](#)
- [Genetics](#)
- [Genome](#)
- [Mutation](#)
- [Nucleic Acid Base](#)
- [Nucleotide](#)
- [Polymerase Chain Reaction](#)
- [Polynucleotide](#)
- [Primer](#)
- [Recombination](#)
- [RNA](#)
- [Taq Polymerase](#)
- [Virus](#)

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Replication Accuracy

- [Fidelity](#)

Reproduction

- [Self-Replication](#)

Respiration

Francisco Montero
Department of Biochemistry and Molecular Biology I, Facultad de Ciencias Químicas, Universidad Complutense de Madrid, Madrid, Spain

Keywords

Cellular respiration · Chemiosmotic hypothesis · Electron transport · Energy transduction · Oxidative phosphorylation

Synonyms

[Oxidative phosphorylation](#); [Respiratory chain](#)

Definition

At cell level, respiration is the process in which biological systems oxidize different substrates, where the oxidizing agent is a substance that is external to the system itself. Historically, the term has been used when the substance which is the external ► [electron acceptor](#) is oxygen (► [aerobic respiration](#)). However, this definition should be

widened to include the cases where the external electron acceptor is a substance other than oxygen (anaerobic respiration).

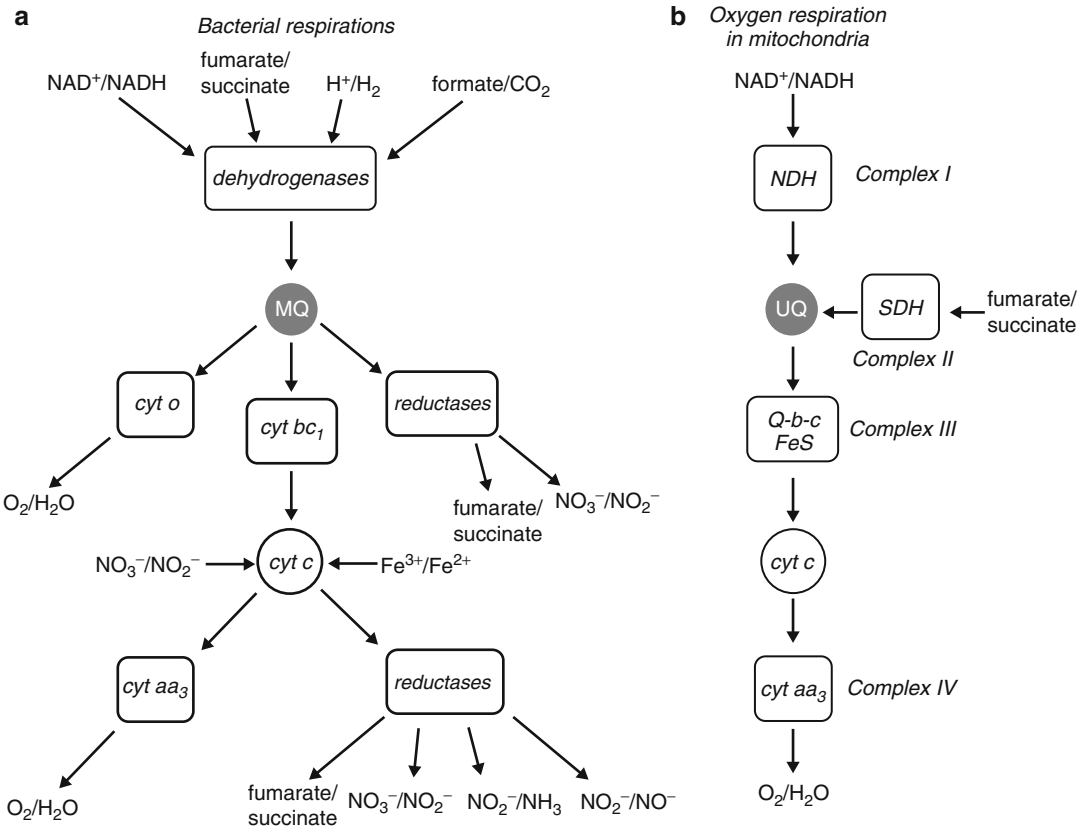
Overview

Respiration is a common way for living organisms to obtain energy. The process is a source of oxidation for various cellular components, such as NADH, succinate, acyl-CoA, etc., which are produced either by the catabolism of substances taken from the exterior or directly from a component taken from the exterior, such as methanol (this is the case for *Paracoccus denitrificans*, which can grow on methanol) or Fe^{2+} (in the case of *Acidithiobacillus ferrooxidans*). The final electron acceptor in the case of eukaryotic cells and multicellular organisms is oxygen, although, in the absence of oxygen, the final electron acceptors in many bacteria are other components, such as nitrate, nitrite, sulfate, or fumarate (compare a and b in Fig. 1). Bacteria are therefore highly versatile with respect to the use of final electron acceptors, and the actual electron acceptor used is frequently dictated by the specific external conditions. For example, although *Escherichia coli* can respire oxygen, in the absence of oxygen it can respire fumarate and nitrate. This ability allows many bacteria to be extremely diverse and adaptable.

The electron transfer from the initial donor to the final acceptor is performed by means of an electron transport across a series of intermediaries, whose composition is universal. When referred to as a whole, these intermediaries are usually called the respiratory chain or electron transport chain. As shown in Fig. 1, three of these intermediaries are proteins (flavoproteins, iron-sulfur proteins, and cytochromes), while one is lipid in character (quinone). In the case of proteins, it is the prosthetic group which takes part in the redox reactions, although the polypeptide, apart from maintaining the global structure of the systems, also modulates the ► [redox potential](#) of the prosthetic groups. The majority of these components are not free in a solution, but form macromolecular complexes inserted in cell membranes, specifically in the internal mitochondrial

membrane in the case of eukaryotic cells or in the plasma membranes of bacteria. Exceptions to this are the quinones, which freely diffuse in the apolar phase of the lipid bilayer of the membranes and some cytochromes, such as cytochrome *c* in mitochondria. The number and composition of these complexes vary from one organism to another, although there are always two of them present: an initial dehydrogenase/oxidase, which takes electrons from the primary donor, and a final oxidase that transfers them to the final acceptor. The composition of both complexes obviously depends on what the initial donors and final acceptors are. Therefore, the initial complex in mitochondria may be NADH dehydrogenase, succinate dehydrogenase, acyl-CoA dehydrogenase, etc., depending on whether the initial donor is NADH, succinate, or acyl-CoA; and the final complex is a cytochrome *c* oxidase that transfers electrons from the cytochrome *c* to O_2 (Fig. 1b). In contrast, *E. coli* displays higher versatility with respect to the final acceptor, as it may be a cytochrome oxidase, but may also be a nitrate reductase, if the final acceptor is nitrate (Fig. 1a).

Why are electron transport chains located in the membranes and so highly organized? As mentioned above, the main purpose of the process is to use the free energy released by redox reactions, translating them into an energy currency that the cell can use for other endergonic processes that take place there. Since the first half of the twentieth century, it has been known that ATP is produced as a result of respiration, which is why this phenomenon is commonly known as oxidative phosphorylation (phosphorylation of ADP to produce ATP as a consequence of the oxidation processes). However, it was a long time before the mechanisms which facilitate energy coupling between the two processes were clearly established. Today, it is universally accepted that the first energy coupling does not take place directly between oxidation and phosphorylation, but between oxidation and the expulsion of H^+ from the membrane in which the process takes place. That is to say, the first energy coupling takes place between a chemical reaction (oxidation-reduction reaction) and a transport process (H^+) across a membrane. In other words, the



Respiration, Fig. 1 Examples of respiratory chains. (a) The diversity of bacterial respirations is shown as a combinatorial of electron donors and acceptors (shown as pairs of acceptor/donor) of diverse reducing potential. The electron flow (arrows) is coupled with the generation and maintenance of a proton-motive force through a membrane where the electron transport chain components are located. (b) The oxygen respiration in mitochondria is a subset of

electron transport machineries of bacterial origin. Multi-subunit transporters are represented as boxes, whereas monomeric cytochrome *c* is represented by a circle; membrane-soluble quinones (*MQ* menaquinone, *UQ* ubiquinone) are shown in gray; *cyt c* cytochrome, *FeS* iron-sulfur cluster, *NDH* NADH dehydrogenase, *SDH* succinate dehydrogenase

chemical reaction “energizes” the membrane, causing a proton electrochemical potential difference between the two sides. The H^+ reentry is coupled to the ATP synthesis, a process in which a protein complex, which has been given the generic name of proton-translocating **ATPase** or ATP synthase, is involved. This is why membranes are so important throughout the process.

As has been mentioned above, during respiration, there is a coupling between a chemical reaction (redox reactions) and a transport process (of H^+). In order for the coupling to take place, the respiratory chain complexes have to be organized, which means that the different groups which take part in the reactions are specifically

positioned relative to each other and with respect to the inner and outer part of the membrane (anisotropic distribution). Some of the complexes couple the processes using pumps. Essentially, redox reactions cause conformational changes in the proteins of the complex and induce pK variations in certain lateral amino acid chains, which finally lead to a proton transport from the interior of the system toward the exterior. In other cases, coupling occurs through loops, as the complexes have alternating groups which take part in redox reactions which involve and do not involve protons, respectively. These groups release the first protons, taken from the interior during the reduction process, to the

exterior on being oxidized, if the following acceptor does not accept protons.

Basic Methodology

- Methods for the detection of redox centers. Different techniques have been required, depending on the nature of these centers. For this reason, cytochromes have usually been detected using spectroscopy absorption, since these molecules have very different absorption spectrums in the visible region depending on their state of oxidation. Electron spin resonance spectra (ESR) have frequently been used in the case of iron-sulfur proteins, while a combination of both the above techniques has been used for quinones. Redox potentiometry has also been frequently used in order to measure the redox potentials of the different intermediaries in the respiratory chain.
- One of the crucial points in the coupling of processes is determining the stoichiometry of the coupling. In the case of the respiratory chain, the stoichiometry is the relation between the number of protons expelled across the membrane and the number of electrons transported in the respiratory chain. A classic experiment for measuring this relation in the case of mitochondria is the oxygen pulse. This consists of adding a controlled amount of oxygen and a reducing substrate (e.g., succinate) to a suspension of mitochondria incubated in anaerobic conditions, and an ADP-free medium, and using H^+ microelectrodes to detect variations in the concentration. Variations of this experiment can be carried out using submitochondrial particles (particles obtained with a suspension of mitochondria exposed to ultrasound, in which the membrane is inverted relative to the membrane of the intact mitochondria) or with liposomes in which different complexes of the respiratory chains have been inserted after having been separated by treatment with detergents.
- X-ray diffraction of crystallized complexes. This has been used to determine the three-dimensional structure with atomic resolution

of many respiratory chain complexes. Up until now, the majority of them were from bacteria, since mitochondrial complexes are made up of a larger number of subunits which are more difficult to crystallize. This experimental determination has played a key role in explaining the precise mechanisms and sequence of events in electron transport in the respiratory chain, as well as determining the loop and pump mechanisms required to couple the transport to proton expulsion.

Key Research Findings

The chemiosmotic hypothesis of coupling between electron transport and ATP generation mechanisms was proposed by Peter Mitchell in 1961. He suggested that a proton electrochemical potential gradient is generated between both sides of the internal mitochondrial membrane and is an intermediary in both processes (respiration and ATP generation). Almost simultaneously, similar experiments suggested that there are identical mechanisms for ATP generation in bacteria and for photosynthetic phosphorylation (ATP generation in chloroplasts and photosynthetic bacteria, as a result of light absorption).

The three-dimensional structures of many respiratory chain complexes have been obtained since the last decade of the twentieth century. From these, many of the mechanisms for the electron transport through the respiratory chain as well as the mechanisms for the translocation of protons across the membranes coupled with this transport have been elucidated.

Phylogenetic analyses indicate that the last universal common ancestor have been a cellular entity with the ability to synthesize ATP using the electrochemical potential gradient generated by electron transport chains.

Applications

Over time, our understanding of the respiration of many bacteria has increased, in particular with regard to extremophiles, such as *Acidithiobacillus*

ferrooxidans, which lives in very acid environments and respire oxygen, even though the ► [electron donor](#) in its respiratory chain is Fe^{2+} from the surroundings (one could say it “eats” Fe^{2+}), as well as for many other bacteria which have different electron donors and acceptors. This increased understanding has enabled us to envisage systems where the respiratory chain organization is much simpler and helped us to come closer to the evolutionary origin of this mechanism, thereby allowing us to make conjectures about possible organizations in scenarios different to those on earth.

Furthermore, the elucidation of respiratory systems has led to a wider understanding of many physiological mechanisms, such as heat generation in mammals, or the cause of oxidative stress and possible solutions. An understanding of these mechanisms will, in a not too distant future, enable us to modify them to obtain specific results.

Cross-References

- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [ATPase](#)
- [Chemoorganotroph](#)
- [Electron Acceptor](#)
- [Electron Donor](#)
- [Electron Transport](#)
- [Mitochondrion](#)
- [Nitrogen Cycle, Biological](#)
- [Proton Pump](#)
- [Redox Potential](#)

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Respiratory Chain

- [Respiration](#)

Restriction Endonuclease

- [Restriction Enzyme](#)

Restriction Enzyme

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

R

Synonyms

[Restriction endonuclease](#)

Definition

A restriction enzyme is an endonuclease that binds and cuts double-stranded ► [DNA](#) at a specific nucleotide sequence. Some restriction

enzymes cut both strands, generating blunt ends whereas others generate sticky ends. Restriction combined with DNA modification, which impede the cutting of the DNA, is a protection system against the introduction of foreign DNA sequences into prokaryotic systems. These enzymes have been instrumental in the development of ► [cloning](#) and genetic engineering techniques.

Cross-References

- [Cloning](#)
- [DNA](#)
- [Enzyme](#)

Rhea

Therese Encrenaz
LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Rhea, discovered by Giovanni Domenico ► [Cassini](#) in 1672, is the largest of the mid-sized icy satellites of Saturn. Its distance to ► [Saturn](#) is 527,000 km (or 8.7 Saturnian radii). Its diameter is 1528 km and its density is 1.24 g/cm³, typical of a water-ice body. Rhea was first observed by Voyager 1 in 1980 and then more extensively explored since 2005 by the Cassini orbiter. The surface of Rhea is heavily cratered with little differentiation, with the exception of Izanagi crater, which is 250 km in diameter. Rhea has no orbital resonance with any other satellite, which accounts for the lack of tidal heating and hence of geological activity.

Cross-References

- [Saturn](#)
- [Voyager, Spacecraft](#)

Rheology, Planetary Interior

Vlada Stamenković¹ and Frank Sohl²

¹Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA

²Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

Keywords

Mantle convection · Planetary interior dynamics · Plate tectonics · Rock creep (diffusion dislocation) · Viscosity · Tectonics

Definition

Rheology (from the Greek words *ῥεῖ* (*rhei*), “to flow,” and *λόγος* (*logos*), “teaching”) is the science of the flow and the deformation of matter in response to an applied stress.

Overview

Planetary interiors and surfaces are composed of solid and liquid silicate ► [rocks](#), metals, and ices, which deform and flow under an applied non-hydrostatic stress σ (in [Pa]). If the applied stress is small, the material behaves elastically. This means that the material returns to its initial state after the stress is removed. Real planetary materials exhibit a plastic, nonreversible rheological component, in addition to their elastic behavior. In this case, the material does not fully return to its initial state after the stress is removed.

Plastic rheologies are characterized by a maximum stress, called yielding stress, above which perfect elasticity is lost. For nonelastic rheologies the relative deformation, called strain ϵ (dimensionless) and caused by a constant stress σ_0 , is time dependent.

Any time-dependent stress-strain relation is called creep, and planetary rheology studies the flow laws of the creep of planetary materials.

There are three regimes of creep behavior: the transient (I), the stationary or steady-state (II), and the tertiary (III) creep regime. Figure 1 shows the time dependence of creep for the three different regimes when a constant stress σ_0 is applied.

The elastic component leads to an instantaneous deformation resulting in a constant strain ε_0 . For small times, creep is in the transient regime (I), where strain increases with a decreasing rate. There are many ways of describing transient creep mathematically, but all fail at certain timescales (see Jaeger et al. 2007 for in detail discussion). One possible mathematical description is to use:

$$\varepsilon_1(t) = a_1 \cdot t^{b_1} \text{ with } 1 > b_1 > 0 \quad (1)$$

where $\varepsilon_1(t)$ is the strain in regime (I) as a function of time t . This approach, however, fails for $t \rightarrow 0$ as the strain rate approaches infinity. It also does not smoothly transfer into the steady-state creep regime (II) at intermediate times, where the strain ε_2 increases linearly with time:

$$\varepsilon_2(t) = a_2 \cdot t \quad (2)$$

For long timescales, the tertiary regime (III) is reached where the strain $\varepsilon_3(t)$ increases with an increasing rate, until material failure occurs.

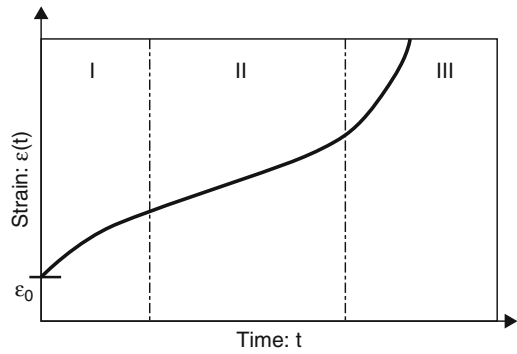
A more realistic description of planetary creep $\varepsilon(t)$ would involve the instantaneous (elastic) material response combined with the three time-dependent (plastic) creep regimes described above:

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_1(t) + \varepsilon_2(t) + \varepsilon_3(t) \quad (3)$$

Several rheological models partly satisfy the creep behavior shown in Fig. 1.

We discuss briefly some of them: Fig. 2 shows a summary of rheological models, which are often applied to the flow behavior of geological materials present in the interiors and lithospheres of planetary bodies.

In response to an applied stress σ_0 , elastic material behavior results in an instantaneous strain ε_0 (Fig. 2a), which can be described in terms of a spring with elastic constant k :



Rheology, Planetary Interior, Fig. 1 Schematic view of distinct creep regimes (strain evolution with time) in the event of constant stress applied: instantaneous (elastic) response, (I) transient, (II) stationary, and (III) tertiary creep regime. See text for further explanation

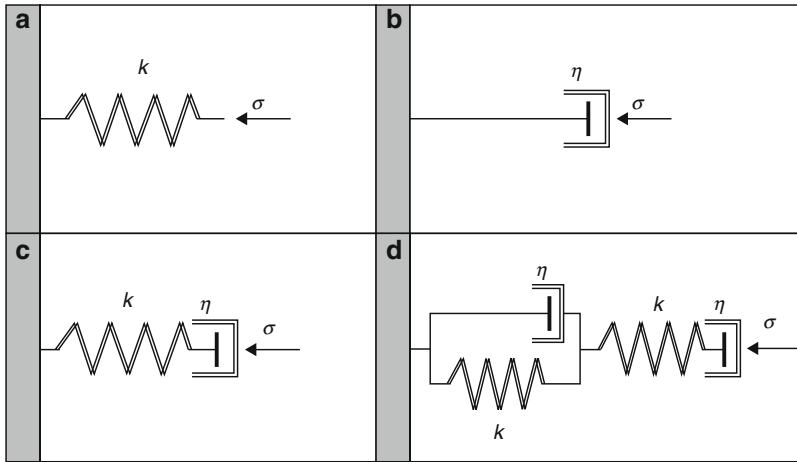
$$(\sigma = k \cdot \varepsilon) \rightarrow \left(\varepsilon_0 = \frac{\sigma_0}{k} \right) \quad (4)$$

In this model, any material relieved from the applied stress reversibly returns to its initial state.

To model irreversible, plastic processes, such as the stationary creep domain (II), a viscous rheology is needed, which is described by a dash-pot with the ► viscosity η (Fig. 2b). Here, strain increases linearly with time.

$$\varepsilon = \frac{\sigma_0}{\eta} \cdot t \quad (5)$$

The Earth's mantle and also the interiors of many other planetary bodies are often modeled in terms of a Maxwell or a Burgers rheology. The Maxwell rheology is described in Fig. 2c. It is represented by a serial combination of elastic and viscous elements. It therefore describes the instantaneous and the stationary creep to a certain degree. For stresses varying on short timescales, the Maxwell body responds like an elastic spring while on long timescales the Maxwell body flows. The transition between these two regimes occurs at the Maxwell time η/k . To also include transient creep (I), it is necessary to combine a Maxwell rheological element in series with a so-called Kelvin element (elastic and viscous elements in parallel). We then obtain the model of the rheology of a Burgers body, shown in Fig. 2d. The Burgers rheology is best suited to model the rheology of



Rheology, Planetary Interior, Fig. 2 Four model representations to illustrate the rheology (strain evolution with time) of rock: (a) an elastic spring can be used to illustrate the elastic response to stress, (b) a dashpot represents plastic deformation in regime (II), (c) an elastic spring in

series with a dashpot represents a Maxwell viscoelastic rheology, and (d) an elastic spring in parallel with a dashpot and in series with an elastic spring and a dashpot, finally, represents the Burgers elastic, transient (I), and viscous response (II)

planetary mantles at a broad range of deformational timescales, as described in the stress-strain relation of rocks shown in Fig. 1. None of these models consider tertiary creep (III).

Basic Methodology

Here, we focus on the rheology of ► mantle material, necessary to model convection and heat transfer in planetary interiors. Mantle material is modeled on geological timescales by using the steady-state creep regime only.

The steady-state parameter a_2 in Eq. 2 depends, among other factors, on stress σ and temperature T . The stress dependence can be described by a general power-law creep with dimensionless exponent n .

$$\varepsilon_2(t) = a_2(\sigma, T) \cdot t = a_2(T) \left(\frac{\sigma}{\sigma_0} \right)^n \cdot t \quad (6)$$

Here $a_2(\sigma, T)$ is a characteristic strain rate (in $[s^{-1}]$). Creep is a thermally activated process, initiated by the diffusion or dislocation of impurities. Therefore, an Arrhenius-type law can describe the temperature-dependent part of the characteristic strain rate $a_2(T)$:

$$a_2(T) = a_2(T \rightarrow \infty) \cdot \exp\left(-\frac{G^*}{RT}\right) \quad (7)$$

$G^* = H^* - TS^*$ is the molar activation Gibbs energy change of the process (in $[J/mol]$), H^* is the molar enthalpy change, S^* is the molar entropy change, $a_2(T \rightarrow \infty)$ is the theoretical strain rate at infinite temperature and R is the universal gas constant. For a negligible molar entropy contribution, we can focus on the enthalpy change (Karato 2008). This leads to a strain rate stress relation for general power-law creep (Karato and Wu 1993):

$$\dot{\varepsilon}(t) = A \cdot \left(\frac{\sigma}{\mu} \right)^n \cdot \left(\frac{b}{d} \right)^m \cdot \exp\left(-\frac{H^*}{RT}\right) \quad (8)$$

Here A is a constant factor (in $[s^{-1}]$), μ is the shear modulus (in $[Pa]$), b is the length of the Burgers vector (in $[m]$), d is the grain size (in $[m]$), and n, m are dimensionless power-law exponents.

For mantle rheologies, two cases are important:

1. For diffusion-controlled processes linear (Newtonian) creep is important. Here $n = 1$ and $m = 2$ (Karato and Wu 1993). Therefore, the strain rate varies strongly with the grain size of the rock and linearly with differential

stresses. Linear creep is expected to dominate the Earth's lower mantle.

2. In the Earth's upper mantle, dislocation creep is expected to dominate the rheology. Non-linear (non-Newtonian) creep is then assumed to control the flow of rock. In this case, $n \approx 3$ and $m = 0$ (Karato and Wu 1993). Therefore, the flow is insensitive to grain size but depends strongly on the applied stress σ .

Key Research Findings

- The habitability of planets depends on their thermal state, which on the other hand is strongly affected by the thermal history of the planet's interior. The thermal transport within planetary interiors is controlled by the viscosity of mantle material, which depends on the material rheology. Typical viscosities of Earth mantle material range from 10^{17} to 10^{23} Pas (Ranalli 1995).
- ► [Plate tectonics](#) and ► [magnetic fields](#) (around active stars) might contribute to make a planet habitable – and they both depend on the rheology of a planet's mantle: one necessary criterion to obtain plate tectonics is that convective stresses have to overcome lithospheric plate yield stresses. Regenauer-Lieb et al. (2001) have shown that water can promote the initiation of plate tectonics.
- Magnetic field generation depends on the transported heat flux out of the core, which depends on the viscosities in the lower mantle, whereas the rheological creep law determines the viscosities.

Applications

The applications include mantle convection, creep mechanism, geomorphology, tectonics, yielding, plate tectonics, ices (► [Europa](#)), and glaciers (Earth).

Future Directions

Due to the large uncertainties in the exact rheology of planetary interiors, upper limit viscosities

obtained from these flow laws vary for Earth by a factor of 10^6 (Ranalli 1995). For ► [super-Earths](#) viscosity uncertainties are much larger and hence our understanding of ► [super-Earth](#) interiors is limited (Karato 2011; Stamenković et al. 2011, 2012). High-pressure experiments are needed to completely understand the thermal and compositional state of the interior of the Earth, other terrestrial planets, and ► [super-Earths](#).

Cross-References

- [Enthalpy](#)
- [Europa](#)
- [Heat Transfer, Planetary](#)
- [Interior Structure, Planetary](#)
- [Lithosphere, Planetary](#)
- [Magnetic Field, Planetary](#)
- [Mantle](#)
- [Planet](#)
- [Planetary Evolution](#)
- [Plate Tectonics](#)
- [Rock](#)
- [Stagnant Lid Convection](#)
- [Super-Earths](#)
- [Terrestrial Planet](#)
- [Viscosity](#)

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Ribonucleic Acid

► RNA

Ribonucleoside

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In biochemistry, a ribonucleoside is an organic molecule derived from the condensation of a nitrogenous base and the C¹ atom of ribose via a glycoside linkage. Examples of pyrimidine ribonucleosides include uridine and cytidine. Thymine ribonucleoside is sometimes called 5-methyluridine, while thymidine represents the deoxynucleoside of thymine. Pyrimidine ribosides are linked via their N¹ nitrogen atoms. The purine ribosides include adenosine and guanosine, linked via their N⁹ ring atoms. The glycoside linkage may be α - or β -, depending on which face of the ribose ring the nitrogen heterocycle is bonded on. Biological ribosides are β -linked. Nucleosides are phosphorylated to give nucleotides.

Cross-References

- [Nucleic Acids](#)
- [Ribonucleotide](#)
- [RNA](#)

Ribonucleotide

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A nucleotide is a phosphorylated nucleoside. ► [Ribonucleosides](#) may be phosphorylated via the oxygen atoms found at C², C³, or C⁵ of the ribose ring. Ribonucleotides have one, two, or three phosphate groups attached to the ribose sugar. In some ribonucleosides, a phosphorus group is bound to two oxygen atoms of the ribose ring, yielding a cyclic nucleotide. Some important examples of these include cyclic 3', 5' adenosine monophosphate (cAMP), an important cellular signaling molecule, and the 2', 3' cyclic nucleotides which may be formed during the nonenzymatic hydrolysis of polyribonucleotides. Ribonucleotides are incorporated into nucleic acids as their triphosphates, with the liberation of pyrophosphate during polymerization. An extremely important energy-carrying ribonucleotide is adenosine triphosphate (► [ATP](#)).

Cross-References

- [ATP](#)
- [Nucleic Acids](#)
- [Ribonucleoside](#)
- [RNA](#)

Ribopyranosyl Nucleic Acid

- [p-RNA](#)

Ribose

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

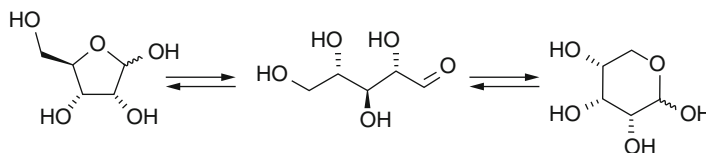
Definition

Ribose is a five-carbon ► [monosaccharide](#) with three chiral centers (aldopentose) found in ribonucleic acid (RNA) and several coenzymes (ATP, B₁₂, NAD(P)H, etc.) with the formula (C₅H₁₀O₅). Ribose has all the hydroxyl groups on the same side in the Fischer projection. Ribose can exist in two enantiomeric forms, D and L. Biological nucleic acids use the D version. Ribose is the precursor to deoxyribose in biology. In water, ribose exists in equilibrium as furanose, open-chain, and pyranose forms (from left to right in Fig. 1). The pyranose form is predominant (76%). D-Ribose must be phosphorylated to d-ribose 5-phosphate before it can be used by the cell's enzymes. Ribokinase catalyzes this reaction. Once phosphorylated, D-ribose 5-phosphate is used for the biosynthesis of the ► [amino acids](#) tryptophan and histidine and in the pentose phosphate pathway. D-Ribose 5-phosphate is further converted to phosphoribosyl pyrophosphate for the biosynthesis of nucleotides.

Cross-References

- [Monosaccharide](#)
- [RNA](#)

Ribose, Fig. 1 Three forms of ribose



Ribosome

Juan P. G. Ballesta
Genome Dynamics and Function, Centro de
Biología Molecular Severo Ochoa, Madrid, Spain

Keywords

Antibiotics · Decoding · Peptide bond
formation · Ribonucleoprotein particle ·
Translation

Synonyms

[Microsome](#); [Translation machinery](#)

Definition

The ribosome is the central component of the ► [protein](#) synthesis machinery in the cell. It contains both ► [RNA](#) and protein and is composed of two subunits. Ribosomes are essential for accurate ► [translation](#) of the mRNA-encoded genetic message; they biosynthesize ► [proteins](#) by catalyzing the peptide bond formation between tRNA-bound ► [amino acids](#).

Overview

Ribosomes are composed of about 65% RNA and 35% proteins distributed into a small and a large subunit. In contrast to the ribosomal proteins (r-proteins), the ribosomal RNA (rRNA) has been highly conserved during evolution and contains numerous posttranscriptional modifications and peculiar structural features like pseudo-knots and other RNA-RNA tertiary interactions. Ribosomes are present in all organisms from the three

domains of life (*Bacteria*, *Archaea*, and *Eukarya*) and in two eukaryotic organelles originated by ancient ► [endosymbiosis](#) of bacteria (mitochondrion and chloroplast).

The prokaryotic ribosomal subunits have a sedimentation coefficient of 30 S (S stands for Svedberg, the unit of sedimentation coefficient which is proportional to the mass of the particle) and 50 S, respectively, and join to yield a 70 S ribosome with a mass M_r of around 2.7×10^6 and a diameter of 200 Å. In eukaryotes, the complete 80 S ribosome, formed by 40 S and 60 S subunits, has a M_r of 4.2×10^6 and diameter of 300 Å. The crystal structure of the prokaryotic ribosome has shown that the particle inside is mostly made of rRNA: one 16 S RNA molecule in the small subunit and two, 5 S and 23 S RNA molecules, in the large subunit. The r-proteins, about 20 and 30 in the 30 S and 50 S subunits, respectively, are mainly in the surface with extensions that interpenetrate the rRNA to strengthen the particle structure (Moore and Steitz 2005).

During translation, the ribosome binds one mRNA and two tRNA molecules, which can be positioned at three well-defined sites, A, P, and E, at different steps of the process (Burkhardt et al. 1998). Both subunits have different functions (Ogle and Ramakrishnan 2005; Korostelev and Noller 2007). The small subunit participates in the decoding process by controlling the accuracy of the interaction of the mRNA ► [codons](#) with the tRNA anticodons. The large subunit stabilizes the tRNA binding at the A, P, and E sites, displays the peptidyl transferase activity (which catalyzes the formation of the peptide bonds that link together the ► [amino acids](#) in proteins), and contains a GTPase-associated domain involved in the interaction of essential GTP-hydrolyzing factors. Most ribosomal functions are directly associated to the rRNA, while r-proteins optimize the activity by providing the appropriate conformation (Moore and Steitz 2005). During translation, the large subunit rotates relative to the small subunit in a ratchet-like manner, which drives the displacement of the ribosome along the mRNA (Frank and Spahn 2006).

A comparable core structure is present in all ribosomes despite which taxonomic group they

belong to. Ribosomes from eukaryotic organelles are of the prokaryotic 70 S type (Harris et al. 1994). In the cytoplasm, larger 80 S eukaryotic ribosome extra RNA loops are found as continuous insertions in the conserved rRNA core where additional proteins bind (Spahn et al. 2001). The role of these additional components is unknown but might perform some control function.

The ribosome is the target of a number of ► [antibiotics](#), which bind to the rRNA and block ribosomal functions (Yonath 2005). Consequently, translation and cell growth stop. The antibiotic specificity for either prokaryotic 70 S or eukaryotic 80 S ribosomes determines its clinical usefulness (Vazquez 1979).

Cross-References

- [Amino Acid](#)
- [Antibiotic](#)
- [Codon](#)
- [Endosymbiosis](#)
- [Gene](#)
- [Genetic Code](#)
- [Genetics](#)
- [Protein](#)
- [RNA](#)
- [RNA World](#)
- [Translation](#)

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Ribosylaminoadenine

► [Nucleoside](#)

Ribosylaminocytosine

► [Nucleoside](#)

Ribosylaminoguanine

► [Nucleoside](#)

Ribosylaminouracil

► [Nucleoside](#)

Ribozyme

Michael P. Robertson
Department of Molecular Biology MB42, The
Scripps Research Institute, La Jolla, CA, USA

Keywords

Catalysis · RNA · RNA world

Synonyms

[RNA enzyme](#)

Definition

An abbreviation of “ribonucleic acid ► [enzyme](#).” Broadly defined as an ► [RNA](#) molecule that catalyzes any specific chemical reaction even though it may not always satisfy the strict definition of “enzyme,” specifically with respect to multiple turnover and self-modification.

History

The concept of catalytically active RNA was first postulated in the late 1960s as part of an elegant scenario to describe the origin of life (Woese 1967; Crick 1968; Orgel 1968). Subsequently, the unexpected discovery in the early 1980s that ribozymes were, in fact, active and essential components of contemporary living organisms was a paradigm-shifting breakthrough. Tom Cech, studying intron splicing (an intron is a region of RNA that interrupts the protein-coding region of some messenger RNAs and which must be removed in a process called RNA splicing before the mRNA can be correctly translated into a protein) (Kruger et al. 1982), and Sidney Altman, investigating ribonuclease P (an RNA/protein enzyme that cleaves the leader sequence from precursor transfer RNAs to generate mature tRNAs) (Guerrier-Takada et al. 1983), demonstrated that the catalysts of their respective chemical transformations were, remarkably, the RNA molecules themselves. For their discoveries, Cech and Altman shared the 1989 Nobel Prize in Chemistry.

Overview

Prior to the discovery of ribozymes, it was assumed that proteins were the sole catalysts in biology. Since their initial discovery, roughly a dozen families of natural ribozymes, distributed across all three domains of life, have been isolated. They primarily catalyze various phosphoester transfer reactions, such as RNA splicing and other site-specific cleavage/ligation of the RNA backbone. Their closely related catalytic repertoires are achieved through a variety of unique structural scaffolds. These are utilized in a variety of fundamental cellular processes ranging from regulation

of gene expression to genome replication, but at the chemical level, specializing in reactions that alter the connectivity of the ribose-phosphate backbone of RNA. A notable exception to this rule is the ► [ribosome](#) (the cellular machine responsible for making proteins in all known life), which is composed of both RNA and protein. It was shown in 1992 that the chemical step of peptide bond formation could be reconstituted in ribosomes from which nearly all of the protein had been removed, a strong indication that the RNA was the catalytic component (Noller et al. [1992](#)). This hypothesis was confirmed 8 years later by the X-ray crystal structures of the ribosome showing that the catalytic center of the ribosome is constructed of RNA, with no protein within a radius of 18 Å, thus making the ribosome itself the supreme example of ribozyme catalysis (Nissen et al. [2000](#)).

In vitro evolution and selection has greatly expanded both the number of known ribozymes and the diversity of their catalytic repertoire by enabling the isolation of new ribozymes that have never before been observed in nature (Joyce [2004](#)). The number of in vitro selected ribozymes has now far surpassed that of the naturally occurring ones and includes a wide range of diverse functionalities. The ► [RNA world](#) (Gilbert [1986](#)) hypothesis of the origin of life posits that all contemporary life can trace a direct line of descent to ribozyme-based organisms that flourished and then faded about 4 billion years ago. In vitro selection has been the primary investigative tool used to test the feasibility of this hypothesis, and much of what is known about ribozymes has been learned in this pursuit (Ellington et al. [2009](#)).

Like RNA, DNA is also able to fold into complex three-dimensional structures and catalyze chemical reactions (Joyce [2004](#)). These catalysts are often referred to as deoxyribozymes or DNAzymes. They have not been observed in nature but were discovered using in vitro selection.

Cross-References

- [Aptamer](#)
- [Enzyme](#)

- [Evolution, In Vitro](#)
- [Ribosome](#)
- [RNA](#)
- [RNA World](#)

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Rice-Ramsperger-Kassel-Marcus

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Synonyms

RRKM

Definition

Rice-Ramsperger-Kassel-Marcus (or simply RRKM) is a chemical kinetics theory allowing the estimation of unimolecular reaction rates from a few parameters of the potential energy surface. The RRKM theory is an improved form of the Rice-Ramsperger-Kassel (RRK) theory in which the rate an excited reactant molecule breaks down is treated as a function of the energy it contains. The RRKM theory was developed from the RRK theory by taking Eyring's transition state theory, and the way the various normal-mode vibrations and rotations contribute to reaction, into account. The RRKM theory assumes that the rate is proportional to the number of ways of distributing the energy among the internal degrees of freedom of the reactant, in such a manner that the critical energy is localized in one particular degree of freedom. It can be a powerful tool for studying gas-phase molecular reactions, such as those that occur in planetary atmospheres or in the interstellar medium.

Right Ascension

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The right ascension is one of the two coordinates of the equatorial system of reference, used by astronomers to locate a celestial object on the sky. It is the coordinate measuring the angular distance along the ► [celestial equator](#) between that object and the ► [“Vernal point”](#), which is in first approximation a fixed point with respect to the stars. The Vernal point is the location on the sky where the Sun crosses the equatorial plane at the March equinox. Right ascension is measured in units of hours, minutes, and seconds, positively toward the east. Because of the ► [precession](#) of

the equinoxes, the Vernal point moves slowly with time, so that the coordinates (right ascension and ► [declination](#)) must be associated with an indication of the date (the equinox) at which they are valid.

Cross-References

- [Coordinate Systems](#)
- [Declination](#)
- [Equinox](#)
- [Vernal Point](#)

Rille

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute
of Geological Sciences, Freie Universität Berlin,
Berlin, Germany

Synonyms

[Graben](#); [Groove](#); [Lava tube](#)

Definition

Rilles (derived from the German term in geomorphology for grooves) are elongated and narrow depressions on the lunar surface with a high length-to-width ratio resembling channel-like features. Rilles are of endogenic origin: the so-called arcuate and sinuous rilles are both associated with volcanism and lava and are due to contraction cooling and subsidence or collapsed lava tubes, respectively. The so-called straight rilles are considered to be of tectonic origin and caused by the extension of the ► [crust](#).

Though similar features exist on other ► [terrestrial planets](#), the term “rille” is generally reserved for lunar surface features.

Cross-References

- [Crust](#)
- [Rima, Rimae](#)
- [Terrestrial Planet](#)

Rima

- [Rima, Rimae](#)

Rima, Rimae

Stephan van Gasselt
Planetary Sciences and Remote Sensing, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Synonyms

[Graben](#); [Groove](#); [Lava tube](#); [Rima](#)

Definition

Rimae are arcuate, sinuous, or straight grooves on the lunar surface and are thought to have an endogenic origin, that is, either tectonic or volcanic. On July 30, 1971, Apollo 15 landed near Rima Hadley (also termed Hadley Rille, 25°N, 3°E) and took photographs of that area. Rima Hadley is a steep-walled meandering rille that has a length of more than 100 km, a width of 1–2 km, and a depth of up to 400 m. It is of lava-flow origin and is the only place where lunar ► [rock](#) outcrops have been observed. Thus far, 111 lunar features have been named rimae.

Cross-References

- [Apollo Mission](#)
- [Rille](#)
- [Rock](#)

Rio Tinto

David C. Fernandez-Remolar
State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Taipa, China
CNSA Macau Center for Space Exploration and Science, Macau, People's Republic of China

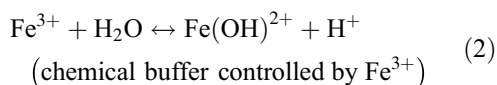
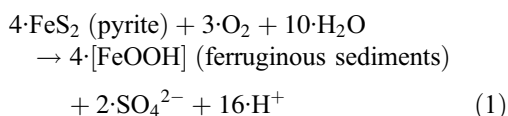
Keywords

Hyperacidic extreme environment · Acidophiles · Fluvial system · Ferruginous deposits · Mars analog · Biosignatures

Acronyms

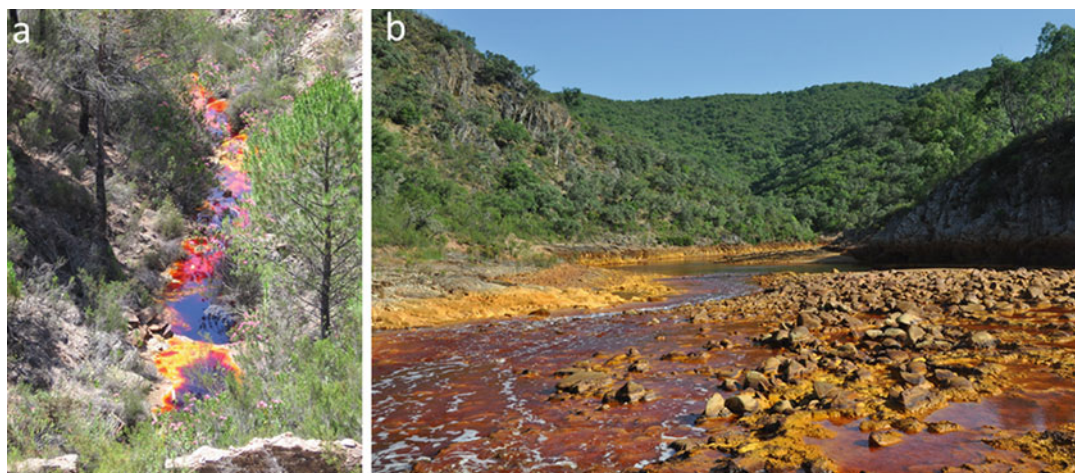
IPB	Iberian Pyrite Belt
IPBSL	Iberian Pyrite Belt Subsurface Life
MARTE	Mars Analog and Research Technology Experiment

Chemical Formula



Definition

Río Tinto is a 100-km-long acidic fluvial system (Fig. 1) emplaced in the IPB (Leistel et al. 1998) considered as a chemical environmental analog of Mars (Fernández-Remolar et al. 2005). Since the paleolithic (Mayoral et al. 2021), the Rio Tinto basin has been populated by different cultures and civilizations (chalcolithic, bronze, and iron), which have mined the rich metallic ore bodies for copper, silver, and gold for millennia. The fluvial system is integrated into a wider acidic



Rio Tinto, Fig. 1 Images showing the Río Tinto acidic system in the headwaters around Peña de Hierro (a), and in the Berrocal area (b) showing red deposits enriched in ferric oxyhydroxides and oxysulfates that are sourced in the subsurface bio-oxidation of the sulfide ore bodies by

iron and sulfur oxidizers. The Río Tinto waters experience a high saturation in Fe^{3+} and SO_4^{2-} -bearing ions by means of evaporation conferring a high preservation potential for biological information

domain that included the fluvial basin of the Odiel River, where early Quaternary deposits of acidic origin are also found. Río Tinto Headwaters are composed of two main acidic streams sourced in Peña de Hierro and Cerro Colorado areas, respectively. Its peculiar geochemistry is maintained by different low-pH springs sourced on a pyrite ore body aquifer (Gómez-Ortiz et al. 2014) that is bio-oxidized by iron and sulfur bacteria. The Río Tinto springs are connected to the aquifer by a diverse set of normal faults which is recharged with meteoric waters replenishing the oxygen to the underground chemolithotrophs (Fernández-Remolar et al. 2008b). In this frame, the acidic springs are sourced in the acidic subsurface waters outflowing through the same group of faults. The Río Tinto microbial life displays a high microbial diversity despite the extreme conditions based on a low pH and high metal concentration (Amils and Fernandez Remolar 2020). The outstanding mineralogy of the fluvial Río-Tinto system is analogous to the mineral association found in some Mars regions like Meridiani (Fernández-Remolar et al. 2005; Squyres and Knoll 2005). Consequently, Río Tinto is considered as a valuable terrestrial analog of Mars for inferring geochemical conditions that were involved in the formation

of iron-rich minerals that formed under the same hyperacidic solutions on Mars billions of years ago (Ehlmann and Edwards 2014).

Overview

The acidic environment of Río Tinto in Southern Spain (Fig. 1) is the result of the biooxidation of IPB sulfide ore bodies by chemolithotrophs over the last 25 million years (Essalhi et al. 2011; Fernandez-Remolar et al. accepted). The bio-oxidation results from a two-stage process (Sand et al. 2001) starting with the pyrite-rich ore body oxidation to SO_4^{2-} and Fe^{2+} followed by oxidation of Fe^{2+} to Fe^{3+} . The oxidation of the sulfide ore body is a complex process initiated by the decomposition of pyrite with ferric iron serving as the oxidizing agent, which produces great quantities of Fe^{2+} in solution. After that, Fe^{2+} is oxidized to Fe^{3+} by iron oxidizers using O_2 as the electron acceptor, which is newly available as oxidizing agent for pyrite through chemolithotrophic metabolism. Under acidic conditions, ferric cation is very soluble and functions as a buffer (see chemical formula 2 above) that maintains the pH between 1.5 and 3.5 (Fernández-

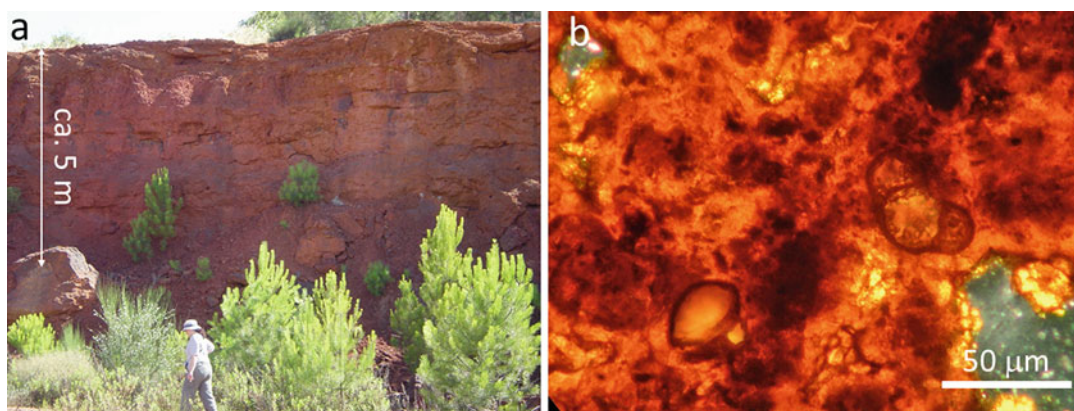
Remolar et al. 2003; Gómez et al. 2004). In the multistage oxidation process, the low-pH underground waters enriched in iron and sulfate are exposed to evaporation mainly during the hot season (late spring to early fall), experiencing a subsequent overconcentration to produce acidic brines. Furthermore, the microbial oxidation of pyrite is an exothermal process that, under certain geological conditions, can result in heat accumulation in the subsurface (Fernández-Remolar et al. 2008a). Consequently, both pH and thermal control have been considered as ecological mechanisms with homeostatic properties that could benefit microbial communities on surface and subsurface habitats (Fernández-Remolar et al. 2008a; Gómez et al. 2004). The surface and subsurface areas of the Río Tinto system are greatly influenced by seasonal changes which control the input of rainwater and oxygen to the system (Fernández-Remolar et al. 2003). During the wet season, weathering of silicates, erosion in headwaters, and sedimentation in the fluvial are favored, whereas the precipitation of sulfate assemblages is the main sedimentary process in the dry season (Fig. 2). Therefore, the sedimentary record on the surface environment alternates between detrital fine-grained deposits, iron oxides, and sulfates. The exploration of the Río Tinto basement through the MARTE and IPBSL projects (Amils et al. 2013; Fernández-Remolar

et al. 2018; Stoker et al. 2008) has shown that it has a diverse microbial community is subjected to a varying pH and redox ranging from acidic and aerobic in shallow areas to quasi-neutral and anaerobic in deeper areas, where methane and carbonates are formed by microbial mediation (Fernández-Remolar et al. 2008b, 2018; Puente-Sánchez et al. 2014). The activity of the fluvial environment has been recorded over the last two million years in different terrace levels that have preserved valuable biological information in the form of mineralized structures of micro and macroorganisms, suggesting that biological structures could be fossilized under the same extreme conditions on Mars billions of years ago (Fernández-Remolar and Knoll 2008). Furthermore, the molecular analysis of the ancient ferruginous rocks that were produced under the extreme conditions of the Río Tinto acidic basin supports that the organic compounds and biomolecules are also preserved. Samples from the gossan deposits (> 25-6 Ma) and the upper terrace (2.1 Ma) have provided a diverse association of different biological molecules and inorganic metabolic traces (Fig. 3) (Fernandez-Remolar et al. accepted). While the preservation mechanisms of biomolecules are not fully understood, they might be associated with a fast decrease in water activity coupled with salt mineralization. It strongly reduces or even can inhibit the microbial activity that is associated



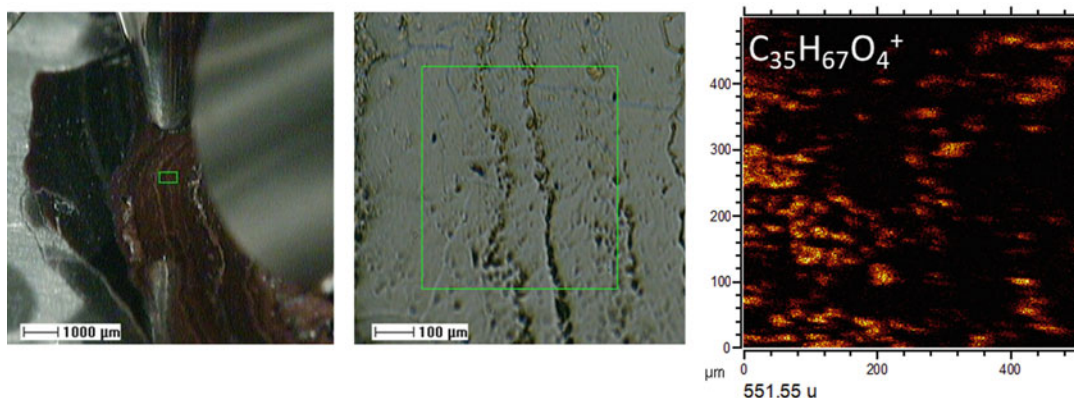
Río Tinto, Fig. 2 The red color in water (a) results from the high concentration in different Fe^{3+} plus ionic complexes (e.g., FeSO_4^+ , FeHSO_4^{2+}) that are stable under a pH of 1–3. The riverbed sediments correspond with amorphous polymers of iron and sulfates, which are the precursor of different ferric oxysulfates and amorphous oxyhydroxides precipitating on the river bottom as successive coating layers. The corrugated pattern covering the riverbed (a) corresponds with coated streamers during

successive seasons. In shallow areas, under the extreme summer conditions (b), the acidic brine can eventually evaporate out to precipitate a dark reddish amorphous deposit which is mainly composed of jarosite. Copiapite can also precipitate (b) by pumping evaporation producing characteristic yellowish efflorescence's. Such materials mature to goethite and hematite over time, fossilizing primary sedimentary structures (c) that are found in the terrace ferruginous deposits



Rio Tinto, Fig. 3 Early Pleistocene Upper Terrace (a) cropping at the Alto de la Mesa location (see Fernández-Remolar and Knoll 2008) preserving different micro and macrostructures of biological origin that have been

fossilized by coating and permineralization. (b) Shows the preservation of bisaccate pollen of *Pinus* sp. in the Upper Terrace that is associated with abundant remains of plants, fungi, and insects



Rio Tinto, Fig. 4 ToF-SIMS analysis of a finely laminated deposit collected from the Early Pleistocene Upper Terrace (Fernández-Remolar et al. 2005) showing the occurrence of diacylglycerides at m/z 551.55 ($C_{35}H_{67}O_4^+$) that outline filamentous structures

perpendicular to the laminations. Same lipidic compounds like diverse fatty acids, diacylglycerides, and sphingolipids have been found in the more ancient deposits of gossan dating back to >6 Ma and up to 25 Ma

with organic degradation. Under these circumstances, the preservation of organic compounds and biomolecules could have likely occurred in the ancient acidic deposits of Mars (Fig. 4).

Cross-References

- [Acidophile](#)
- [Biosignature](#)
- [Mars Analogues](#)
- [Terrestrial Analog](#)

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Rise of Atmospheric Oxygen

► Great Oxidation Event

Riverbeds

► Valley Networks

RNA

William G. Scott

Department of Chemistry and Biochemistry, The Center for the Molecular Biology of RNA, University of California at Santa Cruz, Santa Cruz, CA, USA

Keywords

Catalytic RNA · Messenger RNA · Nucleic acid · Ribosomal RNA · Ribozymes · RNA world · RNAi · Transfer RNA

Synonyms

Ribonucleic acid

Definition

Ribonucleic acid (RNA) is one of two principal types of nucleic acid found in all cellular life. RNA consists of a polymer of ribonucleoside phosphates, each unit of which, in turn, is comprised of a ► **pyrimidine base** or ► **purine base**, a ► **ribose** sugar, and a ► **phosphate**. RNAs encode genetic information (e.g., RNA viruses), serve as intermediates in gene transcription (e.g., mRNA), and also play structural, regulatory, and catalytic (e.g., ► **ribosome**) roles in cellular biology.

Overview

Central Dogma of Molecular Biology

Francis Crick proposed a simple scheme, shown below, that he entitled “The Central Dogma of Molecular Biology” to serve as a unifying axiom for the emerging field of molecular biology: DNA → RNA → Protein, i.e., “DNA makes RNA makes Protein.” Information flow was held to be from left to right only, with DNA encoding genetic information, proteins as gene products serving as the main form of genetic expression, and RNA serving an intermediary role.

Although DNA encodes the information required for protein synthesis, it must first be *transcribed* into messenger RNA (mRNA), and then the three-nucleotide genetic code must be *translated* into an amino acid sequence during protein synthesis. In addition to mRNA, which serves as the physical template for translation, adapter molecules, known as transfer RNA (tRNA), match the ► **nucleotide** triplets of the genetic code in the mRNA to individual amino acids, which are covalently linked to each tRNA molecule. Protein synthesis takes place on the ribosome, an RNA-protein complex, whose structure is mainly comprised of ribosomal RNA (rRNA) molecules. The catalytic center of the ribosome is thought to be comprised entirely of rRNA, which also implies the peptidyl transferase of the ribosome is a ribozyme or a catalytic RNA. Bacteria, Archaea, and Eukarya all possess DNA genomes; however, a large subset of viruses possess single-stranded or double-stranded RNA genomes. RNA has recently been shown to be extensively involved in cellular gene regulation via pathways collectively referred to as RNA interference (RNAi).

Messenger RNA (mRNA)

The genetic information encoded in DNA is not immediately available for translation into protein sequences. Rather, this information must first pass through an RNA intermediary known as messenger RNA. Genes are transcribed by RNA polymerases, enzymes that copy a specific sequence of DNA in a template-dependent fashion, producing a complementary single-stranded RNA. Depending upon

the organism, this primary RNA transcript may undergo additional processing steps (e.g., capping, splicing, 3'-polyadenylation) and nuclear export (in the case of eukaryotes) before it becomes a mature mRNA available for translation into a protein sequence.

Mature mRNA molecules typically possess a 5'-untranslated region (5'-UTR), a ribosome-binding and translational start site, a continuous coding region, one or more stop codons (a translational termination site) and a 3'-untranslated region (3'-UTR), and a polyadenine terminus. Both UTRs may contain regions of RNA that participate in translational (and sometimes transcriptional) regulation. The coding region may be discontinuous in the primary transcript, requiring that the intervening sequences of noncoding RNA (or introns) be excised and the remaining coding regions (exons) be ligated, a process collectively termed pre-mRNA splicing. The coding region in a mature mRNA is almost always continuous and consists of a linear sequence of nucleotide triplets, called *codons*, each of which codes for an individual amino acid. The mRNA thus serves as a mobile template for the assembly of a protein by the ribosome.

Transfer RNA (tRNA)

The one-to-one correspondence between an amino acid (the monomeric building blocks from which proteins are synthesized) and a nucleotide triplet codon is physically manifested in the form of transfer RNA (tRNA). Unlike mRNAs, tRNAs are comparatively small (~75 nt) noncoding RNAs that fold into a regular, well-defined globular three-dimensional structure. tRNAs serve as shuttle molecules, one end of which becomes covalently attached to a specific amino acid (via a reaction catalyzed by tRNA synthetase) and the other end, termed the anticodon, forms standard Watson-Crick hydrogen-bonded base pairs with the corresponding codon within an mRNA when both are bound to the ribosome. tRNAs having covalently bound amino acids are referred to as aminoacylated tRNAs, and these (along with the mRNA template) are the substrates used by the ribosome for enzymatic peptide synthesis.

Ribosomal RNA (rRNA)

The ribosome is an RNA/protein complex that catalyzes peptide bond synthesis reactions in a template-dependent manner to *translate* the genetic code into protein sequences. The substrates consist of aminoacylated tRNAs and an mRNA template. The ribosome itself is comprised of two subunits, conventionally termed the large subunit (which contains the peptidyl transferase reaction center) and the small subunit (which binds the mRNA template). Each of these subunits, in turn, is comprised of RNA and protein components. The RNAs define the core structure and appear to be primarily responsible for catalyzing the chemical step of peptide bond formation, as well as forming the binding sites for mRNA, the tRNAs, and the interface between the ribosomal subunits. The proteins are primarily found on the surface of the ribosome and appear to play more ancillary (but nonetheless essential) roles. The small subunit of the ribosome is comprised of several proteins and one RNA molecule (16S rRNA in prokaryotic systems and 18S rRNA in eukaryotic systems, where S indicates ► [Svedberg units](#)). The large subunit of the ribosome is comprised of several proteins and more than one RNA molecule (23S rRNA and 5S rRNA in prokaryotic systems and 28S, 5.8S, and 5S rRNA in eukaryotic systems). The 23S rRNA in prokaryotes and the analogous 28S rRNA in eukaryotes are believed to possess all of the components required to catalyze the chemical step of the peptide transfer reaction; hence, these RNAs are examples of enzymatic RNAs or ► [ribozymes](#).

Catalytic and Enzymatic RNAs (Ribozymes)

Until the early 1980s, it was presumed that all enzymes were proteins. It was then discovered that the self-splicing catalytic activity in group I introns in certain protozoans (e.g., *Tetrahymena*) and the enzymatic processing of precursor tRNA transcripts by the RNA/protein complex RNase P in bacteria were in fact catalyzed by RNA. Subsequently, several other RNA enzymes, or ribozymes, have been discovered. Inarguably, the most important of these, described in the previous paragraph, is the peptidyl transferase activity of the ribosome; hence, the ribosome is the most fundamental and important ribozyme. With

the exception of the ribosome, all naturally occurring ribozymes catalyze either phosphodiester isomerization reactions (leading to both RNA backbone cleavage and ligation) or phosphodiester hydrolysis reactions (leading exclusively to RNA backbone cleavage).

Genomic RNA

All eukaryotic, archaeal, and bacterial genomes are comprised of double-stranded DNA. However, many viruses possess either single-stranded or double-stranded RNA genomes. An important subset of these viruses are known as retroviruses and are characterized in having a life cycle in which an RNA strand that invades the host cell is reverse transcribed by an RNA-dependent DNA polymerase into DNA and the complementary DNA becomes integrated within the host's genome (the human immunodeficiency virus (HIV) is one such example). RNA viruses that are not retroviruses include the common cold virus, influenza viruses, severe acute respiratory syndrome (SARS) virus, polio, and many others.

RNA Interference (RNAi)

Within the last decade, we have begun to understand that small (typically ~21-nucleotide) noncoding RNA molecules that are the products of cellular processing reactions are intimately involved in gene regulation via a series of related mechanisms collectively known as RNA interference (RNAi). Briefly, these mechanisms involve intermolecular interactions between the small noncoding RNAs and mRNAs, or in some cases, direct interaction with the nucleosome.

RNA World Hypothesis

The discovery that RNA can be catalytic provides a logical escape from the conundrum implicit in the Central Dogma of Molecular Biology. Specifically, if proteins are required to replicate ► [nucleic acids](#) and nucleic acids are required to encode proteins, which came first? This sort of paradox is typically invoked as an example of “irreducible complexity” by those arguing in favor of the necessity of a supernatural origin of life. However, if a single type of molecule, such as RNA, is capable of both information storage and catalysis, it means, in principle, that RNA has the

capacity to self-replicate. A self-replicating RNA thus avoids the chicken or egg paradox objection of “irreducible complexity” and permits suggestion that some of the earliest self-replicating molecules may have been RNAs. This conjecture, originally articulated by Carl Woese and Francis Crick, has been formulated and given the title of the ► [“RNA World.”](#) Of course, no one knows if life evolved from an RNA world, but it may be possible to give an experimental proof of principle by creating self-replicating RNAs in vitro. In vitro RNA evolution is now a commonly used laboratory technique for devising various aptamers and catalysts. Although ligase ribozymes have been developed that can copy other RNA sequences in a template-dependent manner (a prerequisite to propagation of RNA), a true self-replicase ribozyme remains elusive.

Cross-References

- [Evolution, In Vitro](#)
- [Nucleic Acids](#)
- [Nucleoside](#)
- [Nucleotide](#)
- [Oligonucleotide](#)
- [Purine Bases](#)
- [Pyrimidine Base](#)
- [Ribose](#)
- [Ribosome](#)
- [Ribozyme](#)
- [RNA World](#)

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RNA Enzyme

- [Ribozyme](#)

RNA Life

- [RNA World](#)

RNA Ligase

Burckhard Seelig

Department of Biochemistry, Molecular Biology and Biophysics & BioTechnology Institute, University of Minnesota, St. Paul, MN, USA

Keywords

RNA world · SELEX · Ribozyme · Artificial protein enzyme

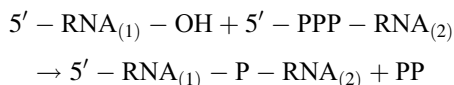
Definition

RNA ligases are enzymes that catalyze formation of a covalent linkage between two oligoribonucleotides via a phosphodiester bond. In the context of the “RNA world” hypothesis, this linkage reaction would have been of great importance to generate longer, more complex RNA molecules from shorter oligonucleotides, which are easier to synthesize from mononucleotides.

Overview

Because no dedicated RNA ligase ribozymes had been found in nature, the SELEX technology was

applied to isolate artificial ribozymes from a combinatorial library of random RNA. The identified ribozymes catalyze the bond formation of a 5'-triphosphorylated RNA to the 3'-hydroxyl group of a second RNA molecule forming the natural 3–5' phosphodiester linkage (Bartel and Szostak 1993):



These ribozymes were the first artificial ribozymes created in the laboratory and are also some of the most efficient RNA enzymes made to date. Subsequently, the RNA ligase ribozymes were optimized through in vitro evolution to catalyze RNA polymerization (Johnston et al. 2001). This activity would have been the most crucial catalytic function in an “RNA world” enabling the replication of the RNA genome.

Artificial deoxyribozymes that catalyze the same RNA ligation reaction as above were also isolated in the laboratory, using a similar in vitro selection approach (Purtha et al. 2005).

No natural protein enzyme is known to catalyze this RNA ligation reaction shown above. Yet, natural protein enzymes can ligate two RNA molecules by the chemically different reaction linking a 5'-monophosphate RNA to a 3'-hydroxyl RNA while using adenosine triphosphate as a cofactor. In contrast, laboratory evolution using the mRNA display technology has generated an artificial protein enzyme from combinatorial libraries of randomized proteins that catalyze the same RNA ligation chemistry as the ribozymes (Seelig and Szostak 2007). This artificial protein enzyme was found to have an unusual novel structure that is unlike extant proteins. This new enzyme can be considered a model primordial catalytic fold as it has not been shaped by billions of years of natural evolution (Chao et al. 2013).

Cross-References

- [Combinatorial Library](#)
- [Enzyme](#)
- [mRNA Display](#)

- [Protein](#)
- [Ribozyme](#)
- [RNA World](#)

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RNA Polymerase

Juli Peretó

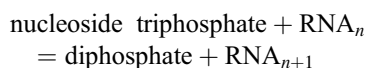
Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

[DNA \(or RNA-\)-dependent RNA polymerase](#); [RNA replicase](#)

Definition

RNA polymerase is an enzyme which catalyzes the addition of a ribonucleoside triphosphate to the 3' – end of a RNA strand using a template. The systematic name of this enzymatic activity is nucleoside triphosphate-RNA nucleotidyltransferase, and the catalyzed reaction can be represented as



DNA-directed RNA polymerases (EC 2.7.7.6) use DNA templates, whereas RNA-directed RNA polymerases (EC 2.7.7.48) use RNA templates. These enzymes can initiate a chain de novo. In eukaryotes different RNA polymerases participate in the transcription of the diverse types of RNA. In prokaryotes, a multimeric RNA polymerase performs the transcription of the different classes of RNA.

History

Sam Weiss, Audrey Stevens, and Jerard Hurwitz discovered independently the DNA-dependent RNA polymerase activity in 1960.

Cross-References

- [RNA](#)
- [Template](#)
- [Transcription](#)

RNA Replicase

- [RNA Polymerase](#)

RNA Replicase Ribozyme

Mark A. Ditzler
Ames Research Center, Moffett Field, CA, USA

Definition

An RNA replicase ribozyme is an RNA enzyme (ribozyme) that catalyzes the replication of RNA sequences. RNA replicase ribozymes are a central feature of RNA world theories of the origin of life.

History

The term RNA replicase was introduced to describe protein enzymes that polymerize RNA in an RNA-dependent manner (Haruna et al. [1963](#)). These protein enzymes replicate the genomes of RNA viruses through the template-directed polymerization of mononucleotides. It was not until decades later that ribozymes capable of similar polymerization reactions and RNA replication were identified through directed evolution in vitro (Johnston et al. [2001](#); Lincoln and Joyce [2009](#)).

Overview

The replication of information-containing molecules by a replicase provides a means of establishing heritability. The emergence of such a replicase would therefore satisfy one of the fundamental requirements of life. RNA's dual biological role of both catalyzing chemical reactions and storing genetic information suggests the possibility of a simple evolving system in which RNA acts as both the replicase and the replicated genome. This possibility of supporting an evolving system with a single type of molecule has motivated a number of efforts to identify and characterize RNA replicase ribozymes. While these ribozymes are not observed in extant biology, RNA-catalyzed replicase activity has been characterized in vitro.

Replicase function can be realized through the ligation of short oligomers. RNA replicase ribozymes that link together short RNA oligonucleotides have been used to generate cooperative, self-replicating systems in vitro. The ribozymes in these systems were adapted either from biological RNA sequences (Vaiday et al. [2012](#)) or from ribozymes evolved from random sequences in vitro (Lincoln and Joyce [2009](#)). These systems demonstrate that RNA-only systems can support self-replication. They do, however, depend on an external supply of oligonucleotide substrates to sustain self-replication, which places limits on the extent to which the behavior of these systems can be applied to understanding the origin of life.

These limits are partially addressed by attempts to identify RNA replicase ribozymes that depend on simpler substrates.

RNA replicase ribozymes that use simple nucleotide monomers as substrates may have greater relevance to the origin of life than replicases that depend on the ligation of oligonucleotides. Ribozyme-catalyzed replication of RNA genomes from monomers requires the existence of ribozymes with template-directed RNA polymerase activity. The existence of such ribozymes has been demonstrated through the iterative application of directed evolution in vitro (Johnston et al. 2001). Initially, ribozymes evolved to catalyze the ligation of two RNA oligonucleotides also exhibited limited polymerase activity (Eklund and Bartel 1996). This activity was enhanced through additional applications of directed evolution to generate more efficient polymerase ribozymes (Johnston et al. 2001; Zaher and Unrau 2007). One polymerase ribozyme is capable of polymerizing >200 nucleotides in a template-directed manner (Attwater et al. 2013). This polymerase ribozyme is only 202 nucleotides long, which suggests that RNA self-replication may be possible. This specific ribozyme has sequence-dependent requirements that prevent it from using its own full sequence as a template for polymerization and therefore does not possess self-replicase activity. An RNA self-replicase that utilizes nucleotide monomers to generate additional copies of itself has not yet been identified.

Cross-References

- [Nucleotide](#)
- [Origin of Life](#)
- [Ribozyme](#)
- [RNA](#)
- [RNA World](#)
- [Self-Replication](#)

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RNA Self-Replication

- [Template-Directed Polymerization](#)

RNA Splicing

- [Splicing](#)

RNA Synthesis

- [Transcription](#)

RNA World

David P. Horning
Department of Molecular Biology, The Scripps
Research Institute, La Jolla, CA, USA

Keywords

In vitro evolution · Ribosome · Ribozyme · RNA

Synonyms

[RNA life](#)

Definition

The RNA world is a hypothesized early stage in the evolution of life that may have preceded the ► [last universal common ancestor](#) (LUCA) of all modern organisms. In this scenario, ribonucleic acid (► [RNA](#)) was the sole information-rich biopolymer, performing both the catalytic and genetic roles played by proteins and deoxyribonucleic acid (DNA), respectively, in the modern cell. The proposed vestiges of the RNA world are found throughout modern biology, most notably in the central functional roles of RNA found in protein translation.

Overview

Darwin's prediction that all modern life has descended from a single, primitive common ancestor has been thoroughly confirmed by modern biology (Grant and Carpenter 2003). Indeed, comparative genomics has begun to shed light on the genome content of the ► [last universal common ancestor](#) (LUCA), revealing a biochemically sophisticated cellular organism with an extensive metabolism and a fully modern form of protein translation (Koonin 2003; Becerra et al. 2007). To some extent, we can infer that the LUCA itself evolved from more primitive organisms, as paralogous genes present in the LUCA must have descended from a much smaller complement of ancestral genes, but determining how this organism functioned runs into a central dilemma (Wolf and Koonin 2007).

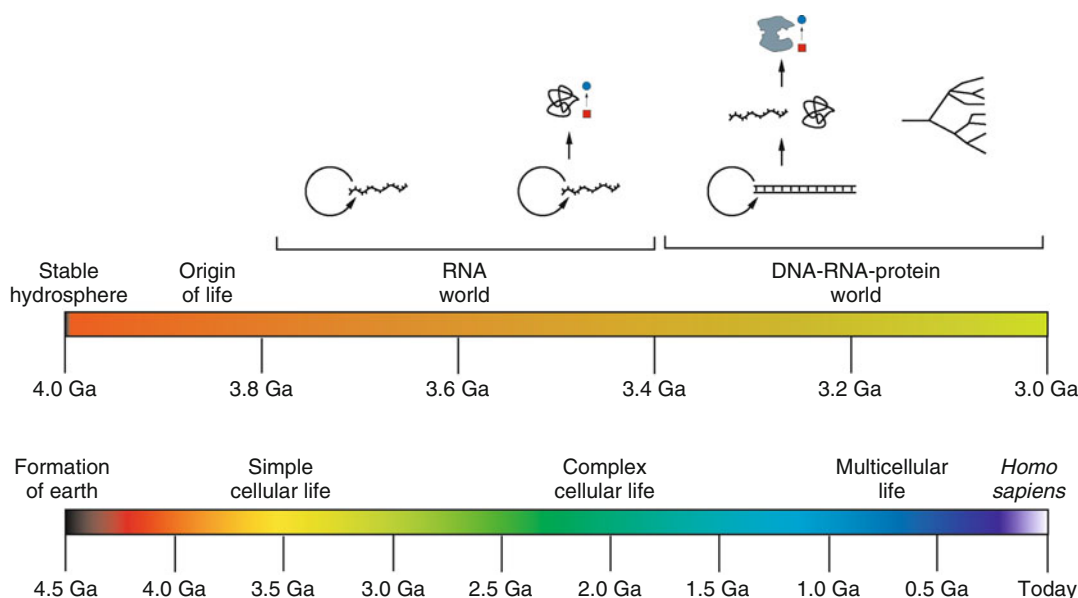
Biology fundamentally uses two classes of informational biopolymer: nucleic acids and proteins. Genetic information is stored and transmitted through inheritance in ► [nucleic acid](#) polymers, primarily in the form of DNA. The ► [phenotype](#) of the cell and by extension the whole organism are directed by proteins, which can fold into complex three-dimensional structures, catalyze diverse chemical reactions, and perform sophisticated mechanical transformations. The central dogma of molecular biology holds that genetic information flows between nucleic acids and from nucleic acids to proteins

but not between proteins or from protein into nucleic acid. This doctrine poses a paradox: proteins are the biopolymer of phenotype, performing the catalytic tasks needed to run a cell, while nucleic acids are the biopolymers of ► [genotype](#), information carriers par excellence. How could either have evolved without the other?

The RNA world offers a solution by predicting that ancestors of modern cells existed in which the primary, if not sole, information-rich biopolymer was RNA. RNA would have both stored genetic information and performed the basic operations of the cell, including RNA replication – it acted as both genotype and phenotype (Gilbert 1986). Extensive evidence has been found to support both the historical and functional claims of this hypothesis – modern life does appear to be descended from heavily RNA-based organisms, and RNA catalysts can perform many of the diverse functions performed by proteins in modern biology, including the replication of nucleic acids (Dworkin et al. 2003; Joyce 2002; Benner et al. 1989; Gesteland et al. 2006).

The history of life before its divergence from the LUCA, according to this model, can thus begin to be outlined (Fig. 1). Self-replicating RNA emerged on Earth by some mechanism and began to evolve. This replicating RNA diversified, assumed varied catalytic tasks, and formed a genome of significant complexity. Once RNA organisms invented a rudimentary ability to synthesize polypeptides, evolution led, eventually, to coded protein translation. The RNA world ended as proteins proved to be superior functional biopolymers and gradually took over most, though not all, of the catalytic tasks in the cell. DNA, a more chemically stable nucleic acid, evolved to replace RNA as genetic material in most organisms as well, though it is unclear whether this occurred before or after the invention of protein (Dworkin et al. 2003; Joyce 2002; Benner et al. 1989).

This entry will review the evidence for the existence of the RNA world and the current understanding of how it arose, evolved, and was replaced by modern DNA-RNA-protein life. The basic methodologies used to examine the RNA world will be briefly introduced, and then the



RNA World, Fig. 1 The postulated rise and fall of the RNA world during the evolution of life, from early self-replicating RNA to complex, RNA-controlled metabolism,

to the invention of translation, followed by diversification of all modern branches of life

current state of RNA world research will be reviewed in reverse chronology: beginning with evidence for the RNA world from modern biology and the transition into modern life, followed by efforts to understand how RNA life could function and evolve, and ending with the various possibilities by which RNA replication may have first emerged. Finally, different avenues of research poised to shed new light on the RNA world, and how such research may begin to intersect with other fields in the origin of life, will be reviewed.

Basic Methodology

Searching for “Molecular Fossils” in Modern Biology

Protein enzymes generally adopt more stably folded structures and a greater range of catalytic strategies than RNA enzymes (Cech 2009). This advantage would ensure that organisms that catalyzed protein translation would displace earlier RNA life via Darwinian evolution, in the process eliminating the less efficient ribozymes of the RNA world. Ancient paralogous protein sequences and folds indicate that a period of

rapid expansion of protein functions via duplication and specialization occurred prior to the common ancestor in all major aspects of cellular activity (Koonin 2003; Becerra et al. 2007; Wolf and Koonin 2007). Pathways must have existed to perform these tasks prior to the expansion of proteins, but no extant organism with these original pathways has been found.

Fortunately, biological evolution is notorious for leaving “frozen accidents” – traits present in modern organisms that appear unnecessary but arose in ancestral organisms in a different environmental context and became fixed in the organismal body plan, too critical to the functions of many other traits to tolerate subsequent modification. One oft-cited example is the recurrent laryngeal nerve in mammals that takes an extended and unnecessary detour down the neck and around the aorta to travel from the brain to the larynx, a relic of evolution of the nerve’s layout in fish, which have a circulatory system architecture quite different than that of mammals (Ridley 2004). The same could be expected to have occurred in the transition from RNA- to protein-based catalysis, with catalysts and reaction pathways originally evolved in RNA organisms conserved in modern

descendents, “molecular fossils” of the ancient RNA world. Biochemical and structural investigations of basic molecular and cellular activities, particularly in translation, have found a wealth of these relics.

In Vitro Evolution of RNA: Filling in the Gaps in the RNA “Fossil Record”

Barring the fortuitous discovery of a true “living fossil” of the RNA world, an RNA organism that has survived to the present day in some niche inimical or inaccessible to protein-based life, most of the content of the ancient RNA world genome will remain unknown. Directed in vitro evolution technologies offer an alternative: use the power of Darwinian evolution and modern synthetic biology to develop new ribozymes that “fill in the gaps” in the RNA genome by catalyzing reactions necessary to the RNA world (Joyce 2004, 2007; Müller 2006).

Darwinian evolution will act on any biopolymer that undergoes iterative cycles of sequence amplification, mutation, and selection for a particular function. All of these steps can be accomplished in vitro: PCR can amplify any DNA sequence, while other enzymes can be used to convert RNA into DNA and back again; a PCR protocol can be modified to introduce high rates of point mutations or recombination between distinct sequences; and selection of activity can involve any physical or chemical method that will selectively isolate RNA sequences with some desired feature, such as binding a specific ligand or catalyzing a particular reaction (Joyce 2004). Up to 10^{15} distinct sequences can undergo selection simultaneously. A tremendous number of functional RNA sequences have now been evolved, including both ligand-binding RNA ► [aptamers](#) and reaction-catalyzing ► [ribozymes](#). The range of activities discovered sheds light on a number of facets of the possible biochemistry performed in an RNA world.

The Emergence of the RNA World: Prebiotic Chemistry and Pre-RNA Life

The RNA world was originally proposed to solve a paradox of modern molecular biology, namely, the codependence of nucleic acids and proteins.

As such, the evidence for the existence of the RNA world comes from consideration of RNA relics in modern biology and the range of capabilities found in synthetic ribozymes. The emergence of the RNA world from chemical precursors, in contrast, has largely been a stumbling block; an RNA mononucleotide, let alone a polynucleotide, is a complex chemical that in modern biology is only synthesized by an extended, genetically encoded biochemical pathway. The proposal that prebiotic chemistry produced RNA does not follow from evidence in chemistry, but from evidence in biology that RNA life existed. The distinct views have been explained as the “molecular biologist’s dream and the prebiotic chemist’s nightmare” to emphasize the contrast between what appears necessary for the spontaneous emergence of RNA replication and what appears possible from prebiotic chemistry (Gesteland et al. 2006). A few alternative scenarios have been considered – the “RNA first” theory holds that some series of reactions, either fortuitous or inevitable, gave rise to replicating RNA, and from there, to life; a variety of related “genes first” theories posit that some simpler molecule, also capable of carrying genetic information, arose before RNA, forming a “pre-RNA world” that gave rise in turn to RNA; a number of “metabolism first” theories hold that simple metabolic systems could spontaneously self-organize on the early earth, forming life without genetic polymers, and only later invented RNA.

Key Research Findings

Translation Is Catalyzed by RNA

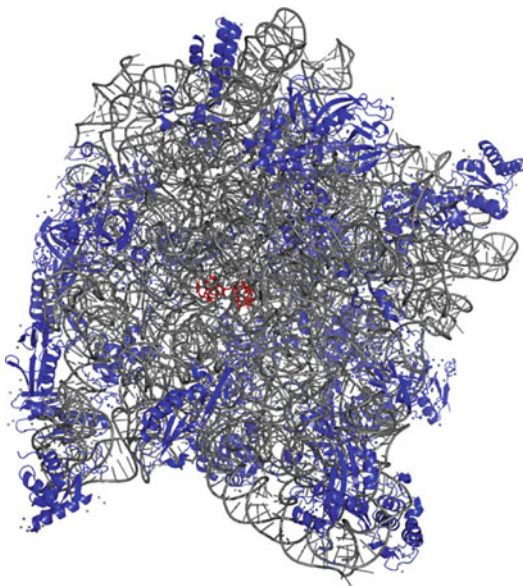
Translation of genetic information from nucleic acid to protein is the critical function that enabled the transition out of the RNA world. It is also the central biochemical pathway in life, and a large fraction of the inferred minimal genome of the LUCA consisted of the genes involved in translation (Wolf and Koonin 2007; Steitz and Moore 2003). As might be expected, “molecular fossils” of the RNA world have proven ubiquitous in translation and constitute the strongest evidence

for the historical existence of an RNA-based ancestor to modern life.

The most significant discovery is that the ► **ribosome**, arguably the most sophisticated nanomachine in biology, is a relic of the RNA world. Biochemical evidence and atomic-resolution structures of the ribosome show that both the mRNA (see ► **RNA**) decoding regions and the peptidyl transferase center that specifically catalyzes peptide bond formation between amino acids (protein synthesis) are surrounded by rRNA, not ribosomal proteins (Fig. 2) (Steitz and Moore 2003; Schmeing et al. 2005; Noller 2005). More succinctly, the ribosome is a ► **ribozyme**.

Proteins play important but largely ancillary roles in translating, folding, and stabilizing the ribosome and aiding in mRNA translocation (Steitz and Moore 2003; Noller 2005). A notable exception is that the charging of tRNA with amino acids, which establishes the genetic code, is catalyzed by the aminoacyl tRNA synthetase (aaRS) proteins. A few pieces of evidence suggest that

this was a late innovation. The aaRS proteins group into two distinct, unrelated folds and are paralogous to many other proteins with the same folds (Schimmel 2008; Goldman et al. 2010). Sequence and structural comparisons suggest that the aaRS forms are not ancestral, and translation was producing folded proteins before the aaRS proteins existed (Wolf and Koonin 2007). Some other mechanism of tRNA aminoacylation must have preceded the modern, protein-catalyzed form. It seems significant that the 3'-end of tRNA contributes to catalysis both in the peptidyl transferase center of the ribosome and the acylation site of the aaRS proteins (Schmeing et al. 2005; Hagiwara et al. 2010). Generation of this 3'-end is itself catalyzed by RNase P, which is a true ribozyme, capable of activity in the complete absence of proteins (Scott 2007). A great deal of the roles of tRNA and the aaRS proteins remains open to investigation, but the modern form of this pathway does seem to derive from one in which RNA played a more central role.



RNA World, Fig. 2 The structure of the bacterial 50S ribosomal subunit, composed of ribosomal RNA (gray) and the ribosomal proteins (blue). A transition state analogue (red) is bound to the peptidyl transferase center. Note that the center is composed entirely of ribosomal RNA, while the ribosomal proteins primarily decorate the exterior (PDB ID code 1VQP). (Schmeing et al. 2005)

RNA Processing Is Catalyzed by RNA

Although translation has proven the most fertile ground for discovering RNA relics, other biochemical pathways are also informative. RNA is extensively involved in its own splicing, including the self-splicing Groups I and II ► **introns** and eukaryotic introns spliced by the spliceosome. Like RNase P, self-splicing introns are ribozymes that can function in the complete absence of proteins, though in both specific proteins aid in folding and stabilizing the ribozymes (Scott 2007; Toor et al. 2008). Eukaryotic introns are somewhat more complex, as they are spliced by a multi-subunit RNA-protein (RNP) complex called the spliceosome. One of the small nuclear RNAs (snRNAs) central to its function, the U6 snRNA, has sequence and structural similarity to the Group II intron catalytic core, suggesting that the spliceosome evolved from a ribozyme (Roy and Gilbert 2006; Rodríguez-Trelles et al. 2006).

However, the case for the origin of these ribozymes in the RNA world is not as certain as for the ribosome, as such activity was not necessarily present in an RNA organism. Different theories have introns developing before the origin of

translation, soon afterward, or even after the divergence of the three domains of life from the LUCA (Roy and Gilbert 2006; Rodríguez-Trelles et al. 2006). Regardless of their historical origin, the activities of self-splicing introns and RNase P prove that RNA can function as an enzyme independent of protein and specifically catalyze reactions similar to the basic chemistry of RNA polymer synthesis and replication (Gilbert 1986). Taken together with evidence that the ribosome is a ribozyme, both peptide and RNA syntheses are activities plausibly carried out by naturally occurring ribozymes.

The last few decades have unveiled a wealth of nonprotein-coding RNA with biological activity, to such an extent that the term “RNA world” is now used both to refer to the ancestral role of RNA in the origin of life and the extensive role of RNA in modern biology (Sharp 2009). Although fascinating biologically, it is important to note that there is often little evidence that these RNAs originated in an ancestral RNA world and may have evolved in modern biology to perform tasks for which RNA is intrinsically suited. Still, the diversity of RNA functions indicates the RNA world could have possessed considerable complexity. Moreover, the diverse manners in which RNA and protein have been found to interact may represent a series of “transitional forms” showing that during the early evolution of translation, proteins evolved not as stand-alone catalysts but to assist the activity and folding of existing ribozymes (Cech 2009).

Remnants of the RNA World in Modern Metabolism

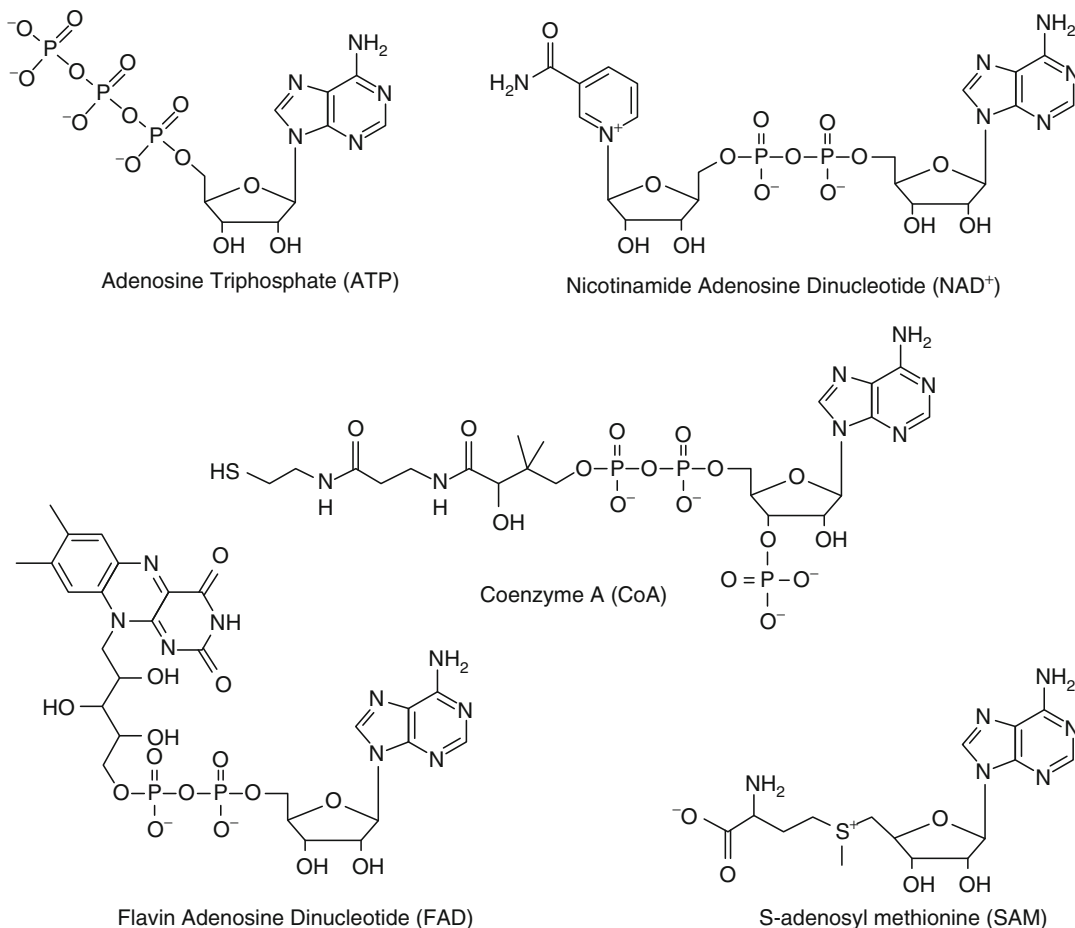
As with RNA macromolecules, “molecular fossils” of RNA metabolism could have been passed on to modern organisms. Many biological cofactors are ribo ► [nucleotides](#), derived from ribonucleotide substituents, or incorporate ribonucleotide moieties (Fig. 3). Most of these cofactors are used in metabolism across all domains of life, for energy transfer (ATP), redox reactions (FAD, NAD⁺), and methyl group transfer (SAM), among other activities, suggesting that they arose very early in the history of life. A ribonucleoside or nucleobase “handle” could

enable ribozyme catalysts to more readily bind the cofactors non-covalently or have them directly attached covalently (Joyce 2002; Benner et al. 1989). Similarly, charged tRNAs are used in metabolic pathways as the source of amino acids for the synthesis of other amino acids, cross-linking of the bacterial peptidoglycan cell wall, and even the synthesis of tetrapyrroles (Francklyn and Minajigi 2010). It is not clear why free amino acids are not used directly, unless the pathway evolved in an era where RNA played a more active role in metabolism.

Separately, a variety of metabolic pathways, including the synthesis of imidazole, thymine, and deoxyribonucleotides, proceed through ribonucleotide intermediates. This does not seem necessary from chemical first principles, but could be explained if these pathways originated in RNA-based organisms where the metabolic synthesis of RNA mononucleotides had already evolved (Joyce 2002). The synthesis of DNA monomers may also indicate whether DNA genomes evolved before or after translation. RNA may be incapable of stably generating free radicals for the reduction of ribose to deoxyribose, and thus, this reaction could not have occurred until proteins emerged (Joyce 2002).

RNA Functionality and Evolvability

Moving beyond functions still performed by RNA in modern biology, in vitro evolution of RNA ► [aptamers](#) and ► [ribozymes](#) has begun to survey the capacity of RNA to perform a variety of functions. RNA sequence space, the set of all possible RNA sequences, has proven to be rich in the distribution of structured RNA and enzymatic activity. Most ribozyme families known today have been evolved de novo, by beginning in vitro evolution with populations of randomly generated RNA sequences. Ribozymes range in length from tens to hundreds of nucleotides and in catalytic rate enhancement of 10–10⁹-fold. Both theoretical and experimental efforts have demonstrated that RNA can explore multiple sequences in the context of the same structure and access new structures by only a few mutations, proving adept at evolving new function through multiple mechanisms. Once the RNA world got started, it



RNA World, Fig. 3 Metabolic cofactors found in all domains of life, used as an energy source (ATP), redox reagents (FAD and NAD⁺), an acyl carrier (CoA), or a

methyl group donor (SAM). All contain an adenosine moiety that does not directly contribute to their chemical function

could have evolved quite quickly (Gesteland et al. 2006; Joyce 2004; Müller 2006; Chen et al. 2007).

In Vitro Evolution of RNA: Translation

The synthesis of protein during translation involves three chemical steps starting from free amino acids: amino acid adenylation, aminoacylation of tRNA, and peptide bond formation. Simple ribozymes discovered via in vitro evolution catalyze each of these reactions. Ribozymes that charge RNA with amino acids, the function of modern aaRS proteins, can be extremely efficient catalysts, occasionally achieving rates greater than the aaRS proteins (Chen et al. 2007). One such ribozyme, evolved to

aminoacylate the acceptor stems of natural tRNA, can substitute for aaRS enzymes in an in vitro translation system, demonstrating the potential functionality of primordial RNA-only translation (Ohuchi et al. 2007). Another ribozyme is the smallest yet discovered, a five-nucleotide RNA acting on a four-nucleotide substrate. It catalyzes both aminoacylation of the substrate from aminoacyl adenylate and peptide synthesis using additional adenylates, suggesting that peptide synthesis could have evolved very early in the RNA world (Turk et al. 2010).

As of yet, no ribozyme has been found to catalyze peptide synthesis by the same mechanism used in the ribosome, via two aminoacylated

RNAs, nor to catalyze coded peptide synthesis, where a peptide of defined sequence is synthesized specifically using an RNA sequence guide (Chen et al. 2007). The simplicity with which nucleic acids can be used to template a variety of chemical reactions suggests that the development of this particular reaction may simply await an appropriately designed selection experiment (Gartner and Liu 2001). More generally, although all the individual reactions of translation have been shown to be catalyzed by ribozymes, no ribozyme or set of ribozymes have been shown to catalyze the reactions in series, producing polypeptides from amino acid and ATP as starting materials. Many aspects of in vitro evolution are still quite rudimentary, and beyond this particular reaction, no set of ribozymes have yet been combined, via rational design or evolution, to catalyze an extended multienzyme pathway. Efforts to achieve such pathways may be one of the most interesting areas to focus in vitro evolution research in the future.

In Vitro Evolution of RNA: Metabolism

Synthesis of ribonucleotides in modern biology proceeds through a number of distinct pathways, which may themselves differ from the mechanisms used prior to translation. However, ribozymes can perform a number of chemical steps necessary to the synthesis of ribonucleotides from simple precursors. These steps include aldol condensation, a possible pathway to synthesize sugars including ribose; glycosidic bond formation between activated ribose and either purines or pyrimidines to form ribonucleosides; and phosphorylation of the 5'-end of a ribonucleoside with ATP, yielding a ribonucleotide (Chen et al. 2007).

In vitro selected ribozymes can also use many modern metabolic cofactors. RNA aptamers have been found that bind nearly any cofactor, and ribozymes have been evolved to attach NAD^+ , S-adenosylmethionine, FAD, and CoA to another RNA. Ribozymes can use NAD^+ to dehydrogenate a benzyl alcohol, ATP to phosphorylate or adenylate other nucleotides or amino acids, and acyl-coenzyme A for both aminoacylation and the Claisen condensation (Chen et al. 2007). In summary, RNA is adept at binding, covalently

incorporating, and using many metabolic cofactors. Unfortunately, as with translation, experiments have focused on the capacity of RNA to perform basic reactions in any format, rather than in formats conducive to forming extended biochemical reaction pathways. The evolution of complex systems of ribozymes remains largely unexplored.

In Vitro Evolution of RNA: Replication

The most important activity in an RNA organism would be RNA replication. Although replication may have begun spontaneously, RNA catalysis would be necessary to replicate a complex RNA genome. A ribozyme capable of self-sustained replication, given a constant supply of substrates, could grow indefinitely, and errors created during replication could have led to the generation of heritable mutations and thus potentially Darwinian evolution. If life is defined as a self-sustained chemical reaction capable of Darwinian evolution, a system of replicating RNA could qualify as one of the simplest imaginable forms of life.

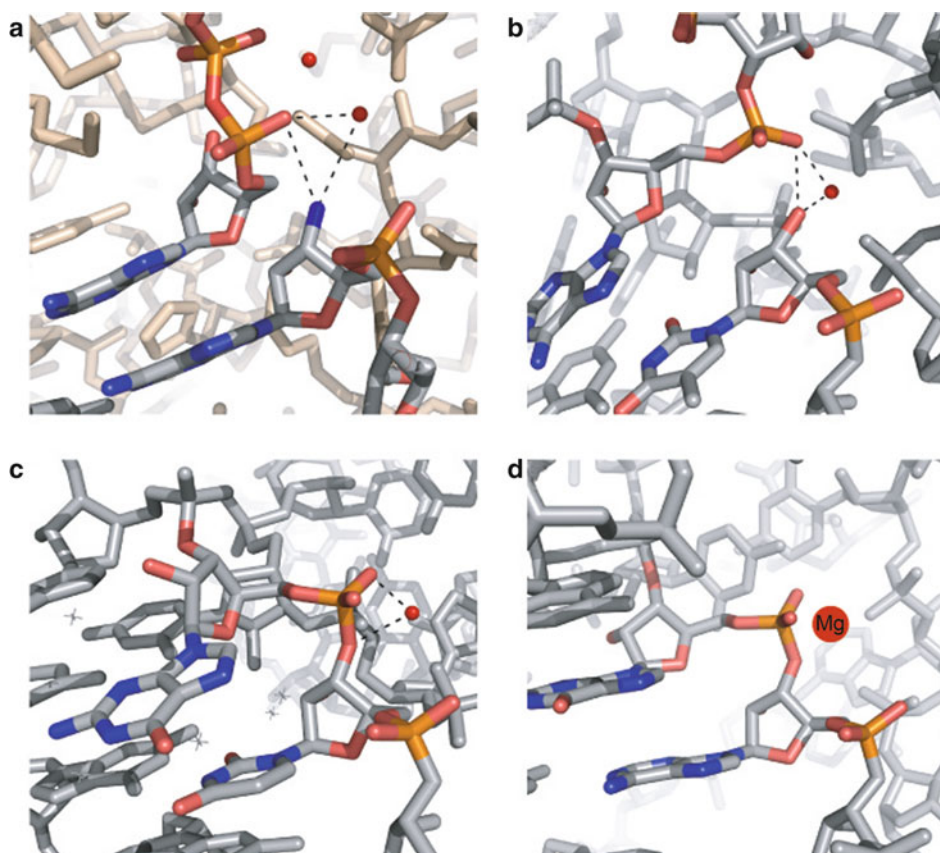
In nature, replication of nucleic acids is achieved by template-directed polymerization of mononucleotide 5'-triphosphates (NTPs), in which the 3'-hydroxyl group of a polynucleotide attacks the α -phosphate of an NTP, releasing pyrophosphate and forming a 3'-5' phosphodiester bond. The first ribozymes evolved in vitro to catalyze the same chemistry were **ligases** rather than polymerases, using a polynucleotide 5'-triphosphate rather than a mononucleotide. This is an easier reaction for a ribozyme to catalyze, as the assembly of both the 3'-hydroxyl and 5'-triphosphate oligonucleotides on a template is spontaneous. Six unrelated ribozyme ligases have been evolved, ranging in catalytic rates from 1 h^{-1} to 1 s^{-1} , and a few other ribozymes perform similar ligations with different regiochemistry or leaving groups. The basic chemistry of template-directed RNA synthesis is apparently readily catalyzed by ribozymes (Joyce 2004).

An interesting convergence can be observed for protein and RNA catalysts of RNA synthesis. Ribozyme ligases depend on divalent cations, typically Mg^{2+} , for activity, as do protein-based polymerases. The atomic-resolution crystal structures of an RNA polymerase protein enzyme, the self-splicing Group

I intron ribozyme, and two distinct synthetic ribozyme ligases can be compared for more details (Fig. 4) (Shechner et al. 2009; Stahley and Strobel 2005; Yin and Steitz 2004). In every case, the enzyme uses a magnesium ion to activate the 3'-hydroxyl nucleophile, stabilize the negative charge on the oxygen of the phosphate electrophile, and coordinate the two groups in a geometry conducive to nucleophilic attack. None of these enzymes are homologous, indicating that magnesium-catalyzed phosphodiester bond transfer is a simple and general catalytic mechanism. The fact that the phosphate backbone of RNA can

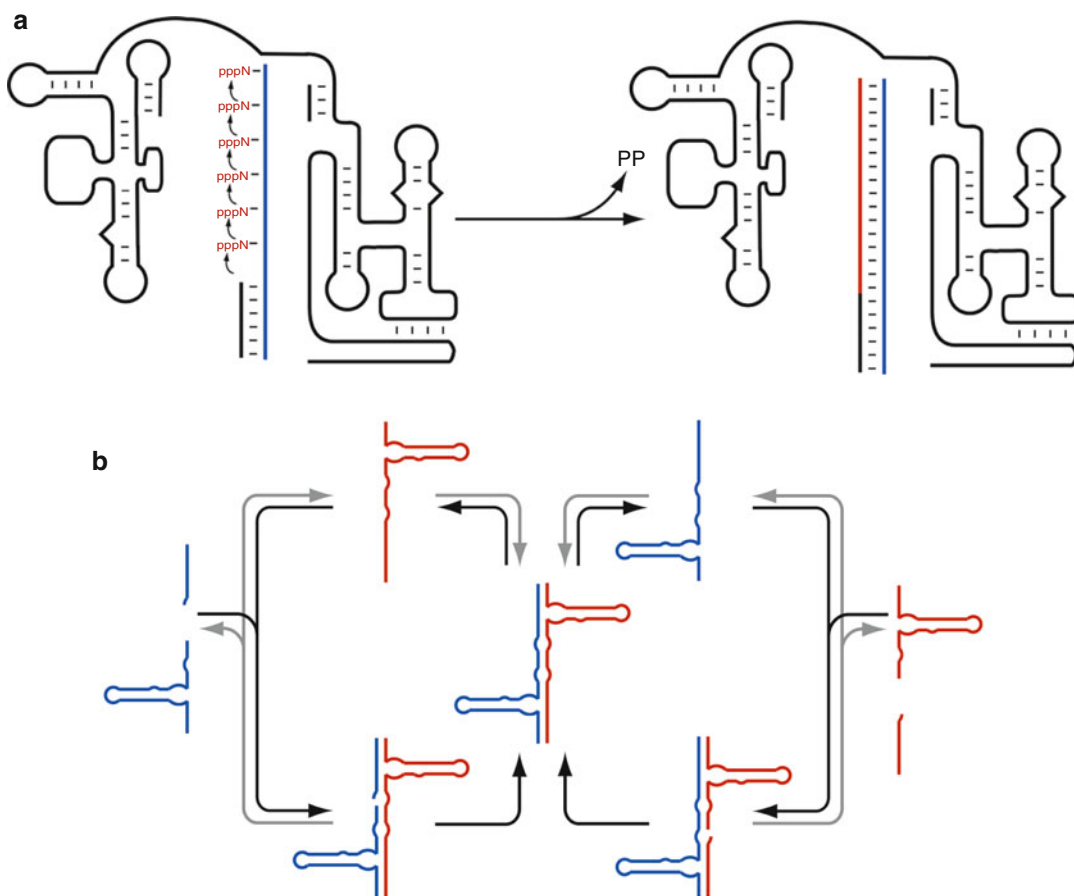
readily coordinate magnesium ions may explain the facility with which RNA can evolve ligase activity.

A great deal of effort has been expended attempting to convert ribozyme ligases into more general RNA polymerases. One ligase, the very active and complex Class I ligase, has undergone extensive further evolution as a general RNA polymerase (Fig. 5a). The results are impressive: the most evolved variant can, on some templates, polymerize 20 template-directed ► [nucleotide](#) additions over the course of a day, with an accuracy of 97% per base (Zaher and Unrau 2007;



RNA World, Fig. 4 Natural and synthetic enzymes that catalyze phosphodiester bond formation between RNA molecules. Shown are the active sites of (a) T7 RNA polymerase (PDB ID: 1S76), a natural protein enzyme; (b) *Azoarcus* Group I self-splicing intron (PDB ID: 1ZZN), a natural ribozyme; (c) the L1 ligase (PDB ID: 20 IU), a synthetic ribozyme; and (d) the Class I ligase (PDB ID: 3HHN), also a synthetic ribozyme. (a) and (b) contain unreacted substrates, and (c) and (d) contain the

reaction product. The catalytic magnesium ion is shown as a red sphere in each image, with contacts between the metal, 3'-OH nucleophile, and the α -phosphate electrophile shown as dashed lines. In (d), a magnesium ion was not visible in the crystal, but its position could be inferred from biochemical experiments. (Robertson and Scott 2007; Shechner et al. 2009; Stahley and Strobel 2005; Yin and Steitz 2004)



RNA World, Fig. 5 Two approaches to RNA replication. (a) The general polymerase ribozyme can synthesize RNA of arbitrary sequence given a complementary template RNA. However, low substrate affinity and poor processivity prevent it from synthesizing more than 20 nucleotides in 24 h (Johnston et al. 2001). (b) The cross-catalytic

replicator consists of a pair of ligase ribozymes that synthesize each other from smaller substrates. The replicator can only copy itself, not an arbitrary RNA sequence, but populations of such replicators have been shown to evolve. (Lincoln and Joyce 2009)

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Johnston et al. 2001). Nevertheless, to replicate RNA of its own length, the polymerase would need to improve activity by more than tenfold.

Further evolution may be hampered by the original evolution of the ligase fold as a single-turnover enzyme. The main kinetic limitations of the polymerase do not involve maximal activity, but rather extremely low-affinity binding to its substrate RNA and poor processivity, adding only one to three nucleotides before it releases the substrate and must rebind. Novel selections, either on this polymerase or de novo RNA populations, will need to focus on enforcing

polymerization in a format more conducive to RNA replication (Joyce 2007).

Recently, a simpler form of replication has been achieved using a cross-catalytic replicator made of a pair of ligase ribozymes that synthesize each other from smaller substrate oligonucleotides (Fig. 5b) (Lincoln and Joyce 2009). Fed a constant supply of substrates, the replicator grows exponentially and indefinitely, the first experimental example of self-sustained RNA replication. Moreover, the system appears capable of at least rudimentary Darwinian evolution: fed a variety of substrates, errors in substrate selection by existing replicators generate novel replicators that

“breed true,” replicating themselves rather than the original “parent” replicator. Some of these novel replicators collectively grow more efficiently than the “parent” replicators, eventually taking over the population.

The complexity of the oligonucleotide substrates, the “feedstock,” for these replicators is quite high, and thus, this system cannot plausibly explain the origin of self-replicating RNA. It does, however, demonstrate how very simple ribozyme systems can achieve self-replication, and it seems likely that many such systems can be developed. These replicators are not capable of general replication of any RNA and thus could not, as currently constituted, replicate other RNA genes that might have contributed to metabolism or other activities critical to a cell. Although the replicators evolve, it remains to be seen if they can evolve novel functions, rather than simply improve the existing replication activity. If such capacity for novel evolution is shown, however, the replicator system may well be a form of independent RNA life, capable of bootstrapping itself into higher levels of genetic and functional complexity.

Models of Evolution in Self-Replicating RNA Systems

Theoretical considerations may already suggest how such systems evolve. Primitive replicating systems might have extremely high mutation rates, which provide both opportunities and limitations. With high replication error rates, a population continuously samples all possible nearby variants and thus can evolve rapidly to new genotypes in the presence of changing selection pressures. When mutation rates are too high, however, selection cannot maintain a distinct genotype and the population will fail to evolve. In its simplest form, this limitation requires that genome size must remain less than the inverse of the error rate, and this holds true for genomes ranging in size from small viruses to complex eukaryotes. For a simple replicating RNA molecule, increases in complexity depend on the capacity to improve the accuracy of replication (Joyce 2002; Szathmáry and Maynard Smith 1997).

During the early evolution of life, individual self-replicating RNA species would need to

evolve into the more complex genomes of the modern cell, with ribozymes performing varied non-replicative tasks that aided growth of the cell but did not contribute directly to their own replication. The solution arrived at in biology is cellular compartmentalization. By isolation from the external environment, the benefits of metabolism and replication accrue only to the genes contained within the cell. A number of other solutions, however, may be plausible and have been investigated: including assembly of distinct ribozymes into larger ribosome-like complexes and restriction to two-dimensional surfaces or microscopic pores in minerals (Szathmáry and Maynard Smith 1997). As experimental systems of self-replicating RNA become more sophisticated, it should be possible to test these models directly.

RNA Replication Before Ribozymes

Ribozyme-mediated replication and metabolism could not have emerged without some mechanism of forming RNA polynucleotides. With the absence of the possibility that some other forms of life existed before RNA, these RNA polymers must have been formed by ► [prebiotic chemistry](#). Unfortunately, forming RNA polymers or even activated monomers has proven exceptionally difficult. The prebiotic synthesis of ribonucleotides is discussed below, but even assuming that they can be produced, their polymerization remains a significant hurdle. Spontaneous reactions with 5′-triphosphates are most likely not feasible, as the triphosphate, although high in energy, is kinetically stable – templated ligation of RNA oligomers is extraordinarily slow, comparable to the rates of RNA hydrolysis (Gesteland et al. 2006).

Monomers activated with other leaving groups, such as mononucleotide 5′-phosphoimidazolides, can polymerize spontaneously, and the presence of an RNA template can in some cases direct the polymerization of the complementary sequence. However, both 2′–5′ and 3′–5′ regioisomers of RNA are formed, and adenosine and uridine monomers do not polymerize well. Solutions to these problems exist: ► [montmorillonite](#) clays can accelerate and increase the regiospecificity of untemplated polymerization, producing polynucleotides in excess of 40 bases.

Polymerization with base intercalators or in the eutectic phase of water ice accelerates ► [template-directed polymerization](#), including that of adenosine and uridine monomers. Still, no reaction scheme has yet shown robust template-directed RNA synthesis (Gesteland et al. 2006).

Non-prebiotic RNA analogues can achieve considerably better results, with the most advanced system capable of polymerizing mixed sequences from a template, but currently limited by accumulation of mutations that inhibit further polymerization (Schrum et al. 2009). Theoretical treatments suggest that Darwinian evolution could arise rapidly once accurate replication is achieved (Nowak and Ohtsuki 2008). If progress continues, this system may represent a much simpler form of nucleic acid replication relative to the ribozyme cross-replicator and may reveal how Darwinian evolution can emerge from extraordinarily simple, uncatalyzed chemical reactions.

Emergence of Ribonucleotides

The demonstration of a plausible, prebiotic route to ribonucleotide monomers has proven to be an extraordinarily difficult task. Prebiotic chemistry is a broad field, and diverse reactions have been found that yield components of ribonucleic acid. Three general conclusions can be drawn from the data thus far collected (Joyce 2002; Gesteland et al. 2006):

1. The components of ribonucleotides could have been available on the early Earth. Sugar-like molecules, purines, and pyrimidines have all been found in varying quantities in meteorites, and plausible prebiotic syntheses have been demonstrated for all three. Both phosphate and inorganic polyphosphates would also have been present on the early Earth.
2. The synthesis of ribose and the natural nucleobases to high purity relative to other analogues is much more difficult. The autocatalytic formose reaction produces ribose in very low yields relative to other sugars, though ribose can be favored by interaction with borate minerals, reaction with cyanamide and selective crystallization, or selective diffusion across prebiotic fatty acid membranes. Besides

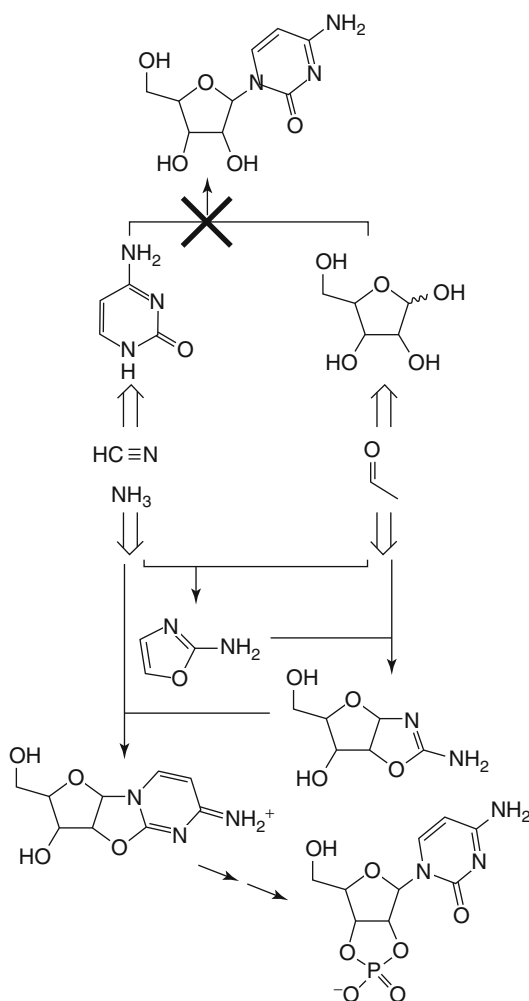
the synthesis of adenine as a major product from cyanide polymerization, similar problems exist for the nucleobases.

3. The synthesis of ribo► [nucleosides](#) and ribonucleotides from these constituents is even more difficult. The synthesis of purine ribonucleosides from a purine and ribose is inefficient and yields a variety of isomers and side products, while the synthesis of pyrimidine ribonucleosides directly from the biological pyrimidines and ribose appears even more difficult. Phosphorylation can occur under some extreme conditions, but generally produces a mixture of multiply phosphorylated products.

Given these difficulties, a route to relatively pure, activated mononucleotides seems implausible. However, a recent approach may have revitalized the field by integrating the chemistries of nucleobase and sugar synthesis, and phosphorylation, to produce the two biological pyrimidine ribonucleotides (Fig. 6) (Powner et al. 2009). Cytidine and uridine 2',3'-cyclic phosphates are produced in a series of reactions that completely avoid the intermediate synthesis of free ribose or pyrimidines, mixing reactions between the very distinct chemistries of nucleobase and sugar synthesis. Further progress will require demonstration of similar routes to the purine ribonucleotides as well as plausible mechanisms for the isolation of the starting materials for subsequent reactions, neither small tasks. The problem of a plausible polymerization mechanisms, described previously, also remains. Still, the possibility that a route to the origin of RNA life from prebiotic chemistry can be found has improved significantly.

Life Before RNA

Ribonucleotides are complex molecules that are biosynthesized by a series of genetically encoded metabolic pathways. It may be that RNA is so complex that it can only be plausibly synthesized by the metabolism of a living organism. If so, it follows that RNA itself was not the first form of life but rather a product of it, just as protein macromolecules were invented by RNA-based life. The appeal of this idea, of course, is that the



RNA World, Fig. 6 Two routes to the prebiotic synthesis of pyrimidine nucleosides from simple starting materials. The top route attempts to synthesize cytosine and ribose separately. Reactions between the biological pyrimidines and ribose to form ribonucleosides have thus far proven unsuccessful. The bottom route uses a series of coordinated reactions in which pyrimidines and ribose do not form separately, and incorporation of phosphate yields the final product, cytosine 2', 3' cyclic phosphate (as well as uridine 2', 3' cyclic phosphate after UV irradiation, a step not shown). (Powner et al. 2009)

difficulty of synthesizing RNA prebiotically is avoided. Instead, an entirely distinct form of life must be described and shown to arise more readily than RNA life.

One potential candidate would be another biopolymer, particularly one with a capacity, like RNA, to undergo templated replication. If such a

polymer also proved more amenable to spontaneous synthesis, it could very well have arisen first, only later giving way to RNA due to, perhaps, the superior activity of ribozymes. Investigation of nucleic acid analogues has demonstrated that the ribose-phosphate backbone can be changed substantially while retaining the ability to base-pair with a complementary sequence and that a whole family of nucleic acid-like molecules can function as genetic polymers (Eschenmoser 1999; Nielsen 2007). The most notable of these, from an origin's perspective, have been threose nucleic acid (TNA) and peptide nucleic acid (PNA) (Gesteland et al. 2006). Threose and amino acids may have formed more abundantly on the early Earth than ribose, and both polymers are more stable than RNA. Still the prebiotic synthesis and polymerization of these analogues, or others, remain to be demonstrated.

More arcane possibilities have also been considered. The templated growth of clay minerals may be capable of some rudimentary form of replication and evolution, and the fact that such minerals are known to catalyze a variety of prebiotically relevant reactions, including RNA polymer synthesis, offers a potential route for the transition into an RNA world (Joyce 2002). Many other scenarios propose that simple autocatalytic reaction cycles involving small organic molecules could spontaneously self-organize, grow, and even evolve (Segre 2000; Copley et al. 2007). The plausibility that such cycles could form, and their ability to evolve, remains disputed (Orgel 2008). Experimental demonstration that such a cycle can replicate independently of genetically encoded catalysis would be a tremendous breakthrough, but, as with many other scenarios for the origin of life, experimental demonstrations are lacking.

Future Directions

A Concerted Pathway to Nucleic Acid Polymers

The strong evidence for the existence of the RNA world from modern biology suggests that a route to RNA polymers on the early Earth exists, either

directly or via the origin and evolution of some even more primitive form of life. However, there is no clear evidence as to what that route was. Distinct theories for the origin of life may very well outnumber researchers, but viable experimental models most certainly do not. Addressing this imbalance will be critical to further progress.

Significant advances have been made in a number of related fields. Mechanisms for the origin of homochirality; the growth, division, and competition between prebiotic vesicles; and the concentration of prebiotic building blocks from dilute solutions have all been demonstrated experimentally recently (Budin and Szostak 2010). The potential to combine these mechanisms and integrate them with experimental models of RNA synthesis may yield robust experimental frameworks for the origin of living systems from simple physicochemical mechanisms.

Self-Replicating Darwinian Systems

At least one system of RNA self-replication has been developed and shown to undergo limited Darwinian evolution. Other systems offering simpler and more complex forms of replication may be forthcoming. Further development of these systems could eventually produce synthetic nucleic acid-based life and open up new avenues to explore the RNA world model by direct observation. The propagation of these replicators under diverse experimental conditions could reveal how RNA life adapts and evolves. Of particular interest will be the exploration of how RNA genomes increase in complexity and the mechanisms by which new ribozymes, and the chemical pathways they control, evolve. It is unclear where such investigations can lead, but they offer the best methods available to understand the biochemistry of life's earliest ancestors.

The End of the RNA World and Its Legacy in Modern Biology

The vestiges of RNA ancestry in modern organisms are extensive. Research is now beginning to focus on using such evidence to investigate how modern biology evolved from simpler precursors. Knowledge of the modern form of translation and the interactions between RNA and protein, for

instance, may reveal how and why coded protein translation originally evolved. The earliest roles of polypeptides may have been as structural cofactors to RNA, a role still seen in many ribonucleoproteins, including the ribosome (Noller 2004). Structural evidence suggests that the peptidyl transferase center, and not the mRNA decoding regions, may be the most ancient part of the ribosome and could have existed originally as a dimerized ribozyme only 150 nucleotides long (Bokov and Steinberg 2009; Agmon et al. 2009). Similarly, the tRNA acceptor stem, to which amino acids are attached, may predate and can function independently of the tRNA anticodon stem used to decode mRNA (Schimmel and Ribas De Pouplana 1995). Early peptide synthesis may well have involved a simple peptidyl transferase ribozyme that used a series of tRNA-like substrates to synthesize polypeptides of predefined or even random sequence. It remains to be seen if more evidence from modern biology or in vitro evolution experiments can shed light on the origin of translation.

More broadly, novel roles for RNA in biology are being discovered at an incredible rate, and there remain many broad classes of nonprotein-coding RNA whose function is still uncharacterized. Small RNA molecules covalently attached to acyl-CoA and NAD⁺ cofactors have been identified in bacteria. Their significance remains unknown, but given the proposal that nucleotide-tagged cofactors originated in the RNA world, the possibility that these RNA molecules represent relics of ancient ribozyme-controlled metabolism cannot be discounted (Kowtoniuk et al. 2009; Chen et al. 2009). Other classes of larger RNAs with unknown function have also been catalogued (Weinberg et al. 2009). The activity of these RNAs will no doubt be fascinating, and some may very well prove to have an origin in the ancient RNA world.

Cross-References

- ▶ [Aptamer](#)
- ▶ [Evolution, In Vitro](#)
- ▶ [Last Universal Common Ancestor](#)

- ▶ Nucleic Acids
- ▶ Nucleoside
- ▶ Nucleotide
- ▶ Prebiotic Chemistry
- ▶ Ribosome
- ▶ Ribozyme
- ▶ RNA

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Roche Limit

Jérôme Perez
Applied Mathematics Laboratory, ENSTA
ParisTech, Paris Cedex 15, France

Keywords

Gravitation · Stability · Tidal effect

Synonyms

Roche radius

Definition

The Roche limit is the orbital distance below which a satellite is tidally destroyed by the body around which it is orbiting. Édouard Roche is the French astronomer who first calculated this theoretical limit in 1848.

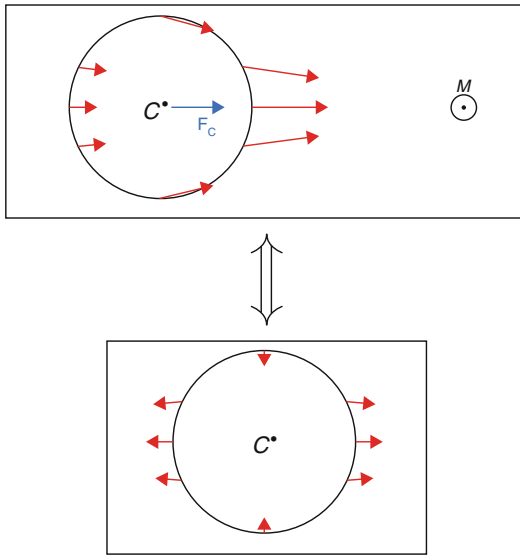
Overview

Tidal forces are simply the difference in gravitational forces felt by different parts of an extended body. The force of gravity felt by a satellite orbiting a primary body (e.g., by a moon orbiting a planet or a planet orbiting a star) decreases as the inverse square of the orbital distance such that different parts of the satellite feel different gravitational forces. From the point of view of the satellite, this results in a stretching because the side that is closest to the primary body is pulled more strongly than the side farthest from the primary (see Fig. 1).

This tidal stretching acts to elongate the satellite, increasing the distance between the opposite sides of the body and therefore increasing the strength of the tidal force. This stretching is counteracted by the satellite's self-gravity and internal cohesive forces. The Roche limit is simply the distance below which the tidal stretching overwhelms the satellite's self-gravity and tears the satellite apart. A simple formula for the Roche limit R_ℓ is

$$R_\ell \simeq \kappa \left(\frac{\rho_p}{\rho_s} \right)^{1/3},$$

where ρ_p and ρ_s represent the mass density of the primary body and the satellite, respectively. The



Roche Limit, Fig. 1 Tidal forces, as seen in the absolute reference frame (*top*) and in the body's reference frame (*bottom*)

numerical factor κ is of order unity and quantifies the satellites' internal cohesion (i.e., κ depends on the nature of the satellite).

Most of Saturn's rings are partially located inside the Roche limit of Saturn, which explains why they cannot accumulate into a larger body. The Roche limit is not to be confused with the Roche radius, usually referred to as the Hill radius.

Cross-References

- [Gravitation](#)
- [Tides, Planetary](#)

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Roche Radius

- [Hill Radius/Sphere](#)
- [Roche Limit](#)

Rock

Nicholas Arndt
ISterre, University Grenoble Alpes, Grenoble, France

Definition

Rock is the naturally occurring solid material of the Earth and other planetary bodies such as rocky planets, ► [asteroids](#), and ► [comets](#). Its composition is variable, depending on its mode of formation and the types of constituent minerals and organic substances. There are three main types of rock: ► [igneous rocks](#), which form by crystallization of magmas, either slowly and deep within the crust (plutonic rocks) or by rapid cooling at a planetary surface (volcanic rocks); ► [sedimentary rocks](#), which either result from the crystallization of chemically precipitated substances (on Earth commonly biologically mediated), the deposition and cementation of detrital grains, or the lithification of organic substances; and ► [metamorphic rocks](#), which are produced when the other two types of rocks are subjected to elevated temperatures and pressures. These three types of rocks are part of a “rock cycle” in which the main drive is ► [plate tectonics](#).

Cross-References

- [Basalt](#)
- [Evaporite](#)
- [Granite](#)
- [Igneous Rock](#)
- [Metamorphic Rock](#)
- [Mineral](#)
- [Plate Tectonics](#)
- [Sedimentary Rock](#)
- [Silicate](#)

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Rocky Planet

► [Terrestrial Planet](#)

Rodinia

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

Rodinia is one of the oldest known ► [supercontinents](#). It existed in the Neoproterozoic, from about 1100 to 750 Ma; it comprises the oldest portions of almost all the present-day landmasses. The North American Craton formed its core, flanked by fragments now present in northern Europe, Africa, South America, India, and Antarctica. It was probably centered in the southern hemisphere, and since it persisted through the period of extreme cold known as the ► [Snowball Earth](#) of the Cryogenian period, large parts of it were probably covered by ice caps. It has been proposed that the ecosphere turnover and bioradiation events in the Ediacarian and in the Cambrian could have been triggered by the consequences of the Rodinia breakup to Earth's atmosphere and hydrosphere.

Cross-References

► [Laurasia](#)
► [Pangea](#)
► [Plate Tectonics](#)
► [Snowball Earth](#)
► [Supercontinent](#)

Rosetta Spacecraft

Hervé Cottin
Univ Paris Est Creteil and Université Paris Cité,
CNRS, LISA, F-94010 Créteil, France

Keywords

Asteroid · Comet · ESA · Lander · Philae ·
Spacecraft

Definition

The Rosetta mission was a Planetary Cornerstone Mission in the European Space Agency's program Horizon 2000. It had a rendezvous in August 2014 with the →comet →67P/Churyumov-Gerasimenko to study its nucleus chemical and physical properties, and the development of its atmosphere as the comet approaches the Sun. Rosetta followed the comet for about 2 years before and after its perihelion in August 2015. The mission was terminated with a controlled crash on the comet's nucleus on September 30, 2016. Rosetta spacecraft was carrying an instrumented lander called →Philae delivered to the nucleus on November 12, 2014. On its way to the comet, Rosetta flew by asteroids 2867 →Steins and 21 →Lutetia.

Overview

Rosetta was the first space mission whose goal was to land on a cometary nucleus and follow a comet for about 2 years. It was first conceived to explore comet 46P/Wirtanen. However, because of a failure of an Ariane 5 rocket in December 2002, the mission was postponed, and a new target had to be chosen: →67P/Churyumov-Gerasimenko (hereafter 67P). Rosetta was finally launched by an Ariane 5 G+ from Kourou (French Guyana) on March 2, 2004. Its journey toward the comet was 10 years long and employed four planetary gravity-assist maneuvers (Earth-Mars-Earth-Earth). Rosetta reached its target in August 2014

and released →Philae that landed on the nucleus on November 12, 2014, at about 3 AU from the Sun. Then, Rosetta escorted the comet before and after its perihelion in August 2015 (at 1.3 AU from the Sun), witnessing the comet’s increasing activity as it gets closer to the Sun and its decrease when the comet moved away on its orbit. The end of the nominal mission was originally scheduled in December 2015. However, ESA decided to continue the mission until the spacecraft was too far away from the Sun to receive sufficient energy from its solar panels to be operated. The mission was terminated on September 30, 2016, with a controlled crash of the spacecraft on the nucleus, allowing last measurements in close vicinity of the nucleus. Important dates of the Rosetta mission are given in Table 1.

The science objectives of the mission were: (1) a global characterization of the nucleus (dynamic properties, surface morphology, and composition); (2) the determination of the chemical, mineral, and isotopic compositions of volatiles and refractories in a nucleus, as well as the links between the gaseous and the solid phases; (3) the study of the development of cometary activity and the processes in the surface layer of the nucleus and the inner coma (dust/gas interaction); and (4) the study of the evolution of the interaction region of the solar wind and the outgassing comet during perihelion approach.

Rosetta Spacecraft, Table 1 Rosetta important dates

3/02/2004	Launch
03/2005	First Earth gravity assist
02/2007	Mars gravity assist
11/2007	Second Earth gravity assist
09/05/2008	Asteroid Steins flyby (distance 17,000 km)
11/2009	Third Earth gravity assist
07/10/2010	Asteroid Lutetia flyby (distance 3000 km)
08/2014	Orbital insertion with comet Churyumov-Gerasimenko
12/11/2014	Philae landing
08/2015	Perihelion passage
12/2015	Planned end of the nominal mission
30/09/2016	End of mission

The mission’s name refers to the Rosetta stone that gave Champollion a crucial clue to understanding Egyptian hieroglyphs. The lander was called Philae, following the name of the island on which an obelisk was found. Its association with the Rosetta stone helped Champollion in his discovery. As the Rosetta Stone provided the key to an ancient civilization, the Rosetta instruments were designed to unlock the information kept in the oldest building blocks of our solar system: the comets.

Basic Methodology

Rosetta’s design is based on a central cuboid structure (2.8 × 2.1 × 2.0 m). The total launch mass is 2900 kg, including Philae (100 kg), 165 kg of scientific payload, and 1720 kg of propellant. The nominal solar array output was 850 W at 3.4 AU.

Rosetta payload consists of 12 scientific instruments onboard the orbiter and 10 on the surface science package (Philae) (Table 2). During the 2 years of the mission, the spacecraft has performed a complex navigation program in the vicinity of comet 67P in order to: (1) fulfill the science objectives of the mission by enabling operation of all instruments that required various orientations and distances from the nucleus, but also to (2) keep the spacecraft at a safe distance in order to avoid to be damaged by the dust particles ejected from the nucleus, especially during the period of high activity of the comet around perihelion.

Key Research Findings

The Rosetta mission has produced a considerable number of results showing that the comet 67P nucleus is a binary object formed by the low-speed collision of two distinct bodies during the early stages of the formation of the solar system (Fornasier et al. 2021; Massironi et al. 2015). It is made of two parts of about 4.10 × 3.52 × 1.63 km

Rosetta Spacecraft, Table 2 Rosetta and Philae instruments

Rosetta	
Observation	
OSIRIS	Optical, Spectroscopic, and Infrared Remote Imaging System
Alice	UV spectrometer (70–205 nm)
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (0.25–5 μm)
MIRO	Microwave Instrument for the Rosetta Orbiter (1.3 and 0.5 nm)
Composition analysis	
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (Gas)
COSIMA	Cometary Secondary Ion Mass Analyzer spectrometer (Dust)
MIDAS	Micro-Imaging Dust Analysis System (atomic force microscope)
Physical properties of the nucleus and the coma	
CONSERT	Comet Nucleus Sounding Experiment
GIADA	Grain Impact Analyzer and Dust Accumulator
RPC	Rosetta Orbiter Plasma Consortium
RSI	Radio Science Investigation
SREM	Standard Radiation Environment Monitor
Philae	
APXS	Alpha-p-X-ray spectrometer
CIVA	Panoramic camera and infrared microscope
CONSERT	Comet Nucleus Sounding Experiment
COSAC	Cometary Sampling and Composition experiment (gas chromatograph)
MUPUS	Multipurpose Sensors for Surface and Subsurface Science
ROMAP	Rosetta Magnetometer and Plasma monitor
PTOLEMY	Evolved gas analyzer: isotopic composition (mass spectrometer)
ROLIS	Rosetta Lander Imaging System (descent camera)
SESAME	Surface Electrical, Seismic, and Acoustic Monitoring Experiments
SD-2	Drill, sample, and distribution system

in size for the larger lobe and $2.50 \times 2.14 \times 1.64$ km for the smaller one (Jorda et al. 2016). Its mass is 1.0×10^{13} kg with a density of about 0.5 g cm^{-3} , pointing to a rather large porosity of about 70–75% (Jorda et al. 2016). On a

microscopic scale, the cometary matter is built on multiscale particles resulting from hierarchical accretion. The activity of the nucleus is characterized by continuous degassing, which generates a diffuse, permanent coma marked by jets visible for hours emitted by regions rich in CO₂ or H₂O frost. This degassing leads to progressive erosion seen through collapsing cliffs or the appearance of fine lines in smooth areas. These processes remain superficial because the interior of the core is insulated from solar heating by its low thermal inertia. The surface is a succession of terrains with pits, depressions, boulders, and smooth areas. The nucleus rotates in about 12.4 h. It has been inferred from the various instruments of Rosetta that the nucleus refractory to ice ratio bulk composition could range from 3 to 6, with higher values being possible (Choukroun et al. 2020). However, high uncertainty remains attached to this value.

In this entry, the focus is given to results that have an astrobiological relevance. They relate to the organic content of the nucleus and the nature of volatile elements and water that may have contributed to the building of Earth’s atmosphere and oceans.

Regarding the composition of the atmosphere of the comet and the inventory of the diversity of its molecular composition, the ROSINA mass spectrometer has identified in the gaseous phase a wide variety of volatiles compounds, adding dozens of molecules (especially organic) to the list of already known compounds (Rubin et al. 2019). Among them, the detection of →glycine, the simplest amino acid, must be noted (Altwegg et al. 2016). This is a confirmation of its presence that was shown in the cometary samples returned to Earth with the →Stardust mission (Elsila et al. 2009), but at that time it was unclear whether glycine was indigenous from the comet →Wild 2 or synthesized from precursors during the analytical procedure that leads to its detection in Stardust samples. Although the presence of this relatively simple compound can be explained by the photochemistry of molecules such as CO₂ and CH₃–NH₂ in cometary ices (Bossa et al. 2009), and that chemistry from amino acids to the origin

of life certainly involved many complex and unknown steps, its detection contributes to strengthening the idea that comets could bring to Earth molecules involved in the processes that led to the emergence of life. Surprisingly, glycine was detected in the gaseous phase with ROSINA, and not, considering the low volatility of this molecule, in the solid fraction of dust particles by the COSIMA mass spectrometer. This has been interpreted by the fact that glycine was synthesized in the water ice and released into the gaseous phase when it sublimated from dust particles within the first kilometers after being lifted from the nucleus (Hadravský et al. 2019). Furthermore, ammonium salts, classical organic reagents used in the laboratory in studies related to prebiotic chemistry, have also been detected with ROSINA (Altwegg et al. 2020).

One of the mission's most eagerly awaited measurements was the D/H ratio in water. Taking into account the orbit of 67P and the measurements made in other comets, especially those from the Jupiter family like the target of Rosetta, a value close to that of the terrestrial oceans (1.5×10^{-4}) was expected. However, Rosetta revealed, with the ROSINA instrument, the highest ratio for a comet to date ($5.3 \pm 0.7 \times 10^{-4}$) (Altwegg et al. 2014). The statistics remain too weak among comets to conclude on the cometary contribution of terrestrial water. However, the isotopic measurements of xenon offer better constraints. The isotopic anomaly of the xenon of the terrestrial atmosphere (called U-Xenon), with regard to the measurements Rosetta, can only be explained if the composition of the early Earth's atmosphere was 20% cometary and 80% meteoritic ($\rightarrow$ chondrite) (Marty et al. 2017). 67P-type comets would therefore have contributed only slightly to the formation of the Earth's oceans and atmosphere, but 67P being the only comet in which xenon has been measured, more robust constraints will only be achieved with similar measurements in more objects.

In the gaseous phase, the high abundance recorded for O₂ ($\sim 4\%$) is unexpected, given its high reactivity and low interstellar abundance (Bieler et al. 2015), as is the detection of atomic

phosphorus (Altwegg et al. 2016), the origin of which could be PO also observed in the atmosphere (Rivilla et al. 2020). Nevertheless, phosphorus was also detected in the solid phase in dust particles ejected from the nucleus. There, it has been shown that it was not embedded in an oxidized form in minerals like apatite (Gardner et al. 2020).

The refractory component of the nucleus could be analyzed by mass spectrometry thanks to the study of dust particles coming from the nucleus, captured and analyzed with the COSIMA instrument. These particles are made in mass of roughly half of a nonhydrated mineral phase and half high molecular weight organic matter (Bardyn et al. 2017). This latter shows some similarities with the $\rightarrow$ insoluble organic matter (IOM) found in carbonaceous chondrites (Fray et al. 2016). The hydrogen abundance is higher in comets than in meteorites (Isnard et al. 2019) as well as D/H (Paquette et al. 2021), suggesting less processing by heat or radiations and a probable heritage in the interstellar medium.

At the surface of the nucleus, spectroimaging revealed a global coverage potentially consisting of aliphatic organics (Raponi et al. 2020) and ammonium salts (Poch et al. 2020), while the low albedo would be due to dark polyaromatics combined with opaque minerals such as FeS (Quirico et al. 2016). In addition to these remote observations of the nucleus from the spacecraft, during the very short duration of the $\rightarrow$ Philae lander odyssey at the surface of 67P, direct mass spectra measurements could be made as dust particles serendipitously entered and sublimated inside COSAC and PTOLEMY instruments at the same time automatic runs of both instruments were performed. Mass spectra could not be univocally interpreted, but they show signs of chemistry induced by UV processing of ice mixtures containing water, ammonia, methane, and carbon monoxide (Goesmann et al. 2015), while PTOLEMY results showed signs of the presence of the polymer of formaldehyde: $\rightarrow$ polyoxymethylene (Wright et al. 2015). An alternate interpretation of the Philae data has been proposed (Altwegg et al. 2017), but globally comparison between COSAC and PTOLEMY measurements with

remote sensing instruments has shown a diversity of organic molecules on the surface of 67P, which is larger than anticipated.

Future Directions

It was the first time such a broad range of instruments were integrated into a space mission. As a result, Rosetta could characterize a cometary nucleus and the evolution of its activity during its journey in the inner solar system very precisely. The mission has generated a considerable amount of data that will require years of work to be interpreted. However, as anticipated as these measurements could be, it must be recalled that comets are a heterogeneous family of objects, and extensive characterization of one of them will not be an extensive characterization of all the comets. This must be kept in mind while extrapolating to the formation of oceans and atmospheres, and if one budgets the amount of organic material delivered to Earth.

It will be extremely challenging to organize a mission as ambitious as Rosetta was. However, two projects are foreseen in the future. First, the ESA Comet Interceptor mission is planned to be launched in 2029 to be parked at a Sun-Earth Lagrange point, waiting for the arrival of a long period or even interstellar comet. Then, another step of exploration of comets would be a challenging refrigerated sample return from the nucleus.

Cross-References

- [Carbonaceous Chondrites, Organic Chemistry of](#)
- [Comet \(Nucleus\)](#)
- [67P/Churyumov–Gerasimenko](#)
- [Deuterium/Hydrogen Ratio](#)
- [Infrared Spectroscopy](#)
- [Insoluble Organic Matter](#)
- [Mass Spectrometry](#)
- [Philae Lander](#)
- [Polyoxymethylene](#)
- [Stardust Mission](#)
- [Water, Delivery to Earth](#)

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Roskosmos

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

Russian federal space agency

Definition

The Russian Space Agency was formed on February 25, 1992, succeeding the organizations involved in the development of the space activities in the Russian federation since 1989. In the early years, the role of the agency was counterbalanced by the authority of various companies, centers, and industries.

Building on past successes of the Soviet era in space, Roskosmos is now in charge of the manned space program and the development of the new rockets (Angara), as well as the improvement of existing ones (Soyuz and Proton). Since the retirement of the US space shuttles, the Russian Soyuz spacecraft are standing as the only means to send and retrieve astronauts and cosmonauts to and from the International Space Station (► ISS). The Russian Progress spacecraft remain the most regular provider of freight to the ISS.

The Russian federal space program includes also the development of satellites and missions of interest for astrobiology. For instance, Roskosmos is since 2013 a major partner of ESA for the Exomars missions, the flagship missions of the European program for the exploration of Mars.

Roskosmos shares with its military counterparts the responsibility and the costs of maintaining launch centers as Baïkonour and Plesetsk and the Y. Gagarin cosmonaut training center known as the “Star City.” The agency is also designing and building a new cosmodrome at Vostochny, in the far east of the Russian federation, to be operational in 2020.

In the next decade, in addition to Earth observation, communication, and navigation satellites, new ambitious missions to the Moon, Venus, Mars, and Europa, as well as new observatories (UV, for instance) are planned.

Cross-References

- ESA
- ISS

References and Further Reading

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Rossiter-McLaughlin Effect

Nader Haghighipour

Institute for Astronomy, University of Hawaii–
Manoa, Honolulu, HI, USA

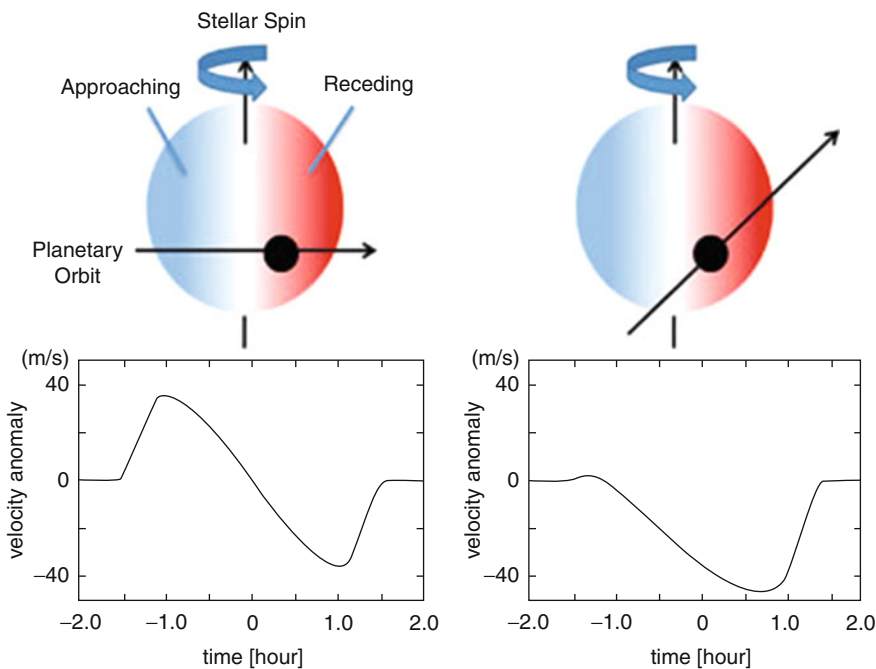
Definition

The Rossiter-McLaughlin (RM) effect is a spectroscopic effect that occurs in a stellar system with a transiting planet. In such a system, in addition to the photometric effect of the transiting planet which manifests itself as a decrease in the flux received from the star, the obscuration of the disk of the star during the transit causes changes in the disk-integrated spectrum

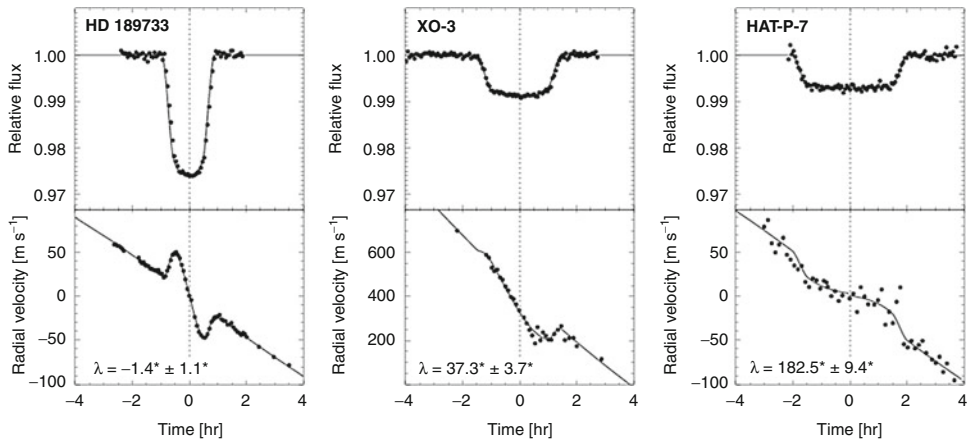
of the star known as the Rossiter-McLaughlin (RM) effect. As a star rotates, the portion of its disk that approaches the observer will have its spectrum Doppler shifted to shorter wavelengths (to the blue), whereas the portion that rotates away from the observer will be red shifted. When a planet transits the star, its passage in front of the star's disk disturbs the abovementioned star's rotational Doppler shift. When the planet blocks the blue-shifted part, the spectrum appears slightly red shifted. The situation is reversed when the planet covers a portion of the red-shifted segment of the stellar disk (Gaudi and Winn 2007) (Fig. 1).

Overview

The Rossiter-McLaughlin (RM) effect was described in two papers by Rossiter (1924) and McLaughlin (1924), which were published back-to-back in 1924 in the same issue of the *Astrophysical Journal*. This effect had, however, been

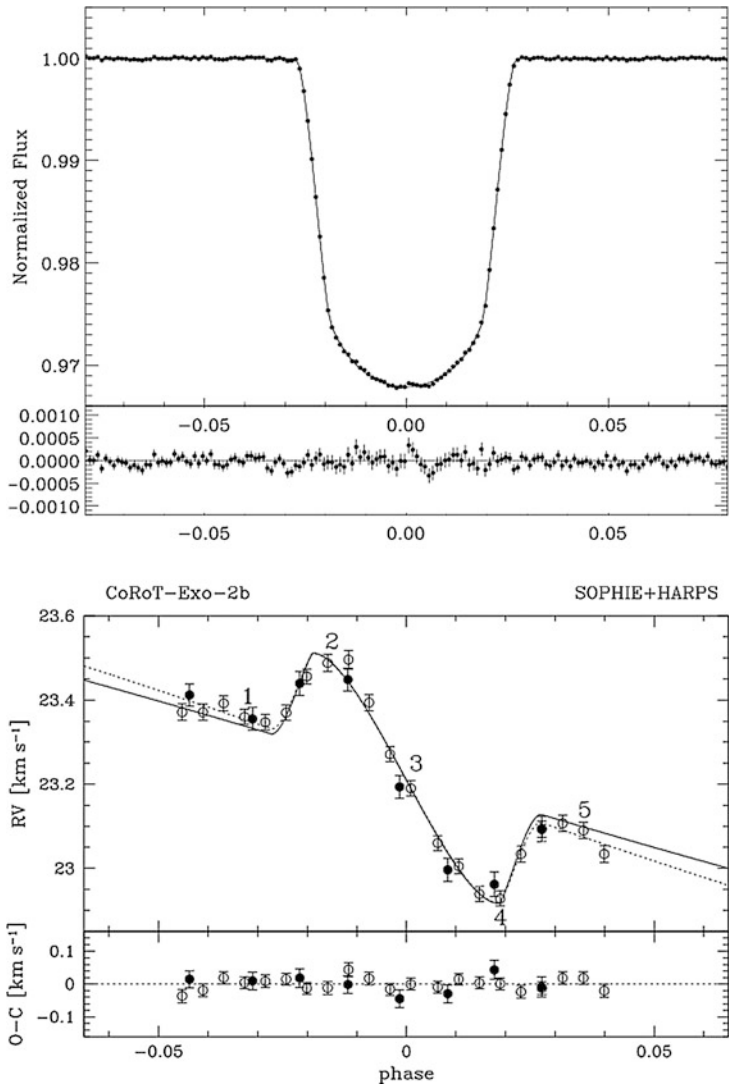


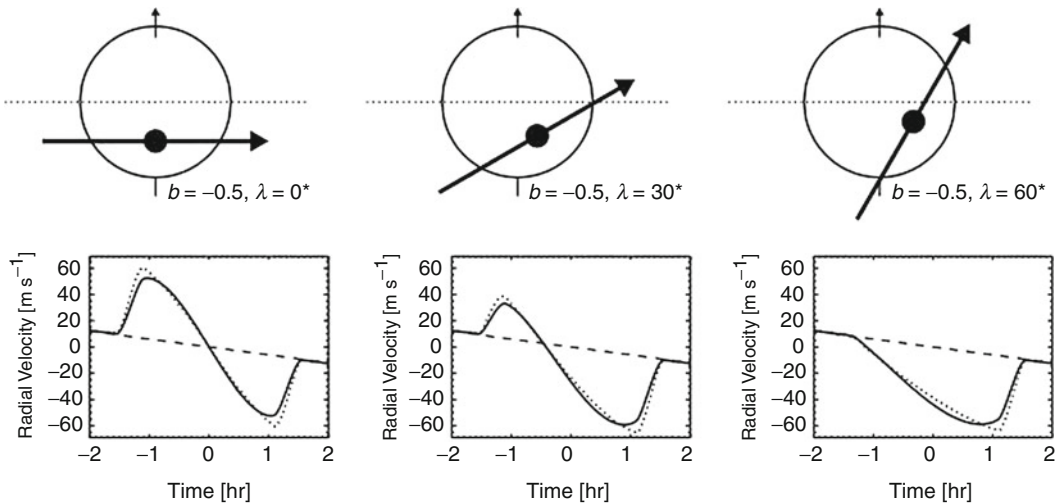
Rossiter-McLaughlin Effect, Fig. 1 Schematic presentation of Rossiter-McLaughlin effect showing the perturbation in the Doppler-shifted velocity (velocity anomaly) produced by the transiting planet



Rossiter-McLaughlin Effect, Fig. 2 The light curve (*above*) and RM effect (*below*) in three exoplanetary systems (Winn et al. 2006, 2009a, b)

Rossiter-McLaughlin Effect, Fig. 3 *Top:* Normalized and phase-folded light curve and residuals of 78 transits of CoRoT-2b (Alonso et al. 2008). *Bottom:* Phase-folded RV measurements and residuals of CoRoT-2b derived by SOPHIE and HARPS showing the Rossiter-McLaughlin effect during the transit (Bouchy et al. 2008)





Rossiter-McLaughlin Effect, Fig. 4 The dependence of the RM effect on the orientation of the planet orbit relative to projection of the stellar rotation axis on the sky (Gaudi and Winn 2007)

recognized in the observations of eclipsing binary stars by Forbes (1911) and Schlesinger (1911). In connection to extrasolar planets, the Rossiter-McLaughlin (RM) effect was first observed by Queloz et al. (2000) and Bundy and Marcy (2000) during transits of HD 209458b. At present this effect has been observed in many transiting systems. Figures 2 and 3 show the RM effect for several exoplanetary systems.

Observation of the RM effect enables one to determine the trajectory of the transiting planet relative to the (sky-projected) stellar rotation axis. Specifically, one can measure the angle between the sky projections of the orbital axis and the stellar rotation axis (Fig. 4).

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Rotation Planet

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, BPParis, France

Definition

All planets rotate around their rotation axes. The rotation period is measured with reference to the distant stars. It is thus also called the sidereal period of rotation, which is different from the duration of the solar day (the time that the Sun takes to go once around the sky as seen from the planet), which is called the synodic period of rotation.

Overview

Because of the angular momentum accreted during their formation, all planets tend to rotate around their axes. The rotation rate is measured by the sidereal period of rotation, which is different from the apparent period of rotation of the Sun in the sky because, while the planet rotates, it is also moving around the Sun on its orbit (Table 1).

During its existence, the rotation of a planet may be modified by tidal effects (see Tides) resulting from gravitational forces from the Sun or a parent star or from a potential satellite. For

instance, if the Sun deforms the planet and creates a bulge in the direction of the Sun (and in the opposite direction), and if the planet rotates more rapidly on itself than its revolution around the Sun, this bulge is shifted from the subsolar point because of the nonelasticity of the planet. This induces a torque on the rotation of the planet, which tends to bring the planet’s rotation into a synchronous state with its orbital period. Such a planet would have a permanent day and night hemisphere. The synchronization time strongly increases with the orbital distance, and in the ► [Solar System](#) only planets closer to their star than the ► [Earth](#) can be affected. However, this could be the case for planets located in the ► [habitable zone](#) around low-mass stars. If the ► [orbit](#) is eccentric, the planet can instead be trapped in a spin-orbit resonance with rotation period = $(2/n) \times$ orbital period (Correia et al. 2008). This is the case for ► [Mercury](#), which rotates in exactly two-thirds of its orbital period (it rotates three times on its axis for every two orbits around the Sun).

In the case of a planet with a thick atmosphere (like ► [Venus](#)), the effect of thermal atmospheric tides must be taken into account. The Sun heats the atmosphere at the subsolar point, inducing a redistribution of the mass of the atmosphere, which also induces a torque. In the case of Venus, this effect is thought to have put Venus into the retrograde slow rotation that is observed today (Correia and Laskar 2001).

Rotation Planet, Table 1 Rotation periods for the eight planets of the solar system and Pluto. Negative periods correspond to retrograde rotation, when the planet appears

to rotate in the opposite direction than its orbital revolution around the Sun

Body	Sidereal period	Synodic period = “day”
Mercury	58.6462 Earth days	175.940 Earth days
Venus	−243.02 Earth days	−116.75 Earth days
Earth	23 h 56 min 4.1 s	24 h 0 min 0 s
Mars	24 h 37 min 22.66 s	24 h 39 min 35.24 s
Jupiter	9 h 55 min 30 s	9 h 55 min 33 s
Saturn	10 h 32 min 35 s	10 h 32 min 36 s
Uranus	−17 h 14 min 24 s	−17 h 14 min 23 s
Neptune	16 h 6.6 min	16 h 6.6 min
Pluto	−6 days 9 h 17.6 min	−6 days 9 h 17.0 min

Cross-References

- [Earth](#)
- [Habitable Zone](#)
- [Mercury](#)
- [Orbit](#)
- [Planet](#)
- [Satellite or Moon](#)
- [Sun \(and Young Sun\)](#)
- [Tides, Planetary](#)
- [Venus](#)

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Rotational Axis

- [Polar Axis](#)

Rotational Speed

- [Rotational Velocity](#)

Rotational Velocity

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Rotational speed](#)

Definition

The rotational velocity is the rate at which a celestial body (star, planet, galaxy) rotates on itself, generally around one of its axes of symmetry. The rotational velocity is the number of revolutions per time unit. Units are cycles s^{-1} or Hz.

The rotational velocity of a body is a result of the ► [angular momentum](#) that is possessed by the matter from which it condensed (e.g., molecular cloud, debris disk, pre-galactic halo). This quantity being conserved during any process of collapse or condensation, the object spins faster, as its size is reduced. A typical rotational velocity of a star like the Sun is one rotation per month; however, young stars can spin at a rate 40 times faster, and in the extreme case of millisecond pulsars, this rate can reach 716 rotations per second. For planets, except for those in our solar system, rotations are not generally known. Jupiter makes one rotation in about 10 h, while one rotation takes 240 days on Venus. The rotational velocity generally decreases with time through several phenomena, such as stellar winds for stars or tidal interactions for planets. In very peculiar cases, it can increase suddenly under the effect of some external forces: this is the case of millisecond pulsars, which are likely old pulsars reaccelerated by accretion of matter.

In stellar and exoplanetary studies, the rotation of the star is an important parameter since it is related to the age and ► [metallicity](#) of the star. When too large, the rotational velocity can hamper the capability to detect a planet through radial-velocity techniques. The rotation direction of a star with respect to the orbital plane of its orbiting planet(s) is now a parameter accessible in few cases, by measuring the Rossiter-McLaughlin effect in transiting planets. Comparing the direction of the axis of rotation of the star and of the normal to the planet's orbital plane gives a clue on the planet formation process: it is predicted that both directions should be roughly identical in a classical formation scheme, as the one accepted for the solar system. Indeed, all its planets but Uranus have their axis of rotation somewhat parallel to the Sun's spin

axis and perpendicular to the common orbital plane (the ecliptic plane). However, this is not a rule for exoplanetary systems: for a very significant fraction ($\sim 1/3$) of the cases where the Rossiter-McLaughlin effect could be detected, the two directions are found largely unaligned. In addition, unalignment is found predominantly in the case of stars hotter than 6,250 K.

Cross-References

- [Angular Momentum](#)
- [Radial-Velocity Planets](#)
- [Rotation Planet](#)

Rotatory Power

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Meguro-ku, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Synonyms

[Optical rotatory power](#)

Definition

Rotatory power refers to a substance's ability to rotate the plane of polarization of polarized electromagnetic radiation, usually visible light. This is typically measured in solution using a polarimeter and then reported as the observed rotation $[\alpha]$:

$$[\alpha] = [\alpha]_{\lambda}^T l c \quad (1)$$

where $[\alpha]$ is the specific rotation, T is the temperature and λ are the temperature and wavelength at which the

measurement is made, l is the path length of the radiation in dm, and c is the concentration in g cm^{-3} . The product of the specific rotation atomic or molecular weight gives the rotatory power.

RQ36

Maximilian Hamm
 Planetology and Remote Sensing, Freie
 University Berlin, Berlin, Germany
 Institute for Planetary Research, German
 Aerospace Centre, Berlin, Germany

Synonyms

[\(101955\) Bennu](#)

Definition

RQ36/(101955) Bennu is a Near-Earth Asteroid (Apollo-type), of spectral type B in Tholen-taxonomy system. It was visited by the NASA/LPL's OSIRIS-REx spacecraft on a sample-return mission (101955). Bennu (formerly RQ36) is a rubble-pile asteroid with spinning-top shape. The mean diameter is 490.1 m with 498.5 m polar extent and 564.7 m $\times$ 536.1 m equatorial extent. Its sidereal rotation period is 4.296 h. Bennu is actively emitting material. The mechanism behind this activity could be stress release during thermally induced rock breakdown. Bennu's surface is dominated by highly porous boulders with low strength. This was a surprise as a smooth surface was expected from ground and space-based telescopic observations. Fine particles or dust are rare on the surface. The bulk density of Bennu is 1190 kg m^{-3} indicating a high porosity. The surface shows high abundance of hydrated minerals and similarities to CI and CM carbonaceous chondrites. It is extremely dark with a global geometric albedo of 4.4%. Bennu shows several similarities to asteroid (162173) Ryugu (JU3).

Cross-References

- [Apollo Asteroid](#)
- [Asteroid](#)
- [Carbonaceous Chondrite](#)
- [NASA](#)
- [Near-Earth Objects](#)
- [OSIRIS-REx](#)

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RRKM

- [Rice-Ramsperger-Kassel-Marcus](#)

Rubble rock

- [Breccia](#)

Rubisco

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

Rubisco is the acronym of D-ribulose 1,5-bisphosphate carboxylase-oxygenase. This ► [enzyme](#) catalyzes the carboxylation of ribulose 1,5-bisphosphate (RuBP) as a first step in the Calvin-Benson-Bassham cycle yielding two molecules of 3-phosphoglycerate. It is a fundamental activity for many autotrophic systems. In the presence of molecular oxygen, the enzyme oxygenates RuBP, yielding a molecule of 3-phosphoglycerate and one of phosphoglycolate (representing a loss of carbon). Rubisco is an old enzyme with a wide phylogenetic distribution among bacteria and archaea. It has been also involved in other, non-autotrophic metabolic functions like a more efficient use of carbohydrates to synthesize lipids in developing plant embryos. Its enigmatic presence also in non-autotrophic species opens the range of its metabolic functions.

Cross-References

- [Calvin-Benson Cycle](#)
- [Carbon Dioxide](#)
- [Enzyme](#)
- [Metabolism](#)

Runaway Gas Accretion

Sean N. Raymond

Laboratoire d'Astrophysique de Bordeaux, CNRS, Université de Bordeaux, Bordeaux, France

Definition

Runaway gas accretion is the accelerated accretion of gas from the ► [protoplanetary disk](#) onto a

growing ► [giant planet](#). The runaway gas accretion phase is thought to occur when the mass in a planetary core's gaseous envelope is comparable to the core mass, and a large reservoir of gas remains in the disk. Runaway gas accretion is quenched when the planet carves an annular gap in the disk, having accreted all the gas within its direct gravitational influence, i.e., its ► [Hill sphere](#). Dynamical instabilities, for example, due to interactions with the gas disk, could however increase the planetary eccentricity and restore a large accretion rate of gas, for massive enough planets.

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Giant Planets](#)
- [Gravitational Collapse, Planetary](#)
- [Hill Radius/Sphere](#)

Runaway Growth

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux, CNRS,
Université de Bordeaux, Bordeaux, France

Definition

Runaway growth is an accelerated phase in planetary growth during which the growth rate scales with the planet mass ($dM/dt \sim M^{4/3}$) such that the largest bodies get larger at a rapid and increasing rate. Runaway growth occurs in cases for which ► [gravitational focusing](#) of small bodies (planetesimals) is very strong. The runaway growth phase is thought to be quite short in most situations and to be stopped when random velocities of the planetesimals are increased to the point where gravitational focusing is stopped and accretion returns to the geometrical regime (where the collision rate is simply proportional to a body's surface area). However, in situations with very strong damping of planetesimal eccentricities (e.g., via ► [gas drag](#)), runaway growth of

► [planetary embryos](#) can be extended all the way to the point at which a growing planet becomes dynamically isolated from its neighbors by accreting all of the mass in its local neighborhood.

Cross-References

- [Dynamical Friction](#)
- [Isolation Mass](#)
- [Planet Formation](#)
- [Planetesimals](#)
- [Viscous Stirring](#)

Rupes, Rupēs

Jörn Helbert
DLR, Institut für Planetenforschung, Berlin,
Germany

Definition

Rupes (Latin for cliff) are lobate scarps on the surface of ► [Mercury](#). Rupes are formed by compressional tectonics. The largest known feature of this kind on Mercury is Discovery Rupes. Discovery Rupes is about 550 km long and stands as high as 1.5 km.

Cross-References

- [Mercury](#)

Russian Astrobiology Center

- [RAC, Russia](#)

Russian Federal Space Agency

- [Roskosmos](#)

Russian Space Research Institute

► [IKI](#)

Rusting

► [Oxidation](#)

Ryugu Asteroid

Anny-Chantal Levasseur-Regourd
Sorbonne Université/LATMOS, Campus Pierre et
Marie Curie, Paris, France

Synonyms

[Asteroid 162173](#)

Definition

(162173) Ryugu is a near-Earth C-type (i.e., carbonaceous) asteroid. It has been, after Itokawa, the second target for an asteroidal sample return, thanks to the JAXA Hayabusa2 mission (Watanabe et al. 2019). Most interestingly, Ryugu in situ observations in 2018–2019 have confirmed, as expected from its classification, the presence of significant amounts of organic molecules, together with hydrated minerals.

Ryugu is a roundish, diamond-shaped body with an equatorial bulge. Such a shape, as previously observed during the Rosetta mission for asteroid (2867) Steins, may result from the re-accumulation of rubbles ejected by the catastrophic disruption of a larger aqueously altered parent body (Kitazako et al. 2019; Sugita et al. 2019). With a size and a mass, respectively, about 865 m and 4.5×10^{11} kg, its density is low ($\approx 1200 \text{ kg m}^{-3}$), as expected for a rubble-pile asteroid, while its rotation period is of 7.63 h. The very

dark surface of Ryugu, with a geometric albedo about 4% at 0.55 μm , suggests a high abundance in organics (Potiszil et al. 2020). Besides, observations from Hayabusa2 provide clues of space weathering and/or radiative heating of the regolith on the surface (Yokota et al. 2021; Kitazato et al. 2021). Quite a few craters have been noticed at low latitudes, together with numerous large boulders that may eventually present porosities above 70% (Sakatani et al. 2021).

Samples of Ryugu, which is estimated to contain hydrated minerals and (possibly complex polymeric) organic molecules, have been successfully collected on its surface and subsurface in 2019 (Morota et al. 2020) and have reached the Earth in December 2020 within Hayabusa2 return capsule. The mass of retrieved samples, corresponding to black granules from the surface and fragments from the subsurface, is about 5.4 g. Preliminary curatorial work on these terrestrially uncontaminated samples is mostly oriented towards organic matter, minerals, and chemistry. While Hayabusa2 mission could be extended to the exploration of other asteroids by 2026 and 2031, precise analyzes of available samples in selected worldwide laboratories should elucidate the formation of Ryugu by capture of rocky debris, the water-organics interactions, and the evolution of organic matter in the Solar System, possibly including the processing of biogenically important molecules.

Cross-References

- [Asteroid](#)
- [Bennu Asteroid](#)
- [C-Asteroid](#)
- [Hayabusa Missions](#)
- [JAXA](#)
- [Near-Earth Objects](#)

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S

S-Process

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The s-process is one of the two main nucleosynthesis processes forming nuclei heavier than those of the iron peak. Neutron captures are slower than beta-decays (hence the s, for *slow*), keeping the flow of matter on the nuclear stability valley. The s-process occurs during helium fusion in stars, neutrons being released through $^{13}\text{C}(\alpha, n)$ or $^{22}\text{Ne}(\alpha, n)$, on timescales of 10^4 years. The latter reaction operates in the cores of massive stars and produces the light s-nuclei (with mass number $A < 90$, like Sr), while the former operates during shell He burning in ► [asymptotic giant branch \(AGB\) stars](#) and produces the heavier s-nuclei (up to ^{208}Pb).

Cross-References

- [Asymptotic Giant Branch Star](#)
- [Nucleosynthesis, Stellar](#)
- [R-Process](#)
- [Stellar Evolution](#)

S₂H

- [Sulfur Hydrides in the Interstellar Medium](#)

Saccharide

- [Carbohydrate](#)

Sagan Carl

Florence Raulin-Cerceau
Maître de Conférences, Centre Alexandre Koyré
(UMR 8560-CNRS/EHESS/MNHN/CSI)
Muséum National d'Histoire Naturelle, Brunoy, France

History

Carl Edward Sagan (November 9, 1934 – December 20, 1996) pioneered Exobiology since the beginning of planetary exploration and played a leading role in the preparation of experiments intended to detect signs of life on other planets. He was associated with the American space program since its beginning in the 1950s and contributed to the *Mariner*, *Viking*, *Voyager*, and *Galileo* missions.

His background in astronomy and astrophysics (University of Chicago) and his strong interest in the origin of life on Earth and elsewhere in the universe led him to combine scientific fields such as biology, chemistry, and astrophysics. He popularized Exobiology with talent and wrote many popular science bestsellers. Above all, he was very famous for cowriting and presenting in the 1980s the TV series *Cosmos: A Personal Voyage*, which was broadcasted all over the world.

Sagan promoted ► [SETI](#) (Search for Extraterrestrial Intelligence) thanks to his fine talent as writer (*Cosmic Connection: An Extraterrestrial Perspective*, 1973) and to the universal messages he added on the *Pioneer* and *Voyager* space probes launched in the 1970s and planned to leave the solar system. He was the author of the novel *Contact* (1985), a story dealing with SETI, which became the basis for the film “*Contact*” (1997), starring actress Jodie Foster (1962–).

His scientific career was also brilliant. He became full Professor at Cornell University in 1971, where he directed the Laboratory for Planetary Studies. He published many renowned papers about the high surface temperatures of Venus, the seasonal changes on Mars, or the reddish haze of Titan (and its *tholins*, a word that he invented). His contributions to Martian exploration (*Viking* experiments) consolidated the field of Exobiology. Editor in Chief of the International Journal *Icarus* during 12 years, he was also the cofounder and first president of the Planetary Society in 1980. He received many awards throughout his career and could be seen as a forerunner in lots of topics, thanks to his hypotheses which were confirmed many times.

Cross-References

- [Galileo Galilei](#)
- [SETI](#)
- [Valles Marineris](#)
- [Viking](#)
- [Voyager, Spacecraft](#)

Sagduction

Hervé Martin¹ and Nicholas Arndt²

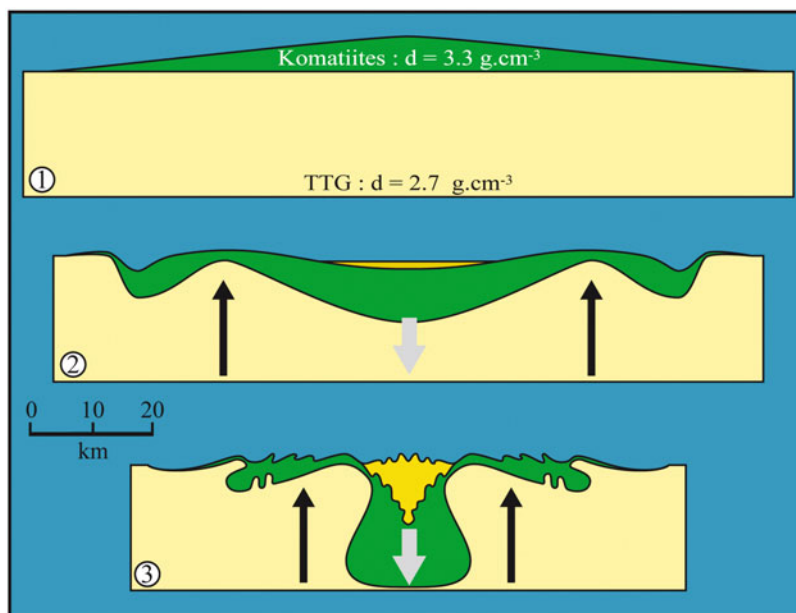
¹Laboratoire Magmas et Volcans, Université Clermont Auvergne, Aubière Cedex, France

²Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

Definition

The concept of sagduction results from the observation that, all over the world, the Archean shields are, in the first order, affected by dome and basin vertical deformations. It consists in downward-moving diapirs (large teardrop-shaped masses of ductile material) composed of dense metavolcanic and metasedimentary rocks. This vertical tectonics is a gravity-driven mechanism (Fig. 1). The deposition of high-density lavas such as komatiites ($d = 3.3 \text{ g/cm}^3$), or even of sediments such as the banded iron formations (BIF; $d = 4.6 \text{ g/cm}^3$), onto a continental crust consisting of TTGs with a lower density ($d = 2.7 \text{ g/cm}^3$), creates a strong, inverse density gradient (Gorman et al. 1978; Barbey and Martin 1987). The return to equilibrium is achieved through komatiite sinking into TTG. Such structures are well documented in Superior Province (Lin et al. 2013), the ► [Pilbara Craton](#), Western Australia (François et al. 2014), as well as in the Dharwar craton in South India (Choukroune et al. 1997; Chardon et al. 1998).

Komatiites are abundant in Archean terranes. Indeed, after 2.5 Ga, Earth's internal temperature became too low, and consequently, basalts were generated instead of komatiites. However, basalt density does not exceed 2.8 or 3 g/cm^3 , which is too low for generating an inverse density gradient, sufficient for sagduction to be initiated. Therefore, as komatiites are necessary to trigger sagduction and that they were no longer generated after 2.5 Ga, sagduction and vertical tectonics also logically ended and disappeared after 2.5 Ga.



Sagduction, Fig. 1 The three main steps of sagduction: (1) In a greenstone belt, high-density komatiites ($d = 3.3 \text{ g/cm}^3$) emplace over lower density ($d = 2.7 \text{ g/cm}^3$) TTG basement rocks, thus generating an inverse density gradient; (2) komatiites sink downward into the TTG basement which favors a relative upward motion of the TTG; and

(3) the movement is amplified creating a sedimentation basin at the center of the greenstone belt. *Green* is komatiites, *pale yellow* is TTG basement, and *yellow gold* are sediments possibly including Banded Iron Formations

If some authors consider that this tectonic style is entirely compatible with plate tectonics, others believe that plate tectonics could not have operated on a hot early Earth.

Cross-References

- [Archean Tectonics](#)
- [Pilbara Craton](#)
- [Plate Tectonics](#)
- [Subduction](#)

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Saglek-Hebron Complex (Northern Labrador, Canada)

Hanika Rizo¹ and Jonathan O'Neil²

¹Carleton University, Ottawa, ON, Canada

²University of Ottawa, Ottawa, ON, Canada

Keywords

Eoarchean · Earth's first crust · TTG · Early differentiation · Magma ocean · Traces of life

Acronyms (Optional)

SHC

Definition

The Saglek-Hebron Complex (SHC) is an Eoarchean granite-greenstone terrane, hosting some of the oldest rocks on Earth, and where some of the earliest traces of life might have been recorded. The SHC is located in northern Labrador (Canada) and is part of the North Atlantic Craton, known as the Nain geological province. The lithologies found in the complex include mafic metavolcanic rocks, ultramafic rocks, and chemical metasedimentary rocks, occurring as large enclaves of up to several hundreds of meters, hosted in Neoproterozoic to Eoarchean felsic gneissic rocks. The SHC rocks are often correlated with those from the Eoarchean ► [Isua supracrustal belt](#) of southern West Greenland.

History (Optional)

Research in northern Labrador started in the late 1960s based on geophysical studies of the Canadian and Greenland cratons associated with the discovery of ≥ 3700 Ma ► [Amîtsoq gneisses](#) on the western coast of Greenland (Black et al. 1971). The Amîtsoq gneisses contain supracrustal enclaves (such as the Isua supracrustal belt), which are comparable to those found in the

Uivak gneisses of the Saglek-Hebron Complex in northern Labrador. Given the lithological similarities and comparable emplacement ages, it was suggested that the Amîtsoq and Uivak gneisses and their supracrustal rocks shared a common geological history (e.g., Bridgwater and Schiøtte 1991). As the oldest terrestrial crust so far discovered, it attracted considerable interest for research between the 1970s and 1990s. The first radiometric dating studies from Hurst et al. (1975) and Barton (1975) revealed an age of 3600 Ma for the Uivak gneisses. Subsequent studies focused on the petrology and geochemistry (e.g., Bridgwater and Collerson 1976), to identify the main lithostratigraphic units in the SHC, as well as using U-Pb geochronology on zircons to refine the chronology of deposition of these units (e.g., Collerson 1983). With the development of new methods of investigation and recent progress in Hadean and Archean geology studies, there has been a renewed interest in research on the SHC since 2015, whose discoveries are summarized below.

Overview

The Saglek-Hebron Complex is an ancient terrane of metamorphosed granitoids and supracrustal rocks located in northern Labrador (Canada) and is part of the North Atlantic Craton. This terrane is one of the handful places on Earth where rocks from the Eoarchean Era (4.0-3.6 billion years) are preserved. The study of these rocks, therefore, provides valuable information regarding the geological processes responsible for the formation of Earth's most ancient crust. The oldest granitoids in the SHC have been dated by U-Pb geochronology on zircons at ~ 3.9 Ga (Collerson 1983; Regelous and Collerson 1996; Shimojo et al. 2016; Komiya et al. 2017; Vezinet et al. 2018; Wasilewski et al. 2021). Younger granitoids are also present in the SHC, with ages spanning from ~ 2700 Ma to ~ 3900 Ma, formed during at least six distinct magmatic events (e.g., Wasilewski et al. 2021) and metamorphosed at ~ 3600 Ma and up to granulite facies at ~ 2700 Ma (Kusiak et al. 2018; Sałacińska et al. 2019). The Nd isotope

composition of those granitoids, along with Hf isotope compositions of their zircons, allows tracking the evolution of the crust through time and comparing this evolution with other ancient terranes. These studies show the granitoids were produced by the remelting of Mg-Fe-rich crust, possibly ► [Hadean](#) in age, as well as the reworking of the Eoarchean felsic crust throughout the Archean (Wasilewski et al. 2021). After the Paleoarchean, the zircon Hf isotope compositions suggest the input of more juvenile material (Wasilewski et al. 2021). This shift in source material has also been observed in other ancient crust outcrops (e.g., Acasta gneisses, Amitsoq gneisses) suggesting a planetary-scale transition for crustal formation processes. Slightly elevated $d^{18}O$ values (up to +6.6%) in zircons from Eoarchean granitoids support interaction of their protolith with hydrosphere at relatively low temperature (150–200°C) (Vezinet et al. 2018).

The SHC supracrustal rocks are mostly metamorphosed basalts locally interbedded with detrital and chemical sediments. ► [Pillow lava](#) structures can be observed, similar to those found in the Isua supracrustal belt (Greenland) and in the Nuvvuagittuq greenstone belt (Canada), evidencing for submarine magmatism on Earth's surface in the Eoarchean. The major and trace element compositions of the metabasalts are similar to those of modern tholeiites (Wasilewski et al. 2019). As opposed to the boninite-like basalts (boninite is a mafic extrusive rock high in both Mg and Si formed in subduction arc environments) found in Greenland (e.g., Polat et al. 2002), metavolcanic rocks from the SHC do not exhibit geochemical evidence of possible subduction-zone settings (Wasilewski et al. 2019). Therefore, while the geochemical composition of the basalts from Greenland suggests plate tectonics had already started in the Eoarchean, similar arguments cannot be made in the SHC. The SHC also includes ► [ultramafic rocks](#), which origin and age have been debated. Collerson et al. (1991) proposed that some of these rocks were similar to ► [komatiites](#), which derive from high-degree partial melts, seen exclusively in the Archean. They also proposed that some ultramafic rocks were 4-billion-year-old

slices of lithospheric mantle, making these the oldest fragments of mantle preserved on Earth. More recent studies, however, have obtained younger 3800–3600 Ma ages from these rocks (Ishikawa et al. 2017; Morino et al. 2017, 2018). Using the major and trace element compositions, Wasilewski et al. (2019) proposed that rather than mantle fragments, these ultramafic rocks were ultramafic cumulates crystallized from komatiitic or picritic basalts. Both, the metabasalts and ultramafic rocks were studied using the short-lived ^{146}Sm - ^{142}Nd system (half-life of 103 Ma), and ^{142}Nd variations found in these rocks suggest that their mantle source differentiated ~4.4 billion years ago (Morino et al. 2017).

Tashiro et al. (2017) studied ~3.95 Ga metasedimentary rocks from the SHC and found large fractionations between $\delta^{13}C$ in carbonates and in graphite (up to 25 per mil), which they interpret as evidence of biological activity in the Eoarchean. The age assumed for these metasedimentary rocks and associated traces of life has however been questioned, since it relies on field relationships and the geochronology of surrounding granitoids (Whitehouse et al. 2019). The use of $\delta^{13}C$ as isotopic biosignatures has also been challenged since abiotic processes, and contamination might mimic the same signatures (Javaux 2019). Nevertheless, evidence of isotopically light $\delta^{13}C$ compositions interpreted as biogenic tracers have also been proposed in other ancient terrains such as the Eoarchean Isua supracrustal belt (Ohtomo et al. 2014), as well as potential fossil evidence in the Hadean ► [Nuvvuagittuq greenstone belt](#) (Dodd et al. 2017). Since pillow lavas in all these terrains imply the presence of liquid water on Earth's surface, life could very well have been developed in the first few hundred million years after Earth's birth.

Cross-References

- [Amitsoq Gneisses](#)
- [Archean Eon](#)
- [Archaean Traces of Life](#)
- [Basalt](#)
- [Biogenicity](#)

- ▶ [Canadian Precambrian Shield](#)
- ▶ [Craton](#)
- ▶ [Crust](#)
- ▶ [Extinct Radionuclides](#)
- ▶ [Geochronology](#)
- ▶ [Graphite](#)
- ▶ [Hadean](#)
- ▶ [Hadean Mantle](#)
- ▶ [Komatiite](#)
- ▶ [Mafic and Felsic](#)
- ▶ [MORB](#)
- ▶ [Nuvvuagittuq Greenstone Belt](#)
- ▶ [Plate Tectonics](#)
- ▶ [Ultramafic Rocks](#)

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restricted Earth return mission. Such samples might contain extraterrestrial materials that, if released, could cause harm to the environment of the Earth and need to be contained. Further, the samples need to be protected from contamination by terrestrial organisms and biomolecules, so that life detection experiments performed on these samples do not detect terrestrial biology by mistake.

The sample receiving facility is the location in which returned sample canisters can be safely opened, and samples identified, sorted, tested, and curated.

The sample safety assessment protocol is performed on samples to determine whether it is safe to release materials (with or without a subsequent sterilization step) to scientists studying the samples in laboratories without containment facilities and practices in place.

Salt Tolerance

- [Halotolerance](#)

Salt-Loving Organisms

- [Halophile](#)

Sample Receiving Facility

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

A sample receiving facility (SRF) is conceptually a high-containment facility (approximating to BSL-4, the most stringent containment used for work with the most dangerous and easily transmitted terrestrial disease agents) for samples returned from another planetary body on a

Cross-References

- [Biological Safety Level](#)
- [Planetary Protection Category](#)
- [Quarantine](#)
- [Sample Safety Assessment Protocol](#)

Sample Safety Assessment Protocol

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

Any spacecraft mission bringing samples to Earth from another planetary body is subjected to an assessment for ► [planetary protection](#) according to the recommendations of the ► [COSPAR](#) planetary protection policy. If the planetary body has (either now or in the past) had the potential to host indigenous life, then the return mission is

categorized as “restricted Earth return.” This means that any returned samples must be subjected to rigorous analysis in order to assess the risk of releasing any possible extraterrestrial life into the Earth’s environment. A sample safety assessment protocol that has been reviewed and concurred by an appropriate nonadvocate group of scientific experts is performed to determine whether extraterrestrial organisms or other hazards are present in materials returned from other planetary bodies, before the sample is confirmed as safe to release to other laboratories or whether the sample must remain contained in the ► [Sample Receiving Facility](#).

History

This Protocol was previously known as the Bio-hazard Assessment Protocol.

Cross-References

- [COSPAR](#)
- [Planetary Protection](#)
- [Sample Receiving Facility](#)

Sanukitoid

Hervé Martin
Laboratoire Magmas et Volcans, Université
Clermont Auvergne, Aubière Cedex, France

Keywords

Archean-Proterozoic transition · Continental crust · Mantle metasomatism

Synonyms

[High-magnesium granodiorite](#)

Definition

Sanukitoids are intermediate to felsic igneous rocks, which possess both modern crust characteristics (i.e., richness in K) and Archean TTG features (i.e., fractionated rare-earth element patterns). Most of them were generated between 2.7 and 2.3 Ga on Earth.

Overview

Sanukitoids, also called *high-magnesium granodiorites*, were first described by Shirey and Hanson (1984). They consist in a complete magmatic series, from diorite to granite, the most common facies consisting in monzodiorites and monzogranites. Typically, they are rich in both K-feldspar phenocrysts and mafic minerals such as biotite and hornblende with sometimes subordinate amounts of clinopyroxene.

Sanukitoids can occur as plutons of all sizes, with a broad range of crustal emplacement levels and degrees of heterogeneity. In the Central Pilbara Craton, Western Australia (Smithies and Champion 1999), sanukitoids form small (<1 km), homogeneous stocks of shallow-emplaced magmas; while in South India (Closepet Granite; Moyen et al. 2001), they form a huge intrusive body that is about 400 km long and 20 km wide and is rooted in the lower granulitic crust.

From the chemical point of view, these rocks possess both modern characteristics (i.e., richness in K) and Archean TTG features (i.e., fractionated rare-earth element patterns). In other words, their composition is intermediate between that of Archean TTG and that of the modern continental crust.

Melting experiments and petrogenetic geochemical modeling (Rapp et al. 2010) show that sanukitoids may have formed by either (1) melting of mantle peridotite previously transformed (metasomatized) by felsic melts having a TTG composition or (2) by reaction between TTG melts and mantle peridotite (assimilation; Martin et al. 2009).

The transitional character of sanukitoids is not only compositional but also chronologic, since most of them were emplaced between 2.7 and 2.3 Ga, at the Archean-Proterozoic boundary, the period when the Earth geodynamics changed from archaic to modern style (Martin et al. 2009; Heilimo et al. 2010; Laurent et al. 2011). Indeed then, the source of juvenile continental crust changed from basalt melting, producing TTG to fusion of peridotites, resulting in calc-alkaline magmas; the tectonic regime changed from horizontal + vertical in the Archean to only horizontal in Paleoproterozoic. All these fundamental evolutions, as well as the disappearance of komatiites after 2.5 Ga, result in the progressive cooling of our planet.

Cross-References

- [Archean Eon](#)
- [Tonalite-Trondhjemite-Granodiorite](#)
- [TTG](#)

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Sarcosine

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Synonyms

[2-\(Methylamino\) acetic acid](#); [N-Methylglycine](#)

Definition

Sarcosine is a ► [nonprotein amino acid](#) and a structural isomer of alanine. While alanine is chiral, sarcosine is achiral since it does not have an asymmetric carbon atom. Its molecular structure is $\text{CH}_3\text{NHCH}_2\text{COOH}$, and its molecular weight is 89.093. Though sarcosine is not a protein ► [amino acid](#), it is a biogenic amino acid and is widely distributed in organisms. It is widely distributed in foods such as egg yolks, meats, and vegetables. Since it has no amino group ($-\text{NH}_2$) but an imino group ($-\text{NH}-$), it requires special care in amino acid analysis, since sensitive amino acid detection often requires derivatization of the amino group. It is one of the most abundant amino acids in prebiotic chemistry. Sarcosine was found in Miller’s spark discharge products and also in extracts from carbonaceous chondrites such as the Murchison meteorite.

Cross-References

- [Amino Acid](#)
- [Nonprotein Amino Acids](#)

Satellite or Moon

Ralf Jaumann

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

The term satellite refers to a natural object that orbits another (larger) body or to an artificial object placed into orbit by human action. Thus, planets that orbit a star may also be considered natural satellites. However, the basic definition of a natural satellite is a celestial body that orbits a planet or a small body and is classically also called a moon. The sizes of natural satellites in our ► [Solar System](#) range from 5268 km for the Jovian moon ► [Ganymede](#) to objects of less than 1 km in diameter. Among the objects classified as natural satellites are 172 objects that orbit planets, 169 of which are in the outer Solar System. Eight satellites orbit ► [dwarf planets](#). A significant number of satellites are known to orbit asteroids (186) and trans-Neptunian objects (TNOs) (84).

Cross-References

- [Callisto](#)
- [Deimos](#)
- [Dwarf Planet](#)
- [Enceladus](#)
- [Europa](#)
- [Ganymede](#)
- [Io](#)
- [Miranda](#)
- [Moon, The](#)
- [Phobos](#)
- [Planet](#)
- [Rhea](#)
- [Small Solar System Body](#)
- [System Solar Formation, Chronology of](#)
- [Titan](#)
- [TNO](#)
- [Triton](#)

Saturn

Therese Encrenaz

LESIA, Observatoire de Paris, PSL, CNRS, Sorbonne University, University Paris-Diderot, Meudon, France

Keywords

Giant planets

Definition

Saturn by order of mass, size, and heliocentric distance is, after Jupiter, the second among the solar system's giant planets. Its mean distance to the Sun is 9.5 AU. Its diameter is 120,530 km or 9.45 times the Earth's diameter and its mass amounts to 95 terrestrial masses. Its density is 0.69 g/cm^3 such that Saturn is the lightest solar system planet. Saturn is best known for its extensive ring system, much larger and more massive than the ones of the other giant planets. Its atmosphere shows a strong dynamical activity and its magnetosphere, perturbed by the ring system, is unique in the solar system.

Overview

Saturn as a Giant Planet

Jupiter and Saturn have the same basic chemical composition, dominated by protosolar gas (mostly hydrogen and helium) which accreted on their rock/ice core at the time of their formation; they are called the gas giants. The difference in density between Jupiter (1.3 g/cm^3) and Saturn can be explained by Jupiter being more than three times more massive than Saturn, thus causing a much stronger compression. Basically, Jupiter and Saturn have the same chemical composition, dominated by the protosolar gas (mostly hydrogen and helium) which collapsed on their rock/ice cores at the time of their formation. Because of hydrogen and helium gas dominating their

composition, they are called the gas giants. In contrast, the two other giant planets, Uranus and Neptune, accreted a minor fraction of protosolar gas around their cores. Their compositions are dominated by water, methane and ammonia, chemical components collectively called planetary ices, and are thus called the ice giants.

Early Exploration

As for Jupiter, the astronomical observation of Saturn started at the beginning of the seventeenth century, when Galileo Galilei turned his first refractor towards the Moon, planets, and stars. Galileo soon noticed that Saturn's shape was slowly evolving, due to the changing orientation of its rings with respect to the Earth, but he was not able to explain this phenomenon. The answer was provided by Christiaan Huygens in 1659 who proposed that a flat equatorial ring was surrounding the planet. In 1675, Giovanni Domenico Cassini discovered the Cassini division in the ring system and, one century later, in 1787, Pierre-Simon de Laplace, on the basis of dynamical studies, concluded that Saturn was surrounded by a large number of narrow rings.

In 1676, Cassini discovered the equatorial belt of Saturn. In 1787, William Herschel measured the flattening of the planet and, 3 years later, the planet's rotational period, which at 10.6 h, shows that Saturn, as Jupiter, is a fast-rotating object. The average angular diameter of Saturn is 16 arcsecs.

Space Exploration

Space exploration of Saturn started with the Pioneer 11 encounter. Launched in 1973 by NASA, Pioneer 11 used a gravity-assist flyby of Jupiter to encounter Saturn in 1979. In addition to a camera, UV and IR photometers, its instruments were specifically designed for the study of both the planet and of the interplanetary magnetic field. Pioneer 11 sent back amazing images of Saturn's rings, discovered two new satellites and a new ring, and explored Saturn's magnetosphere.

Only 1 year after Pioneer's discoveries, the Voyager 1 spacecraft flew by Saturn and brought even more spectacular results. The Voyager

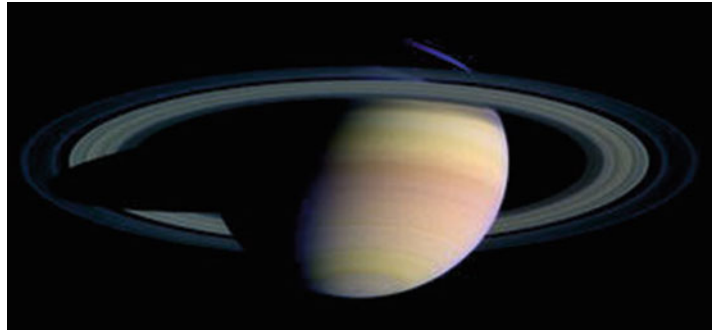
mission, composed of two identical spacecraft, was designed to explore the four giant planets by successive flybys during 1979 and 1989. Saturn was approached in 1980 by Voyager 1 which also flew close to Titan and in 1981 by Voyager 2 which then continued its way to Uranus and Neptune. Voyager 1 measured the atmospheric composition of Saturn, tracked its atmospheric spots, measured its zonal winds, and detected a high-level auroral activity.

Since the Voyager era, Saturn was continuously monitored by ground-based telescopes and by the Hubble Space Observatory. The next milestone was the ambitious Cassini-Huygens mission (see entry), jointly built by NASA and ESA, and devoted to the exploration of the Saturnian system. Launched in 1997, the Cassini orbiter approached Saturn in 2004. On January 14, 2005, the Huygens probe successfully landed on Titan, sending the first images of the satellite's surface. Since 1995, the Cassini orbiter has been exploring Saturn, its rings and satellites, bringing an impressive number of results and discoveries, including the rings' fine structure, cryovolcanism on Enceladus and lakes on Titan. The mission ended on September 15, 2017, with a plunge into Saturn's atmosphere, after having completed observations over almost two seasons of a Saturnian year (Fig. 1).

Dynamical Structure

Alike Jupiter, Saturn's disk shows a zone and belt structure, ascribed to a convective, Hadley-type circulation of a fast-rotating body. The zones are associated to ascending cloudy regions, while the belts are dry regions of subsidence. The cloud structures on Saturn appear less featured than that of Jupiter. The more uniform yellowish colour of Saturn is explained by thicker ammonia clouds resulting from the lower surface temperature of this planet. In spite of this apparent uniformity, Saturn exhibits a strong dynamical activity. At the South Pole, Cassini visible and near-infrared images have revealed the presence of a hurricane with a giant eye, sharing some similarities with terrestrial hurricanes but of a much larger size. In contrast, the northern hemisphere displays

Saturn, Fig. 1 Saturn and its ring system, as observed by the Cassini orbiter. (© NASA)



a hexagonal feature, already observed on the Voyager images that encircle the North Pole at a latitude of 77° N. It is similar to the Earth's polar vortex, except that it possesses six branches instead of being circular. This feature is the signature of a long-lived, complex system of convective cells which extend deep into the planet's troposphere. The mechanism which drives these huge cyclonic features is still not understood.

In December 2010, a huge storm appeared in Saturn's Northern hemisphere at a latitude of 32° N. It rapidly extended over all longitudes to form a large band of white clouds, monitored by the Cassini spacecraft. Five such phenomena have been observed in the past 150 years with a mean period of a Saturnian year (subject to significant fluctuations) and seem to occur during summer solstice when insolation is at its maximum, alternating between equatorial and northern mid-latitudes. The Cassini instruments recorded tropospheric cooling at the location of the storm eruption, suggesting a massive upwelling, and strong stratospheric heating (up to 80 K above quiescent conditions at 2 mbar), probably caused by planetary wave propagation from the tropospheric storm.

Atmospheric Composition and Structure

The thermal structure of Saturn is very similar to the Jovian one, with a troposphere, a tropopause, and a stratosphere. The tropopause is located at a pressure level of 100 mbar, as in the case of the other giant planets. Because of its large heliocentric distance, its temperature (80 K) is lower than at the Jovian tropopause (110 K). Below the tropopause, as in the case of Jupiter, the troposphere

extends downward with an adiabatic gradient. Above the tropopause, in the stratosphere, temperature increases with altitude. The heating takes place at higher altitudes than on Jupiter, which implies different heating mechanisms.

The cloud structure of Saturn is also similar to the Jovian one, but it appears at higher pressure levels due to the colder environment. Thermochemical models predict a NH_3 cloud at about 1.5 bar, a NH_4SH cloud at 4 bars, and an H_2O cloud at about 10 bars. Only, the thick ammonia cloud deck is observed; the other clouds are too deep to be observable. In the stratosphere, a haze is observed, probably due to hydrocarbon condensates.

Similar to Jupiter's, Saturn's atmosphere is dominated by hydrogen (84%) and helium (16%). At the time of the Voyager encounter (1980), a very low helium abundance was inferred from infrared and radio-occultation data. This result was interpreted in terms of helium condensation inside a liquid hydrogen ocean in the interior of the planet: sinking of helium droplets (helium rain), falling toward the centre would lead to the depletion of the helium gas in the outer atmosphere; in addition, it would release some internal energy, as also observed by Voyager (see below section "[Internal Structure](#)"). However, in 2000, Voyager data were reanalysed, which resulted in a higher helium abundance and in better agreement with the Jupiter value. In both cases, the helium abundance is lower than the protosolar value, so that helium condensation within the interior of the planets might be responsible for this depletion, and also accounting partly for the internal energy source required to balance the observed luminosity of the planet.

As a result, the planet's strong dynamical activity, the tropospheric abundance of PH_3 in Saturn is higher than in Jupiter; indeed, PH_3 is a disequilibrium species which is not expected to be observable according to thermochemical equilibrium models. Its presence in the planets' spectra is believed to be the signature of convective motions, particularly strong in the case of Saturn. As in Jupiter, many hydrocarbons are found in Saturn's stratosphere, resulting from methane photodissociation. Oxygen species (H_2O , CO_2) have also been detected by the Infrared Space Observatory (ISO), as in the other giant planets and Titan, and water has been recently monitored with Herschel. The oxygen species are believed to come from an external source, either local (Saturn's rings and satellites) or interplanetary (comets). Enceladus, with its H_2O geysers, is probably the dominant source of oxygen on Saturn.

As Saturn has not yet been explored by an entry probe, we have little information about the abundances of heavy elements. Still, a C/H ratio = 9 can be inferred from the CH_4 abundance; which is consistent with the value expected from a model assuming that giant planets formed from a rock/ice core of about 10–15 terrestrial masses.

Internal Structure

Saturn's interior can be probed indirectly from the measurements of its basic parameters (mass, radius, density) and its gravitational moments. Additional information is deduced from its composition and its luminosity. The Voyager IRIS infrared spectrometer measured the planet's emission over the total infrared range and led to the conclusion that the internal energy of Saturn is 1.78 times the absorbed solar energy, i.e., slightly greater than in the case of Jupiter.

The structure of Saturn, as predicted by theoretical models, is similar to Jupiter's, with a central core of ices and rocks, surrounded by an ocean of metallic hydrogen and a layer of molecular hydrogen, mixed with helium. The central pressure could be about 9 mbar (0.9 TPa) with a central temperature of $\sim 10,000$ K. As mentioned above, the origin of Saturn's internal energy could

partly result from the condensation of helium in addition to cooling upon contraction of the planet which slowly releases gravitational energy accumulated during its accretion phase.

The Magnetosphere of Saturn

Saturn's magnetosphere was unknown prior to the flybys of Pioneer 11 in 1979 and of Voyager 1 and 2 in 1980 and 1981. Since 1995 until 2017, Saturn's environment has been monitored in depth by the Cassini orbiter.

Saturn's magnetic field is almost aligned with the planet's rotation axis. As in the case of Jupiter, the fast rotation of the planet induces a corotation of the plasma and the same general magnetospheric structure. However, Saturn's magnetosphere is coupled to specific sources: Titan, as a provider of H^+ and N^+ ions, the neutral torus of hydrogen and nitrogen, the icy satellites, the rings, and the ionosphere.

Auroral phenomena appear at fixed locations at high northern and southern latitudes. In the radio range, Voyager discovered the Saturn Kilometric Radiation (SKR), auroral and nonthermal radiation, similar to the Auroral Kilometric radiation (AKR) on Earth.

Measuring the radio emission of giant planets is important for determining precisely the rotation period of the planet's interior. From Voyager measurements, Saturn's rotation period was found to be 10 h 39 min 22.4 s. However, subsequent measurements by the Ulysses probe and more recently by Cassini have suggested a rotation period apparently larger by more than 6 min. Recently, it was shown that the rotation period is actually modulated by the solar wind: the dynamical pressure of the solar wind induces changes in the speed of the solar wind as it interacts with Saturn's magnetic field, and thus induces a slight change in the measured radio emission. More recent values of the rotation period are between 32 min 35 s and 10 h 33 min 13 s.

Cross-References

- [Enceladus](#)
- [Giant Planets](#)

- [Jupiter](#)
- [Titan](#)

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Scala Naturae

- [Great Chain of Being](#)

Scale Height

Lisa Kaltenegger
Cornell University, Ithaca, NY, USA

Definition

A scale height H is the distance over which a quantity decreases by a factor of e (the base of natural logarithms). For planetary atmospheres, it is the vertical distance upwards over which the pressure of the atmosphere decreases by a factor of $1/e$. For an isothermal atmosphere,

$$H = kT/\mu g$$

where k is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$), T the mean planetary temperature in Kelvin, μ the mean molecular weight of the planetary atmosphere (kg), and g the

acceleration due to gravity (ms^{-2}). H in a planetary atmosphere is highest for high temperatures and small μ . Assuming absorption features in an atmosphere are proportional to the scale height, they are largest for hot atmospheres with low mean molecular weight (e.g., made out of hydrogen and helium); they have already been detected in transmission spectroscopy for hot extrasolar giant planets.

Cross-References

- [Atmosphere, Structure](#)
- [Atmospheric Modeling, Gray Gas Model](#)
- [Atmospheric Modeling, Non-gray Gas Model](#)

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Scale-Free Networks

Tom Lenaerts
Département d'Informatique, Université Libre de Bruxelles, Brussels, Belgium

Keywords

Complex network · Power law · Scale free · Small world

Synonyms

[Power-law networks](#)

Definition

Networks or graphs are called scale free when their degree distribution, i.e., the distribution of the number of nodes that have a particular degree, decays like a power law (Dorogotsev and Mendes

2003). Researchers have observed that a lot of real-world networks like the Internet or social interaction networks have a topology that comes close to this kind of network.

Overview

The relevance of scale-free networks to represent real-world networks was underlined by the work of Barabási and Albert in 1999 (Barabási and Albert 1999), in which they examined the structure of a number of large networks like the Internet and the coauthorship network between scientists. They showed that these networks follow a power-law distribution, meaning that $P(k)$, which is the probability that a particular vertex in the networks has k interactions, decays as $P(k) \sim k^{-\gamma}$. For instance, the value for γ for the Internet is approximately 2.1 and $\gamma \approx 3$ for the coauthorship network. In addition, they explained the origin of these networks through a simple growth mechanism called the preferential attachment rule. This rule specifies that networks grow by adding new vertices and that these vertices connect not with randomly selected vertices but with popular vertices, meaning here the vertices that already have a high degree. Artificially growing a network in this way produces a network with a power-law degree distribution. This observation was crucial, since prior to their work people mostly assumed that most real-world networks were simply random (small-world) networks (Watts and Strogatz 1998), where the degree distribution corresponds to a Poisson distribution. In the early years after this seminal work, scale-free topologies were discovered in a wide variety of domains, ranging from signaling and metabolic networks to food webs, over different social networks. Yet, it was also observed that a wider variety of heterogeneous topologies exist (Amaral et al. 2000). For instance, Stanley and colleagues observed that the tail of the degree distribution of a movie-actor network decays faster than a power-law network (broad-scale) and that the neuronal network of the worm *Caenorhabditis elegans* decays even faster than a network (single scale). To explain the growth of

the other classes of networks, they extended the growth mechanism with a vertex-dependent aging (or cost) factor. This factor takes into account that there is a limit to how long a vertex can keep receiving new links, which is obviously the case in the movie-actor network. Thus when aging is slow (fast), the scale-free network will turn into a broad-scale (single-scale) network. The research on scale-free networks was immensely popularized by the book *Linked: The New Science of Networks* (Barabási 2002).

Cross-References

- [Bioinformatics](#)
- [Biological Networks](#)
- [Cell](#)
- [Evolution, Biological](#)
- [Metabolism](#)
- [Protein](#)

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Scattering

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Scattering is a process in which a photon, or a particle, interacts with an atom, molecule, or

particle and emerges in a different direction without, or with only a slight, difference in energy. In the interstellar medium, radiative scattering plus absorption by dust grains (in which the photon's energy is converted into heat and possibly lower energy radiation) combine to produce extinction. In planetary atmospheres, scattering by molecules and cloud particles plays an important role in the diffuse reflection and transmission of radiation.

Cross-References

- ▶ [Absorption Cross Section](#)
- ▶ [Extinction, Interstellar or Atmospheric](#)

Schopf Locality

- ▶ [Apex Chert, Microfossils](#)

Science and Society Studies

- ▶ [Social Study of Science](#)

Science Fiction

- ▶ [Imaginary Voyages \(from Antiquity to the Eighteenth Century\)](#)

Science Studies

- ▶ [Social Study of Science](#)

Search for Extraterrestrial Intelligence

- ▶ [SETI](#)

Seasonal Dark Flows

- ▶ [Slope Lineae, Recurrent](#)

Secondary Eclipse

- ▶ [Eclipse](#)

Secular Dynamics

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

Secular dynamics refers to the gravitational interactions and subsequent evolution of orbits among multiple bodies around a central mass. The semi-major axes of secularly interacting bodies remain constant, but other orbital parameters such as eccentricities, longitudes of pericenter, inclinations, and longitudes of ascending node oscillate with time. For low eccentricities and inclinations, motion in the plane is decoupled from motion out of the plane (see also ▶ [“Kozai Mechanism”](#)), that is, the eccentricities and inclinations will oscillate on different timescales, called the secular periods.

Cross-References

- ▶ [Kozai Mechanism](#)
- ▶ [Mean Motion Resonance](#)
- ▶ [Orbit](#)

Secular Resonance

Rory Barnes

Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planetary dynamics, secular resonance is the commensurability of two or more apsidal or nodal precessional frequencies. When multiple planets (more than two) are in a system, their mutual gravitational perturbations cause the shapes and relative orientations of their orbits to change with time (see ► [“Secular Dynamics”](#)). In some cases, the ratios of the frequencies can be close to the ratio of small integers (a commensurability). In these cases, repetitive forces can drive larger or faster oscillations than if the commensurability was not present. This term should not be confused with apsidal libration, which only means the lines of apse are librating.

Cross-References

- [Apsidal Angle](#)
- [Libration](#)
- [Orbit](#)
- [Precession](#)
- [Secular Dynamics](#)

Sedimentary Rock

Daniele L. Pinti

GEOTOP Research Center for the dynamics of
the Earth system, Université du Québec à
Montréal, Montréal, QC, Canada

Definition

A sedimentary rock is a lithified deposit of detrital particles such as gravel, sand, silt, or ► [clay](#); of

(bio)-chemical precipitates (including ► [evaporites](#)) and of organic material. Sedimentary rocks are produced at the surface of the Earth or of a planetary body through processes of mechanical erosion or fragmentation (forming terrestrial regolith and planetary regolith), chemical alteration (both processes reunified under the term “► [weathering](#)”), dissolution, and precipitation. Loose products of those processes are designated as “sediments.” Lithification of sediments through ► [diagenesis](#) brings them to become a lithified sedimentary rock. Sedimentary rocks are usually deposited in sedimentary basins, where the volume of sediments or sedimentary rocks depends on two main parameters: the rate of sedimentation and the space of “accommodation,” the latter increasing through gravity and/or tectonic subsidence. For their nature and mode of formation sedimentary rocks are a record of the past tectonic, climatic, and biological history of the region. The sedimentary record of the Ancient Earth is thus important to investigate, because the lithological, biological, or structural nature of the few sedimentary rocks preserved in Archean terranes can give information on the surface environments where potentially life developed.

Overview

Differently from ► [igneous rocks](#) that form from molten material of the mantle or refusion of the continental crust at depth (*anatexis*) and ► [metamorphic rocks](#) which form at depth under high temperatures or pressures (or both), sedimentary rocks form at the surface of the Earth. Thus, their lithological nature, texture, and fabric reflect or are conditioned by the environmental conditions at the surface of the Earth. Only during the process of lithification (diagenesis), sediments can eventually be buried at temperatures not exceeding 200° C and depths of 10,000 meters. These are the P,T conditions at the boundary between the sedimentary and the metamorphic formational environments.

Sedimentary rocks are classically grouped in three types: clastic or detrital; chemical; and

organic. Clastic rocks are composed of debris of preexisting rocks of any nature, igneous, metamorphic, or even sedimentary. Debris is produced by mechanical erosion and/or chemical weathering, with water interacting with the mineral structure of the rock through mainly ► [hydrolysis](#) (any chemical reaction in which a molecule of water breaks one or more chemical bonds). The first process produces clastic deposits called terrestrial *regolith* (on the Moon, regolith are clastic rocks formed during asteroid impacts). The second, derived from chemical weathering, is named *alterite*. Hydrolysis reaction with silicates can bring to the incorporation of hydroxyls (OH-) in the structure and the transformation into secondary minerals called commonly clay minerals. The silicate structure can be completely dismantled by hydrolysis and residual ions form hydroxides (such as Gibbsite or $\text{Al}(\text{OH})_3$) which are found in extreme weathered soils called *laterites*. Soils are the ultimate transformation of a rock by chemical (and biological) weathering: carbonate rocks can form *calcrete*, while silicate rocks can form a variety of soils; the most weathered being indeed *laterite*. Common clastic sedimentary rocks are conglomerate, sandstone, siltstone, and pelite (or mudstone).

Chemical sedimentary rocks are dominated by evaporites, which precipitate by strong evaporation of seawater along coastal plains (*sabhka*) or closed lakes in arid regions (*playas*). Main evaporitic minerals composing this class of rocks are calcite (CaCO_3), halite (NaCl), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and sylvite (KCl), although many other evaporitic minerals are known. However, being composed of water-soluble minerals, evaporitic rocks are badly preserved in the geological record, and they are mainly found on Earth in sedimentary sequences deposited in the last 500 Ma. ► [Archean evaporites](#) are rare and mainly transformed by later reprecipitation or replacement, as silicified selenite (a variety of gypsum) possibly found in Strelley Pool Chert, Pilbara craton, Western Australia (Lowe 1983).

Carbonates (and perhaps ► [banded-iron formation](#); e.g., Hashizume et al. 2016) are almost always biologically mediated. Since the late

Ediacaran, specialized cells in metazoans precipitate calcite and aragonite from ambient water, forming calcareous endo- or exoskeletons in the shape of shells, tests, spicules, and many other forms. In ► [stromatolites](#) and other microbialites (carbonate bio-construction), photosynthetic activity increases the alkalinity in the near-cell environment, triggering the nucleation and precipitation of aragonite or calcite. Other biological sediments are those deposited in anoxic environments, such as basins with restricted circulation, barred coastal lagoons, or deltaic swamps where organic matter of marine or continental (plants) origin is preserved by complete oxidation.

Most sedimentary rocks are characterized by a large inventory of sedimentary structures, including a variety of bedforms from deposition by highly variable agents under varying conditions. Among them, sedimentary structures controlled by the deposition of sedimentary grains under marine or lacustrine currents, such as *ripple marks* or *cross-bedding*, are important because they give information on paleoceanic currents or, as in case of Archean of the presence of liquid water at the surface of the planet.

Sedimentary rocks are not a prerogative of the planet Earth. Martian exploration has shown numerous evidences of sedimentary rocks on the surface of Mars (e.g., Grotzinger et al. 2011). The presence of numerous sediments deposited clearly in water bodies such as marine and fluvial clastic and evaporitic deposits or mega-floods (e.g., Baker 2009) suggested more clement climatic conditions in the far past of the planet, likely in pre-Noachian, when a magnetosphere protected Mars and allowed liquid water to exist at a global scale.

Cross-References

- [Archean Eon](#)
- [Clay](#)
- [Evaporite](#)
- [Evaporites, Archean](#)
- [Metasediment](#)
- [Microbially Induced Sedimentary Structures](#)
- [Stromatolites](#)

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Sedimentary Volcanism

- [Mud Volcanism](#)

Sedna

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

The ► [trans-Neptunian object](#) (90377) Sedna was discovered in November 2003 by Michael Brown, Chadwick Trujillo, and David Rabinowitz. Its orbit is very elliptical, with a perihelion at 76 AU and an ► [aphelion](#) at 975 AU. Its orbital period is about 11,000 years. Its diameter is

estimated between 1200 and 1600 km and its albedo is about 0.16. It is of a dark red color with little methane or water ice, which suggests the presence of hydrocarbon deposits (or ► [tholins](#)) on its surface. Sedna has been classified as a “detached” ► [trans-Neptunian object](#), which have also been called “extended-scattered” objects or “distant detached objects” (DDO), or as a member of the inner ► [Oort Cloud](#).

Cross-References

- [Kuiper Belt](#)
- [Tholins](#)
- [Trans-Neptunian Object](#)

\$13-Selanyl-2-aminopropanoic Acid

- [Selenocysteine](#)

Selection

Susanna Manrubia

Systems Biology Program, Centro Nacional de Biotecnología (CSIC), Madrid, Spain

Definition

In biology, selection refers to the preferential survival and reproduction of organisms in response to particular phenotypic traits. Limited environmental resources and a growth of populations above its capacity promote competition among organisms and lead to ► [natural selection](#). Natural selection acts at many different levels, from genes and genomic elements to populations. Darwin introduced sexual selection as a preference of females for attractive males: colorful bodies, long feathers, or big horns are instinctually evaluated as a measure of their competence to breed

healthy progeny. Humans perform artificial selection to improve desired qualities in a plant or animal. In vitro evolution is a particular form of artificial selection focused on molecular phenotypes. Though selection acts on the ► [phenotype](#), only heritable traits (coded in the ► [genotype](#)) can be selected.

Cross-References

- [Darwin's Conception of the Origins of Life](#)
- [Evolution, Biological](#)
- [Evolution, In Vitro](#)
- [Genotype](#)
- [Natural Selection](#)
- [Phenotype](#)

Selenocysteine

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Synonyms

[\\$13-Selanyl-2-aminopropanoic acid](#)

Definition

Selenocysteine is a rare biological ► [amino acid](#) found in several enzymes. Its structure is similar to cysteine, but it has a selenium atom replacing the usual sulfur atom, thus forming a selenol group. Selenocysteine is a stronger acid and has a higher reduction potential than ► [cysteine](#). These properties make it optimal for incorporation in proteins involved in antioxidant activity.

Selenocysteine is not directly coded for in the genetic code; rather, it is encoded by a UGA ► [codon](#), which is normally a stop codon. The UGA codon is made to encode selenocysteine by the presence of a SECIS (SElenoCysteine Insertion Sequence) element in the coding mRNA. The SECIS element is defined by characteristic nucleotide sequences and secondary structure base-pairing patterns. In bacteria, the SECIS element is located immediately following the UGA codon in the reading frame for the selenoprotein. In archaea and eukaryotes, the SECIS element is in the 3' untranslated region of the mRNA and can direct multiple UGA codons to encode selenocysteine residues. Unlike the other coded amino acids, no free pool of selenocysteine exists in the cell. Its high reactivity would incur damage to cells. Instead, cells store selenium in the form of the less reactive selenide (H₂Se). Selenocysteine is biosynthesized in situ on a specialized tRNA. In these days, selenocysteine is sometimes included in additional protein amino acids together with pyrrolysine.

Cross-References

- [Amino Acid](#)
- [Codon](#)
- [Cysteine](#)
- [Nonprotein Amino Acids](#)
- [Proteins, Secondary Structure](#)

Selenology

Ralf Jaumann
 German Aerospace Center (DLR), Institute of
 Planetary Research, Berlin, Germany

Synonyms

[Lunar geology](#)

Definition

Selenology (Greek, *Selene*, “Moon,” and *logos* “speech, science”) is the science of the ► [Moon](#). It comprises the study of the structure, composition, physical properties, dynamics, origin, and evolution of the Moon, as well as the processes that formed and shaped the Moon. The term selenology is not frequently used because scientifically and methodologically it is synonymous to “lunar geology.” Thus, the latter is commonly used instead of the term “selenology.”

Cross-References

- [Areology](#)
- [Cratering Chronology](#)
- [Geological Time Scale, History of](#)
- [Moon, The](#)
- [Satellite or Moon](#)
- [Stratigraphy](#)

Self-Assembly

Roderich Groß
Department of Automatic Control & Systems
Engineering, The University of Sheffield,
Sheffield, UK

Keywords

Computation · Formation · Pattern · Structure

Synonyms

[Self-organization](#)

Definition

Self-assembly is the process by which pre-existing components (separate or distinct parts

of a disordered structure) autonomously organize into patterns or structures without external intervention.

Overview

Self-assembly processes are responsible for the generation of much of the order in nature (Philp and Stoddart 1996; Whitesides and Grzybowski 2002). They involve components at different scales, such as molecules, cells, and organisms. The characteristics of the components control how they interact with each other and thus the patterns and structures that emerge. The components must be mobile, being either externally propelled or self-propelled. In many self-assembling systems, the components selectively bind to, or selectively disband from, each other. Such selective binding regulates, for instance, the replication of genetic information in the assembly of the DNA double helix.

Self-assembly processes may be either static or dynamic. In static self-assembly, the systems of components do not dissipate energy and reach an ordered state at global or local equilibrium, whereas in dynamic self-assembly, the systems of components dissipate energy to form and maintain patterns or structures that may be far from equilibrium. An example of static self-assembly is molecular crystallization, and an example of dynamic self-assembly is cell sorting in embryos. In general, dynamic self-assembly systems tend to be more complex than static self-assembly systems. Typically, the components' behaviors (e.g., their binding preferences) are not static but change in response to interactions with other components or the environment. For biological systems, the characteristics of their components undergo evolution as the patterns and structures resulting from the interactions among components are selected for specific functions (Caspar 1966; Sendova-Franks and Franks 1999; Anderson et al. 2002).

Researchers are working toward a more unified theory of self-assembly and a deeper understanding of its elementary functions and limits.

One such attempt is to view self-assembly processes as computations and vice versa. For example, it has been found that systems based on DNA tiles that implement such algorithmic self-assembly can perform Turing-universal computation.

Until now, self-assembly has most widely been applied in the synthesis and fabrication of products from molecular components. However, the potential of self-assembly processes with mesoscopic to macroscopic components is recognized (Whitesides and Boncheva 2002; Groß and Dorigo 2008). At these scales, the characteristics of the components can be precisely controlled and the self-assembly processes can be easily monitored. Potential applications include crystal synthesis with nanometer- to centimeter-scale components, fabrication of electrically or optically functional devices, and autonomous robots with adaptive body plans and functionalities.

Cross-References

- [Molecular Recognition](#)
- [Self-Assembly, Biological](#)
- [Self-Replication](#)

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Self-Assembly, Biological

David Deamer

Department of Chemistry, University of California, Santa Cruz, CA, USA

Keywords

Hydrogen bonds · Hydrophobic effect · Lipid bilayer · Secondary and tertiary protein structures

Synonyms

[Self-organization](#)

Definition

Self-assembly is the process by which certain kinds of molecules in solution are able to associate into larger, more complex structures stabilized by hydrogen bonding and other generally non-covalent interactions.

Overview

The four forces that stabilize the structures of biomolecules are covalent bonds, hydrogen bonds, electrostatic interactions, and the hydrophobic effect. The synthesis of covalent bonds requires a significant expenditure of energy and is not usually associated with self-assembly processes, which are low energy reactions that occur spontaneously without a direct input of metabolic energy. An example of self-assembly is the formation of secondary and tertiary structure of proteins, in which hydrogen bonding is essential. For instance, when peptide chains are synthesized by ribosomes, portions of the growing strand form hydrogen-bonded alpha helices and planar structures called beta sheets. These structures arise spontaneously and are dominant features of

most proteins. Another fundamental biological structure stabilized by hydrogen bonds is the ► [double helix](#) of DNA, in which adenine is paired with thymine with two ► [hydrogen bonds](#), and guanine paired with cytosine with three hydrogen bonds. These are now referred to as Watson-Crick base pairs and more generally as complementary base pairing. If a DNA double helix is separated into single strands, for instance, by heating, upon cooling the two strands reassemble into the original double-helix structure.

A self-assembly process also produces lipid bilayers, the structural barriers composing all cell membranes. The primary contribution to bilayer assembly and stability is the hydrophobic effect that arises from the interaction of hydrocarbon chains with water. If a hydrocarbon chain is inserted into an aqueous bulk phase, the water molecules form orderly cage-like structures around the chain, which decreases the overall entropy of the system. However, if the hydrocarbon chains leave the surrounding water and associate into lipid bilayers, the orderly water-cage structures disperse and entropy of the system increases. The entropy-driven hydrophobic effect also contributes to the folding of protein chains into stable tertiary structures, in which nonpolar amino acids tend to reside in the protein molecule interior, with polar and ionic amino acids lining the surface.

Molecular assemblies stabilized by hydrogen bonding and the hydrophobic effect likely contributed to the increasing complexity of prebiotic structures required for the origin of cellular life.

Cross-References

- [Amphiphile](#)
- [Denaturation](#)
- [Double Helix](#)
- [Hydrogen Bond](#)
- [Lipid Bilayer](#)
- [Micelle](#)
- [Self-Assembly](#)

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Self-Catalytic Activity

- [Abiotic Recombination](#)

Self-Duplication

- [Self-Replication](#)

Self-Organization

- [Self-Assembly](#)
- [Self-Assembly, Biological](#)

Self-Producing Network

- [Autopoiesis](#)

Self-Replication

Raphaël Plasson
Department of Earth and Planetary Science,
Harvard University, Cambridge, MA, USA

Keywords

Autocatalysis · Evolution

Synonyms

[Reproduction](#); [Self-duplication](#); [Self-reproduction](#)

Definition

Self-replication is the property for a system to build a functional and independent copy of itself.

Overview

Self-replication is a general concept that applies to systems of different nature (physical or theoretical) and of different scale (microscopic or macroscopic). It relies on the existence of an internal mechanism for the duplication of the full system. This implies the ability for the duplication mechanism to make a copy of itself. The replicated system becomes a fully functional entity, separated from the parent system, possessing the same properties. Namely, it must be able to replicate itself again. A minimal self-replicative system can be reduced to this sole function, in which case it can do nothing but generate copies of itself – whose function, thus, will be to generate more copies. More complex systems can perform additional functions. In this case, the replicative system must be able to reproduce not only itself but also all the additional mechanisms, so that the replicate can behave similarly to its parent.

Different levels of self-replication can be identified, depending on their accuracy. There can be very strict self-replication systems, producing a copy that is identical to the parent. This is, for example, the case of template ► [autocatalysis](#), where a molecule is able to directly catalyze the formation of an identical molecule (Plasson et al. 2011). More tolerant self-replicating systems allow the possibility of imperfect duplication. This is typically the case for biological systems based on ► [nucleic acid](#) replication, where point ► [mutations](#) are possible, slightly modifying the outcome. Such “general autocatalysis” (Muller 1922) is necessary for the evolution of the system (Vasas et al. 2010). An example of a minimalistic evolvable self-replicative system is the ► [prion](#), an infectious protein that is able to communicate its conformation to normal proteins, which in turn become infectious (Li et al. 2010). In the case of macroscopic systems, the replicate cannot be

strictly identical to the parent – molecule wise – but only similar to it. Such imperfect self-replication can be referred to as reproduction, which is typical of all living beings (Sipper 1998). In this case, the replicate globally possesses the same properties and characteristics as the parent, but is compositionally slightly different.

Key Research Findings

Self-Replication in Life

The self-replication of living organisms is based on genetic ► [replication](#). Each individual is a complex system, able to perform a large set of actions, among which is the ability to produce offspring. The mechanisms for the replication exist at several levels, but all of them are ultimately coded in DNA, bearing all the genetic information. At the molecular level, proteins enable the replication of the DNA molecules, themselves responsible for the synthesis – among other functions – of the replication proteins. At the cellular level, self-replication occurs by the division of one cell into two distinct ones, each containing the same kind of compounds and structures. At the individual level, self-replication is obtained either by division of the being or – in the case of sexual reproduction – by formation and fusion of gametes, each of which contains all the information and tools necessary for building a fully grown organism. Self-replication can ultimately be found at the level of colonies, where a limited number of individuals can separate from the parent colony to grow a new one. At each level, different accuracy of replication exists: DNA is copied with point mutations, crossover mechanisms generate genetic exchanges between chromosomes, sexual reproduction enables reshuffling of genes, etc. This property is crucial for enabling the key property of life, open-ended evolution, rather than endless duplication of identical objects.

Self-Replication in Artificial Life

Self-replication is one of the most fundamental studied properties of all living beings (Sipper 1998). ► [Artificial life](#) describes a minimalistic

theoretical representation of life, in order to understand its specific properties.

Self-replication by a cellular automaton is the first model to have been developed, initiated in the 1940s by von Neumann (1966). Such a system is composed of several cells that are disposed in a grid that can be of multiple dimensions. All cells can be in different states. A set of rules describes how each cell changes from one state to another after a given time step, depending on their present state and their environment. Some of these systems are prone to self-replication; this is typically the case for Langton's self-replicating loop (Langton 1984). This cellular automaton is based on a two-dimensional space, with eight-state cells. An initial 86-cell structure, disposed as a closed loop, is able to duplicate itself and generate a second identical 86-cell loop. ► [Cellular automata](#) can possess simple replicative structures, but can be more complex and replicate additional features. For example, the Tempesti self-replicating loop is similar to the Langton loop, as it is able to self-replicate in a similar fashion, but it additionally possesses a program that is automatically activated: once duplicated, the replicated loop is able to write inside itself the same encoded text than the one of its parent (Tempesti 1995).

Some computer programs are also able to self-replicate. In the 1980s, Core Wars, a computer game initially developed by Dewdney (1984), enabled the creation of programs that fight against each other in a computer environment. The purpose of this game is the destruction of the other programs and the domination of the virtual area. Some programs were successfully able to proliferate thanks to their self-replicating abilities. In more recent software, like Tierra (Ray 1994) or Avida (Lenski et al. 2003), the programs are even prone to open-ended evolution. Computer viruses are malicious application of self-replicating programs. Once designed, they are able to make copies of themselves and propagate inside a computer or from one computer to another via the network or physical media. They are, however, unable to evolve without direct intervention by their programmers (Lenski et al. 2003).

Some computer models intend to reproduce systems that are closer to biological systems.

The purpose is not only to investigate the property of self-replication per se but to understand the process of self-replication as it is implemented in life (Bersini 2010). The first system described in this spirit is the chemoton of Gánti (1975). This model is a minimalistic chemical representation of a cell that is able to maintain its activity and to self-replicate. It contains three interconnected autocatalytic cycles: (1) a metabolic subsystem responsible for the building of the other subsystems, (2) an information subsystem responsible for the system's self-replication, and (3) a membrane subsystem encompassing these subsystems and keeping the compounds within one system. These three subsystems are able to grow altogether, until the point where the whole system can divide to give birth to two separated complete systems.

Kinetics of Self-Replication

The self-replication of a system A corresponds formally to a $A \rightarrow 2A$ transformation: starting from one system, two identical or similar systems are obtained. Such a pattern can be referred to as autocatalysis, in analogy with chemical autocatalysis (Muller 1922). Different kinetic behaviors depending on the kinetic *order* of the autocatalytic mechanism can be observed for the evolution of self-replicating systems (Plasson et al. 2011). This results in different efficiency for their ability to compete with other self-replicating systems. Such dynamics are classically studied in population evolution (Nowak 2006). An *order* smaller than one generates a sub-exponential evolution characterized by the coexistence of all competing self-replicating systems ("survival of all"). First-order kinetics generates an exponential evolution characterized by the proliferation of the most efficient replicator ("survival of the fittest"). *Orders* larger than one generate hyperbolic evolutions characterized by the proliferation of the system initially present in larger quantity ("survival of the first").

The sub-exponential case, with an order inferior to one, is the least interesting, as it does not lead to a clear selective process. However, real mechanisms that seem to possess first-order kinetics may actually present a lower order. This is often the case for the replication of molecules by

template autocatalysis, in which the order falls to one-half on account of the high stability of the dimeric intermediate, which is actually a necessary condition for the selectivity of template replication (Wills et al. 1998).

- [Automaton, Chemical](#)
- [Cellular Automata](#)
- [Evolution, Molecular](#)
- [Origin of Life](#)
- [Replication \(Genetics\)](#)

Future Directions

The elaboration of theoretical self-replicating agents is a way to investigate the possibility for life to emerge from simple chemical systems. Typically, self-replicating programs can spontaneously emerge from an initially random setup. Koza investigated this by letting random programs evolve described by a computationally complete set of functions. He observed a probability of the order of 10^{-6} – 10^{-9} for obtaining the emergence of a self-replicative program that is then able to proliferate as soon as it appears (Koza 1994). In that spirit, designing a simple molecular replicator, able to proliferate without external help, would be a good indication of the possibility of the emergence of molecular replicators on the primitive Earth. Simple oligonucleotide (von Kiedrowski 1993) and oligopeptide (Lee et al. 1997) replicators have been successfully described in the literature. However, template replicators imply the formation of stable dimeric intermediates, leading to a parabolic evolution that undermines their ability to replicate efficiently (Wills et al. 1998). More recent work is oriented toward the design of more complete systems (Szostak et al. 2001), in the spirit of Gánti's chemoton (Gánti 1975). These take into account the necessity of energy transfer for efficient metabolism and for a membrane to enclose the system, in addition to the replicating mechanism itself. Ultimately, and beyond the relevance to the ► [origin of life](#), complete and autonomous self-replicating machines might be engineered (Freitas and Merkle 2004).

Cross-References

- [Artificial Life](#)
- [Autocatalysis](#)

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Self-Replication, Chemical

Alonso Ricardo
Ra Pharmaceuticals, One Kendall Square,
Cambridge, MA, USA

Keywords

Autocatalysis · Cross catalysis · Informational molecule

Definition

Self-replication in astrobiology refers to the ability of a chemical system to make copies of itself without the need for external instructions. The emergence of self-replication is considered to be a necessary step for the origin of ► [life](#).

Overview

Self-replication occurs when an informational molecule (such as a ► [nucleic acid](#)) directs the spontaneous synthesis of a copy of itself. Mechanisms for self-replication can be autocatalytic, where a molecule acts as a template to make a direct copy of itself, or cross-catalytic, where two or more molecules of different informational contents amplify one another. Modern life forms use a complex cross-catalytic mechanism of replication that involves the participation of protein molecules that catalyze the replication of the informational polymer (nucleic acids), which are also involved in the synthesis of the catalysts themselves. Primordial life, however, could have used simpler mechanisms for replication. Nucleic acids are informational polymers that form double-

stranded duplexes following the Watson-Crick base pairing rules and have the intrinsic potential to achieve self-replication via either one of the two previously mentioned mechanisms. This property is central to the RNA world hypothesis for the origin of life (Gilbert [1986](#)). Self-replication is not restricted to nucleic acid polymers, and it has been demonstrated to occur with other types of molecules such as peptides and other non-biological organic compounds.

Experimental approaches for the study of self-replication were initially focused on RNA template-directed polymerization reactions. This work showed that fully complementary polynucleotide duplexes are accessible starting from a single-stranded RNA ► [oligomer](#) (template) and energetically activated ribonucleotide monomers. The efficiency of the polymerization chemistry, however, is dependent on the nucleotide composition of the template, and the rates of polymerization are slow and similar to rates of RNA hydrolysis (Orgel [1992](#)). These combined difficulties have prevented the realization of complete replication cycles of RNA.

The first working example of a self-replicating molecule was obtained with a designed system consisting of two modified trinucleotide oligomers that upon ligation yield a product that could act as a template (catalyst) for a ligation reaction that results in the formation of more copies of itself (von Kiedrowski [1986](#)). This demonstration of autocatalytic self-replication indicated the feasibility of such systems but suffered from product inhibition of autocatalysis as a consequence of duplex formation. Improvements on these model systems were later obtained with variations on the chemistry of the building blocks (Zielinski and Orgel [1987](#)). Examples of self-replication using more complex-designed cross-catalytic molecular systems have also been achieved (Sievers and von Kiedrowski [1994](#)). The use of non-nucleoside building blocks in self-replication studies has improved both the efficiency and our understanding of autocatalytic processes (Tjivikua et al. [1990](#); Terfort and von Kiedrowski [1992](#)). Peptides and supramolecular assemblies of organic molecules represent alternatives to nucleic acid-based self-replication and

have interesting implications in astrobiology due to the different nature of their chemistry (Lee et al. 1996). Despite the interest and effort in this area of research, a robust self-replicating system that can undergo Darwinian evolution has not been experimentally obtained. Current efforts toward that goal are mainly focused in chemical replication studies (Schrum et al. 2009) and in vitro evolution experiments (Lincoln and Joyce 2009).

Cross-References

- ▶ [Activated Nucleotide](#)
- ▶ [Amplification \(Genetics\)](#)
- ▶ [Biopolymer](#)
- ▶ [Emergence of Life](#)
- ▶ [Evolution, In Vitro](#)
- ▶ [Life](#)
- ▶ [Nucleic Acids](#)
- ▶ [Oligomer](#)
- ▶ [Peptide](#)
- ▶ [Protocol](#)
- ▶ [Ribonucleoside](#)
- ▶ [RNA](#)
- ▶ [RNA World](#)
- ▶ [Self-Assembly](#)

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Self-Reproduction

- ▶ [Self-Replication](#)

Self-Shielding

- ▶ [Self-Shielding Effects on Isotope Fractionation](#)

Self-Shielding Effects on Isotope Fractionation

Ko Hashizume
Faculty of Science, Ibaraki University, Bunkyo
Mito, Japan

Keywords

Photochemistry · Photodissociation · Mass-independent fractionation

Synonyms

[Isotope-selective photolysis](#); [Self-shielding](#)

Definition

The self-shielding effect is a phenomenon expected to occur in a gas medium illuminated by a light source, when a molecule in the gas absorbs light with a particular wavelength that may result in its dissociation. The light of this wavelength is gradually attenuated as it travels

through the gas medium, leading to a decreased photodissociation rate of the target molecule. The attenuation rate of the light depends on the abundance of the molecule. When molecules with different combinations of isotopes are photodissociated by different wavelengths, this effect may cause an abundance-dependent isotope fractionation, as opposed to the common mass-dependent fractionation.

Overview

The self-shielding effect may occur when the following conditions are met. (1) Line absorption: The absorption of the photodissociating light occurs only at a narrow range of particular wavelengths. (2) The light with the wavelength of interest reaches to the target molecule, that is, the wavelength is sufficiently intense in the light source and is not shielded by other reasons, for instance, by absorption by other species. Isotope fractionation by the self-shielding effect may occur when the following condition is additionally met. (3) The wavelengths of the photodissociating light for different isotopologues are separated by more than both the abovementioned admitted range and the Doppler width. The fractionation may occur at a certain distance from the edge of the gas medium, determined by the photodissociation cross section and the column density of the isotopologue with the largest abundance.

The self-shielding effect on isotope fractionation was first proposed to occur in a ► [molecular cloud](#), possibly irradiated by ultraviolet (UV) light emitted from a nearby young star (Bally and Langer 1982). They discovered that relative abundances among the isotopologues of carbon monoxide show peculiar variations at a certain distance from the edge of the molecular cloud. Comparing the abundances of $^{12}\text{C } ^{16}\text{O}$, $^{13}\text{C } ^{16}\text{O}$, and $^{12}\text{C } ^{18}\text{O}$, after correction for a possible chemical fractionation, they deduced that $^{12}\text{C } ^{16}\text{O}$, the dominantly abundant isotopologue, was enriched about twice as much as the others. They explained

this observation by the self-shielding effect associated to the isotope-selective photodissociation of CO molecules that may occur upon line absorption of UV.

The same type of isotope fractionations for carbon monoxide and possibly molecular nitrogen is predicted to have occurred in our solar system, in the early solar nebula or in the ancestral molecular cloud, which could be recorded in planetary solid materials. Note that it is not the isotope composition of the gas species (CO or N_2) that could be recorded among the planetary materials but the composition of the photodissociated products. A viable prediction model must contain a reasonable process to accommodate the isotope record of the products into stable compounds, i.e., cold traps. The cold traps proposed are oxides and nitrides (Clayton 2002), or water and organics (Yurimoto and Kuramoto 2004; Lyons and Young 2005), depending on the proposed place (temperature) for the self-shielding effect to have occurred.

Cross-References

- [Fractionation, Mass Independent and Dependent](#)
- [Interstellar Chemical Processes](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Nitrogen Isotopes](#)
- [Optical Depth](#)
- [Oxygen Isotopes](#)
- [Photochemistry](#)
- [Photodissociation Region](#)
- [Protoplanetary Disk, Chemistry](#)

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Semimajor Axis

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Half-major axis](#)

Definition

The semimajor axis of an ellipse is one-half of the major axis, that is, of the longest axis. This is one of the basic parameters when describing the ► [orbit](#) of two bodies in gravitational interaction. It is equivalent to the radius in the case of a circular orbit.

Cross-References

- [Keplerian Orbits](#)
- [Orbit](#)
- [Semiminor Axis](#)

Seminor Axis

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The semiminor axis of an ellipse is one-half of the minor axis, that is, of the shortest axis.

Cross-References

- [Half-Major Axis](#)
- [Keplerian Orbits](#)
- [Orbit](#)

Separation

- [Dichotomy, Planetary](#)
- [Fractionation](#)

Sequence

Carlos Briones
Centro de Astrobiología (CSIC/INTA), Consejo
Superior de Investigaciones Científicas, Madrid,
Spain

Definition

In molecular biology, the term sequence refers to either the order of ► [nucleotides](#) in a nucleic acid molecule – ► [DNA](#) or RNA – or the order of ► [amino acids](#) in a ► [protein](#). Different sequencing methods have been developed since the sequence of the first protein was deciphered by F. Sanger in the 1950s and the first sequences of nucleic acids were unveiled in the 1970s by W. Fiers and later by W. Gilbert and by

F. Sanger. Knowledge of the nucleic acid or protein sequences is currently required for research on many fields of basic and applied biology.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [DNA](#)
- ▶ [Genome](#)
- ▶ [Nucleotide](#)
- ▶ [Protein](#)
- ▶ [Proteome, Proteomics](#)
- ▶ [RNA](#)
- ▶ [Sequence Analysis](#)

Sequence Analysis

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

In molecular biology, ▶ [sequence](#) analysis is the process by which the nucleotide sequence of a nucleic acid, or the amino acid sequence of a ▶ [protein](#), is studied and compared to other sequences. Techniques for sequence analysis include database query, pairwise and multiple sequence alignment, repeated sequence search, mutation screening, and annotation of sequences. In particular, sequence analysis is used to predict the function of newly sequenced genes and proteins through the study of their similarities with other sequences of known function. Bioinformatic tools for sequence analysis are increasingly used in genomics, proteomics, and ▶ [phylogeny](#).

Cross-References

- ▶ [Bioinformatics](#)
- ▶ [DNA](#)

- ▶ [DNA Sequencing](#)
- ▶ [Gene](#)
- ▶ [Genome](#)
- ▶ [Mutation](#)
- ▶ [Phylogeny](#)
- ▶ [Protein](#)
- ▶ [Proteome, Proteomics](#)
- ▶ [RNA](#)
- ▶ [Sequence](#)

Sequencing

- ▶ [DNA Sequencing](#)

Serine

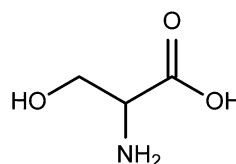
Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

Serine is one of the 20 protein amino acids whose chemical structure is $\text{NH}_2\text{CH}(\text{CH}_2\text{OH})\text{COOH}$ (Fig. 1). Its three-letter symbol is Ser and one-letter symbol is S. Since serine has a hydroxyl ($-\text{OH}$) group in its side chain, it is classified as a polar amino acid. Its molecular weight is 105.09, and its isoelectric point is 5.68. Serine is present in the active sites of many enzymes such as proteases and is widely distributed in the biosphere. Serine, together with glycine, is a predominant amino acid in the hydrolysate of human fingerprints. In the early analyses of carbonaceous chondrites, serine was one of the most abundant amino acids, but later it was found that most of this

Serine, Fig. 1 Serine



amino acid detected was a terrestrial contaminant. In recent amino acid analysis of carbonaceous chondrites, a number of indigenous amino acids were detected, but serine was not common among them. Recently serine was identified in Antarctic carbonaceous chondrites.

Cross-References

- ▶ [Amino Acid](#)
- ▶ [Carbonaceous Chondrites, Organic Chemistry of](#)
- ▶ [Protein](#)

Serpentine

Stephane Guillot
LGCA, Universite de Grenoble, St Martin
d'Hères, France

Definition

Serpentine is a hydrous magnesium-iron phyllosilicate having the chemical formula $(\text{Mg, Fe})_6(\text{OH})_n\text{Si}_4\text{O}_{10}]$. It is greenish, opaque to translucent, light (density of 2.6 g/cm^3), soft (hardness <4) with a greasy luster. All occurrences are microcrystalline and massive in habit, never being found as single crystals. There are three mineral polymorphs: antigorite, chrysotile, and lizardite. Antigorite is stable at high temperatures ($400\text{--}700^\circ\text{C}$) at great depths. Lizardite and chrysotile typically form near the Earth's surface and break down at relatively low temperatures, below 400°C . Asbestos is a fibrous form of serpentine. Serpentine is the hydrous breakdown product of olivine or – more rarely – orthopyroxene. During hydrolysis of the ferromagnesian minerals contained in ultramafic rocks and the formation of serpentine (serpentinization), large amounts of H_2 gas, CH_4 gas, and alkaline solutions are produced. These products possibly made the sites of active serpentinization (around submarine hydrothermal vents) favorable environments for the development of chemotrophic

organisms on the early Earth. It has also been speculated that serpentinization made possible through hydrous alteration of basaltic oceanic crust facilitates subduction. This, in turn, made plate tectonics and crustal segregation by continental growth possible.

Cross-References

- ▶ [Chemoautotroph](#)
- ▶ [Chemolithoautotroph](#)
- ▶ [Chemolithotroph](#)
- ▶ [Fischer-Tropsch-Type Reaction](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Hydrothermal Vent Origin of Life Models](#)
- ▶ [Serpentinization](#)
- ▶ [White Smoker](#)

Serpentinization

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the
Earth System, Université du Québec à Montréal,
Montréal, QC, Canada

Keywords

Carbon isotopes · Chemotrophs · Hydrogen ·
Hydrothermal vents · Methane · Ultramafic
rocks

Definition

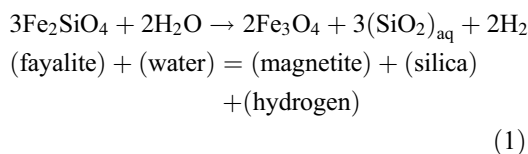
Serpentinization is the process of hydrothermal or metamorphic alteration transforming Fe-Mg-silicate minerals, typically ▶ [olivine](#), but also pyroxene, or amphiboles from ultramafic rocks into serpentine minerals which is a subgroup of phyllosilicates (sheet of silica tetrahedra) of general formula $(\text{Mg, Fe, Ni})_3\text{Si}_2\text{O}_5(\text{OH})_4$. Serpentinite is a rock dominated by a family of soft ductile minerals, notably antigorite and lizardite. Its presence in the mantle wedge helps lubricate the subduction of the oceanic plate. Serpentinization of ultramafic oceanic crust forms hydrogen, methane,

and ammonia. These gases are observed in the hydrothermal springs of the ► [mid-ocean ridges](#) and in ophiolites. The pH of these hydrothermal fluids is generally low at depth, but at low temperature, may be high enough to favor amino acid activity and maintain an environment compatible with life.

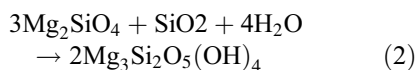
Overview

The process of serpentinization has received much attention by astrobiologists as being a geological process able to furnish a “sustained source of chemically transducible energy” (Russell et al. 2010) and raw material to sustain the emergency of life (Schulte et al. 2006; Schrenk et al. 2013).

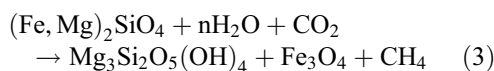
Interaction between the ferrous component of olivine (fayalite) present in the ultramafic oceanic crust releases hydrogen (H₂) according to the reactions:



The silica liberated in the process reacts with forsterite (Mg-olivine, Mg₂SiO₄) to form serpentine (2Mg₃Si₂O₅(OH)₄) according to (Barnes and O’Neil 1969):



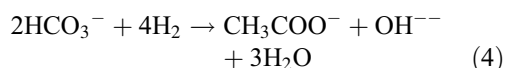
When CO₂ is present, methane can be formed through the following reaction:



A similar reaction with nitrogen produces ammonia. The process of serpentinization around submarine hydrothermal vents where ultramafic rocks react with heated seawater to form serpentine creates favorable environments for organisms using reduced species such as H₂ and CH₄ as a source of

energy (chemotrophy), rather than sunlight in the Hadean ocean. Further reaction with cations of seawater provides an abundant source of protons (H⁺) which could have been used by first organisms for the synthesis of ATP (Russell et al. 2010).

Serpentinization is also an alternative pathway to produce abiotically complex organics in the Hadean ocean, such as methane, n-alkanes, and potentially simple organic acids and N-bearing compounds, as presently observed in abundance in smokers’ effluents. Hydrogenocarbonate is reduced by hydrogen to formate or acetate (Lang et al. 2010) according to:



Reduced carbon species (graphite) produced during the early abiotic stages of serpentinization of ultramafic rocks show isotopic compositions (δ ¹³C from −15‰ to −50‰) mimicking those of organic compounds (McCollom and Seewald 2006; van Zuilen et al. 2002; Lopez-Garcia et al. 2006). These isotopic compositions overlap with those observed in several putative traces of life in Archean rocks, clearly indicating that the isotopic composition of carbon cannot be used alone for determining the biogenicity of those findings. However, the presence of reduced carbon species related to serpentinization is a valuable tracer of chemical activity sustaining chemosynthetic life.

Cross-References

- [ATP](#)
- [ATP Synthase](#)
- [ATPase](#)
- [Black Smoker](#)
- [Black Smoker, Organic Chemistry](#)
- [Chemolithoautotroph](#)
- [Chemolithotroph](#)
- [Graphite](#)
- [Hydrothermal Alteration](#)
- [Hydrothermal Environments](#)
- [Isotope Biosignatures](#)
- [Magnetite](#)
- [Olivine](#)

- [Serpentine](#)
- [Serpentinization \(Mars\)](#)
- [White Smoker](#)

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Serpentinization (Mars)

Vlada Stamenković
Earth, Atmospheric and Planetary Sciences,
Massachusetts Institute of Technology (MIT),
Cambridge, MA, USA

Keywords

Geochemical reaction · Hydrothermal vents · Mars · Methane of Mars

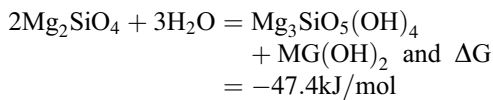
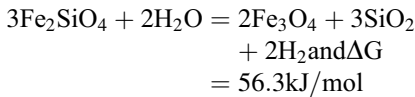
Definition

Serpentinization is the reaction of ultramafic (high in magnesium and iron) ► [minerals](#) with ► [water](#), occurring especially in olivine ($[(\text{Mg}, \text{Fe})_2\text{SiO}_4]$) as well as in pyroxenes (mostly $[(\text{Mg}, \text{Fe})_2\text{Si}_2\text{O}_6]$). The reaction occurs below a critical temperature of about 500–700 K (Oze and Sharma 2007) in the crust and upper mantle of Earth and possibly Mars. Below temperatures of 500 K, the reaction rate decreases rapidly (Martin and Fyfe 1970), although the dependence of the reaction rate on temperature is not well quantified. The hydrated minerals that are formed by serpentinization are called ► [serpentes](#) and contain hydrous magnesium iron phyllosilicates ($[(\text{Mg}, \text{Fe})_3\text{Si}_2\text{O}_5(\text{OH})_4]$), whereas ► [rocks](#) containing serpentes are called serpentinites.

Overview

Serpentes have been detected on Mars by the CRISM spectrometer on the Mars Reconnaissance Orbiter (MRO) (Ehlmann et al. 2009). Serpentinization has been suggested to explain the yet inconclusive and debated observations of ► [methane](#) in the Martian atmosphere (Mumma et al. 2009; Zahnle et al. 2011). It is furthermore speculated to potentially create locally habitable conditions for microorganisms, analogous to hydrothermal vent systems like Lost City near the Mid-Atlantic Ridge at the Atlantis massif on ► [Earth](#) (Kelley et al. 2005). Serpentinization might help to sustain ecological niches by providing heat and ► [hydrogen](#) to be used by autotrophic organisms. Hydrogen released during serpentinization can react with dissolved ► [carbon dioxide](#) in a ► [Fischer-Tropsch-type reaction](#) to produce higher hydrocarbons such as methane, the main nutrient for methanotrophs. But the hydrogen and heat generation rates both depend on the amount of water present, the ambient temperature, and the magnesium number of the reacting mineral. Because of the similar size of magnesium and iron ions, olivine can contain arbitrary magnesium-to-iron ratios, described by the magnesium number x_{Mg} of the reacting

mineral $x_{\text{Mg}} = \frac{\text{mol}(\text{Mg})}{\text{mol}(\text{Mg}) + \text{mol}(\text{Fe})}$. Below are the typical olivine end-member serpentinization reaction for fayalite ($[\text{Fe}_2\text{SiO}_4]$, $x_{\text{Mg}} = 0$) and forsterite ($[\text{Mg}_2\text{SiO}_4]$, $x_{\text{Mg}} = 1$) at $T_0 = 298 \text{ K}$ and $p_0 = 1 \text{ bar}$ and associated Gibbs energies found by Oze and Sharma (2005):



Hydrogen is only produced when iron is present, resulting in the formation of magnetite $[\text{Fe}_3\text{O}_4]$ and quartz $[\text{SiO}_2]$ for fayalite serpentinization. Further analysis (Oze and Sharma 2007) shows that both, the Gibbs energy and the enthalpy, are negative and minimal at large magnesium contents and become positive for x_{Mg} between 0.25 and 0.5 (depending on temperature), making the reaction thermodynamically not favorable and endothermic (heat consuming). The observed magnesium of Martian olivine is lower than on Earth between $0.3 < x_{\text{Mg}} < 0.7$ (Hoefen et al. 2003) but still large enough to provide hydrogen and heat on Mars if enough subsurface water is present.

Cross-References

- [Carbon Dioxide](#)
- [Crust](#)
- [Earth](#)
- [Fischer-Tropsch-Type Reaction](#)
- [Hydrogen](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Mantle](#)
- [Mars](#)
- [Methane](#)
- [Mineral](#)
- [Phyllosilicates, Extraterrestrial](#)

- [Rock](#)
- [Serpentinization](#)
- [Water](#)

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SETI

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Search for extraterrestrial intelligence](#)

Definition

SETI, the Search for Extraterrestrial Intelligence, is an exploratory science that seeks evidence of life in the universe by looking for some signature of its technology. See SETI (the SETI Institute) for more details.

Overview

Are there any technical civilizations out there? Do we have the technology to detect their signals? What would be the most efficient way to decipher their messages? The answers to these questions make the foundation of SETI.

Modern attempts to detect extraterrestrial signals date back half a century, to project Ozma in 1960. Early searches focused on the microwave region of the radio spectrum, where there is minimum interference from natural sources in the Galaxy. From those early beginnings, enormous improvements were achieved in the coverage of radio frequencies and area on the sky, but vast regions of search space remained unexplored. With time, new developments in our own technological capabilities suggested alternative strategies for communication, such as nanosecond optical laser pulses aimed very precisely in extremely narrow and efficient beams.

In the 1980s, NASA became involved in an ambitious SETI program with two prongs; an all-sky survey and a targeted search. The search was mainly in the radio domain, until the congress defunded the effort, just a year after Carl Sagan pushed the ceremonial key in 1992 to initiate the search at the Arecibo Observatory in Puerto Rico. Aside from this program, most of the interest in and support for SETI has come from the public, through a wide variety of initiatives. A pioneering effort by SETI@home harnessed the power of millions of underused computers around the world to analyze data acquired serendipitously with the Arecibo telescope. The Planetary Society supported powerful new searches in both the radio and the optical, and papers reporting null results appeared in professional publications such as the prestigious *Astrophysical Journal*. Despite the lack of success to date, SETI continues in two major directions; Research and Development (R&D) and Projects. R&D efforts include the development of new signal processing algorithms, new search technology, and new SETI search strategies that are then incorporated into specific observing projects.

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SETI, History of

Florence Raulin-Cerceau

Maître de Conférences, Centre Alexandre Koyré
 (UMR 8560-CNRS/EHESS/MNHN/CSI)
 Muséum National d'Histoire Naturelle, Brunoy,
 France

History

The history of SETI (Search for Extraterrestrial Intelligence) began with the 1959 Cocconi and Morrison paper published in *Nature*, entitled “Searching for Interstellar Communications”, establishing the feasibility of interstellar signaling by radio waves. Their authors, the physicists Giuseppe Cocconi (1914–2008) and Philip Morrison (1915–2005) (Cornell University, USA), suggested that the spectral frequency of 1,420 MHz (or 21-cm emission, corresponding to the famous hyperfine line of neutral hydrogen) could be used as the preferential frequency for communication in the Galaxy. In the mean time, radio astronomers were testing the possibilities afforded by a new generation of devices. In such a context, listening to other star systems in the hope of catching artificially produced signals appeared as an exalting challenge.

Independently, the radio astronomer Frank D. Drake (1930–) (Cornell University, USA) was fascinated by the possibility of communicating with other intelligences in the Galaxy. He became the first to test the Cocconi and Morrison hypothesis, at the National Radio Astronomy

Observatory (NRAO) in Green Bank (West Virginia, USA). Drake's project Ozma (named after the fictional Princess Ozma in L. Frank Baum's *Land of Oz*) began in April 1960 when he pointed the 85 ft diameter antenna at two nearby Sun-like stars (Epsilon Eridani and Tau Ceti). Two hundred hours were dedicated to Project Ozma, but, as confirmed by Drake himself, "no signals of extraterrestrial origin were discovered during these preliminary observations."

The year after, a meeting held at Green Bank established SETI as a scientific discipline. During this event, Drake proposed a formula that came to be best known as the ► ["Drake equation"](#), which was supposed to provide a framework to estimate the number of technological civilizations capable of communicating in the Galaxy.

Directly linked to this formula, the ► ["Fermi Paradox"](#) stated that if such extraterrestrial civilizations were existing, they should have mastered space travel and have already undertaken the colonization of the Galaxy (including the Earth). Since there was no evidence of any visit of extraterrestrials to Earth, the (pessimistic and questionable) conclusion was obvious: No other technological civilization could be present in the Galaxy.

No matter what this paradox suggested, concrete SETI programs have been undertaken from the late 1970s up to now (Sentinel, META, BETA, SERENDIP, southern SERENDIP, Phoenix, Optical SETI, Argus, ATA) and successively carried out, in spite of strong difficulties about funds.

Cross-References

- [Drake Equation](#)
- [Fermi Paradox](#)

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Settlement

- [Colonization, Biological](#)

Sewer Gas

- [Hydrogen Sulfide](#)

SFE, France

William M. Irvine
Department of Astronomy, University of
Massachusetts Amherst, Amherst, MA, USA

Synonyms

[French Astrobiology Society](#); [Société Française d'Exobiologie](#)

Definition

La Société Française d'Exobiologie (SFE, French Astrobiology Society) was founded in 2009, replacing an earlier organization of the Centre National de la Recherche Scientifique called the Groupement de Recherche Exobiologie. The goals of the SFE are to coordinate all aspects of astrobiology (formerly known as exobiology) in France, to stimulate interdisciplinary contacts among researchers, and to promote outreach in astrobiology with conferences, workshops, exhibitions, a web site, etc. The SFE is an Affiliated Partner of the NASA Astrobiology Institute (NAI).

Cross-References

- [Astrobiology](#)
- [Exobiology](#)
- [NAI](#)

SgrB2

Brett A. McGuire^{1,2}, Joanna F. Corby³,
P. Brandon Carroll⁴, Anthony J. Remijan²,
Ci Xue³ and Andrew M. Burkhardt⁵

¹Department of Chemistry, Massachusetts
Institute of Technology, Cambridge, MA, USA

²National Radio Astronomy Observatory,
Charlottesville, VA, USA

³University of Virginia, Charlottesville, VA, USA

⁴California Institute of Technology, Pasadena,
CA, USA

⁵Center for Astrophysics | Harvard &
Smithsonian, Cambridge, MA, USA

Keywords

Chemistry · Molecules · Interstellar medium ·
Prebiotic species · Green Bank Telescope ·
Atacama Large Millimeter Array · Herschel
Space Observatory

Definition

Sagittarius B2 (Sgr B2) is an exceptionally massive ($8 \times 10^6 M_{\odot}$; Schmiedeke et al. 2016) giant ► [molecular cloud](#) located ~130 pc (Reid et al. 2009) from Sgr A* – the Milky Way Galaxy’s central supermassive ► [black hole](#) – which is at a distance of ~8.5 kpc from Earth (Genzel et al. 2010). Sgr B2 is within the Central Molecular Zone (CMZ) of the Galaxy, a ~300 pc radius region around Sgr A* that exhibits widespread emission from ► [complex organic molecules](#) (COMs). The Sgr B2 cloud is highly heterogeneous and composed of both compact (hot) and extended (cold) molecular material, molecular ► [maser](#) regions, and ultracompact continuum sources (Remijan et al. 2014).

History

In terms of its astrobiological relevance, Sgr B2 is the preeminent source for the detection and study of new molecules in the ► [interstellar medium](#)

(Remijan et al. 2014). The first interstellar detections of polyatomic molecules including ► [ammonia](#) (NH₃) and ► [water](#) (H₂O) were toward Sgr B2 (Cheung et al. 1968; Cheung et al. 1969). Since that time, study of the region has resulted in the detection of a number of biologically relevant molecules; many of these detections have been the result of extensive ► [molecular line surveys](#) which have been conducted toward the region with a wide variety of facilities, including the Green Bank Telescope, the Herschel Space Telescope, and the Atacama Large Millimeter Array (► [ALMA](#)), with nearly continuous frequency coverage from ~5 to 1,900 GHz (see, e.g., Neill et al. 2012 [1–50 GHz], Turner 1991 [70–115 GHz], Nummelin et al. 1998 [218–263 GHz], Csengeri et al. 2014 [315–375 GHz], Neill et al. 2014 [480–1910 GHz]).

Overview

Structure

Sgr B2 has a complex physical structure with cores of star formation embedded in an extended envelope. Molecular, atomic, and ionized gas have been observed in the extended envelope, appearing without obvious spatial separation between the three phases of gas (Goicochea et al. 2003; Jones et al. 2008). Three main cores of star formation have erupted, namely, the North, Main, and South cores. More than 200 sources with compact, cometary, and shell shapes have been identified in and close to the core, consisting of a mix of H II regions and young stellar objects (Ginsburg et al. 2018). All known molecular masing transitions are detected in Sgr B2, with each transition typically detected at multiple positions near the cores of Sgr B2 (Mehring and Menten 1997; Hoffman et al. 2007). At submillimeter wavelengths, two continuum sources composed of 20 substructures are present in the North core of Sgr B2 (Sgr B2(N)), and a clumpy structure composed of up to 27 components is detected in the main core (Qin et al. 2011, Sánchez-Monge et al. 2017). The submillimeter continuum emission is produced by warm dust in environments with high densities. One of the sub-mm peaks

corresponds to the position of the so-called Large Molecule Heimat, the preeminent source of molecular line emission.

As the most massive known molecular cloud in the Galaxy, Sgr B2 is accessible only at X-ray and radio to far-infrared wavelengths. Sgr B2 is known to have an unusually high flux of X-ray radiation. As no compact X-ray source is observed in Sgr B2, the X-ray radiation is understood as evidence for highly elevated X-ray emission from Sgr A* 300–400 years ago, making Sgr B2 an X-ray ► [reflection nebula](#) (Terrier et al. 2010). Like most clouds in the CMZ, the gas exhibits supersonic turbulence and widespread shocks. The cosmic ray ionization rate is observed to be an order of magnitude higher in Sgr B2 than in most Galactic molecular clouds (van der Tak et al. 2006), and observations of Zeeman splitting of the 21 cm spin-flip transition of HI indicate a high magnetic field strength (Crutcher et al. 1996). Given these conditions, Sgr B2 is regarded as the only Galactic source with an environment analogous to the central regions of starburst galaxies.

Perhaps because of the unique physical environment in this cloud, Sgr B2 hosts the most diverse molecular chemistry observed anywhere outside the solar system.

Chemistry

Indeed, the majority of COMs detected outside our solar system have been detected toward Sgr B2, often exclusively toward this source (Menten 2004). This rich chemical complexity is likely the result of the unique physical conditions that produce favorable conditions for both production and detection of a wide range of COMs. Among the species detected are ► [amines](#), ► [amides](#), cyanides, saturated and unsaturated molecules, alcohols, ► [aldehydes](#), ► [ethers](#), ► [esters](#), ► [carboxylic acids](#), ketones, and epoxides. Of particular interest for astrobiology are the detections of the simplest sugar-related species, ► [glycol-aldehyde](#) (CH_2OHCHO ; Hollis et al. 2004), the first interstellar molecule detected with a branched carbon backbone: *iso*-propyl cyanide ($\text{C}_3\text{H}_7\text{CN}$;

Belloche et al. 2014), and the largest interstellar molecules to possess a peptide bond: acetamide (CH_3CONH_2 ; Hollis et al. 2006) and urea (H_2NCONH_2 ; Remijan et al. 2014, Belloche et al. 2019). Observations using interferometric arrays have also characterized the spatial distribution of emissions from these and other COMs within this source in detail. For example, data from an ALMA survey show the spatial separations of selected $\text{C}_2\text{H}_4\text{O}_2$ isomers toward Sgr B2(N) (Xue et al. 2019). The distinct distribution of the COMs, as well as detections of complex species in both the cold extended envelope (e.g., formamide) and compact regions toward the ► [hot core](#) (e.g., acetamide), demonstrate both the spatial and chemical complexity of Sgr B2.

Cross-References

- [ALMA](#)
- [Gas-Grain Chemistry](#)
- [Herschel Mission](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Radio Astronomy](#)

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SH

- [Sulfur Hydrides in the Interstellar Medium](#)

SH⁺

- [Sulfur Hydrides in the Interstellar Medium](#)

Shadow Zone

► [Oxygen Minimum Zone](#)

Shale

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Definition

Shale is a fine-grained ► [sedimentary rock](#) composed mainly of clay minerals (hydrous aluminum phyllosilicates) with minor proportions of ► [quartz](#), feldspar, calcite, and iron oxides. Because of its small grain size, the constituent particles can settle only in water free of turbulence. This is only the case in nearly stagnant water bodies. Shale is thus deposited in closed basins, estuaries, lakes, and similar depositional settings protected from currents, waves, and wind and in deep water far from continents. Varieties rich in organic material, called black shales, provide valuable sources of information about the earliest forms of life and serve as petroleum source rocks. Shale is converted by ► [metamorphism](#) into mica schist. The occurrence of shale deposits in planetary surfaces would be a good indicator of the past presence of liquid water on their surfaces.

Cross-References

► [Mount McRae Shale](#)

Shark Bay Microbialites

► [Shark Bay, Stromatolites of](#)

Shark Bay Thrombolites

► [Shark Bay, Stromatolites of](#)

Shark Bay, Stromatolites of

Abigail Allwood
Jet Propulsion Laboratory, Pasadena, CA, USA

Synonyms

[Shark Bay microbialites](#); [Shark Bay thrombolites](#)

Definition

Stromatolites are microbially mediated sedimentary structures. The best-known examples are thriving in the shallow waters of Hamelin Pool at the southern end of Shark Bay in Western Australia. Among the first modern ► [stromatolites](#) to be described, the Shark Bay stromatolites provide insights to the biological and physical forces controlling stromatolite growth and are an important analog to ancient stromatolites. The Shark Bay structures include meter-sized, lithified, dome- and club-shaped structures forming at subtidal to intertidal water depths, as well as millimeter-sized, tufted microbial mats forming in the supratidal zone. The lithified stromatolites consist of very coarsely layered detrital sediment accreted over time through microbial trapping and binding of particles and carbonate precipitation.

Cross-References

► [Archaean Traces of Life](#)
► [Biogenicity](#)
► [Stromatolites](#)

Sheet Silica

► [Phyllosilicates](#), [Extraterrestrial](#)

Shepherding

Sean N. Raymond
Laboratoire d'Astrophysique de Bordeaux,
CNRS, Université de Bordeaux, Bordeaux,
France

Definition

Shepherding is the process by which a much larger body constrains the motion of many much smaller objects. Thus, a migrating planet can push ► [protoplanetary disk](#) material inward along with it; in the context of a giant planet migrating toward its central star, ► [planetesimals](#) and ► [planetary embryos](#) can be shepherded by the giant planet via resonances and may enable the formation of close-in super-Earth planets. In planetary rings, small shepherding satellites can constrain the motion of ring particles and hence structure the appearance of the rings.

Cross-References

► [Planetary Migration](#)
► [Saturn](#)

Shergottites

Ana-Catalina Plesa
Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Keywords

SNC meteorites · Rare Earth elements ·
Cosmic-ray exposure age · Noachian ·
Hesperian · Amazonian

Definition

Shergottites are a subgroup of the SNC meteorites named after the Shergotty meteorite. About 78% of the Martian meteorites are classified as shergottites.

Overview

The age of all shergottites has long been debated since some isotopic systems like Pb-Pb indicated an age between 4.1 and 4.3 Ga, corresponding to the Noachian period (e.g., Bouvier et al. 2009), but all other isotopic systems marked these rocks as young samples with ages between 165 and 475 Ma placing them in the late Amazonian epoch (e.g., Nyquist et al. 2001). A young age of shergottites led to a so-called “age paradox,” since young volcanic surfaces from which shergottites might have been ejected by impacts represent only about 20% of the Martian surface (Tanaka et al. 1988). Craters possibly representing the impact locations from which the shergottites were ejected have been identified on the young terrains in Tharsis and Elysium provinces (e.g., Tornabene et al. 2006). However, the Mojave crater, formed on a 4.3 Ga-old terrain, has been found to match the mineralogy of three shergottite samples, that is, Shergotty, Los Angeles, and QUE94201 (Werner et al. 2014). More recent U-Pb and Pb-Pb isotopic measurements, which were performed on the NWA 5298 sample, indicate the crystallization near the Martian surface at an age of 187 ± 33 Ma, and is consistent with a young age of the shergottites (Moser et al. 2013).

The shergottites can be divided into three petrological subgroups (basaltic picritic and lherzolitic shergottites) depending on their olivine content. Basaltic shergottites are rocks composed of pyroxene and plagioclase but do not contain olivine or chromite. Picritic or olivine-phyric shergottites are catalogued as extrusive pyroxene-plagioclase basalts with olivine megacrysts (large olivine crystals surrounded by finer-grained matrix). The third petrological subgroup is defined by lherzolitic shergottites, which are plutonic ultramafic rocks containing at least 40% modal olivine. Depending on the ratio LREE/HREE (light rare earth elements/heavy rare earth

elements) relative to CI chondrites, one can distinguish between depleted (highly depleted), intermediate (moderately depleted), and enriched (slightly depleted) shergottites. Although there are exceptions, most of the enriched shergottites are basaltic; intermediate samples are lherzolitic, while the picritic shergottites are usually depleted. The depleted shergottites have a LREE/HREE ratio close to $0.12 \times$ CI chondrites, while the enriched samples have a ratio close to $1.0 \times$ CI (Bridges and Warren 2006). These different subtypes of the shergottites are thought to hint at different reservoirs in the Martian mantle.

Cross-References

- [Crater, Impact](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Meteorites](#)
- [Meteoritics](#)
- [Shergotty](#)
- [SNC Meteorites](#)

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Shergotty

Ana-Catalina Plesa

Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany

Definition

Shergotty is a 5-kg Martian meteorite discovered in 1865 in Shergotty (now Sherghati), India. It also names a subgroup of the SNC meteorites, the shergottites, representing 78% of the Martian meteorites. Its age has been dated to ca. 165 Ma, although initially Pb-Pb dating indicated an age as old as 4.3 Ga. Shergottite source craters have been identified on young terrains in Tharsis and Elysium provinces. Petrologically, *Shergotty* is a basaltic sample (containing pyroxene and plagioclase but no olivine or chromite), enriched in trace elements.

Cross-References

- [Crater, Impact](#)
- [Isotopic Fractionation \(Planetary Process\)](#)
- [Isotopic Ratio](#)
- [Meteorites](#)
- [Meteoritics](#)
- [SNC Meteorites](#)

Shield

Nicholas Arndt

Emeritus Professor, ISTERre, University Grenoble Alpes, Grenoble, France

Definition

Shield, when used as a geological term, has two meanings. It refers to the old central nucleus of continents (cratons), the typical example being the ► [Precambrian Canadian Shield](#) or the Aldan Shield of Siberia. A shield is composed mainly of granitoids and high-grade ► [metamorphic rocks](#), with ► [greenstone belts](#) in its upper

sections. It is tectonically stable and has typically a low ► [geothermal gradient](#) and a thick ► [lithosphere](#); it is flanked by younger fold belts. A *shield* volcano is a large volcano edifice with shallow-dipping flanks and composed of low-viscosity basaltic lava, such as the Mauna Loa and Mauna Kea volcanoes of Hawaii or ► [Olympus Mons](#) on Mars.

Cross-References

- [Canadian Precambrian Shield](#)
- [Olympus Mons](#)
- [Volcano, Planetary](#)

Shock Devolatilization

- [Impact Degassing](#)

Shock Front

- [Shock Wave](#)
- [Shock, Interstellar](#)

Shock Wave

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Synonyms

[Shock front](#)

Definition

A shock wave is a type of propagating disturbance. Like other waves, it carries energy and

can propagate through a physical medium or, in some cases, in the absence of a material medium, for example, through an electromagnetic field. When an object or disturbance, such as a meteor entering the atmosphere of a planet and its concomitant shock wave, moves faster than its effects can be propagated into the surrounding fluid, fluid near the disturbance cannot change its properties before the disturbance arrives. In a shock wave, the properties of the fluid such as density, pressure, and temperature change almost instantaneously. The energy of a shock wave dissipates relatively quickly with distance.

Many types of shock waves are found in astrophysical environments. Some examples are shock waves accompanying supernovae or blast waves traveling through the interstellar medium and the bow shock front caused by the Earth's magnetic field colliding with the solar wind.

Cross-References

- [Accretion Shock](#)
- [Comet](#)
- [Meteorites](#)
- [Shock, Interstellar](#)
- [Supernova](#)

Shock, Interstellar

Steven B. Charnley
Solar System Exploration Division, Code 691,
Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Synonyms

[Shock front](#); [Shock wave](#)

Definition

A shock is a highly nonlinear compression wave in a medium, which may be a fluid or solid, where

the wave carries energy and where the physical parameters of the medium change abruptly. Astrophysicists recognize two types of shocks in the ► [interstellar medium](#), C type and J type. C-type shocks are supersonic, multi-fluid flow structures occurring in weakly ionized plasma in which the physical variables (density, temperature) undergo a *continuous* change over the scale of the flow. In this case, the speed of the disturbance, the shock speed, is less than that of the magnetosonic speed in the plasma. In contrast, a J-type shock is a supersonic flow structure in which the physical variables (density, temperature) undergo a discontinuous change (*jump*) at the shock front. In this case, the speed of the disturbance, the shock speed, is greater than that of the sound speed in the gas. Interstellar shocks are produced, for example, by the propagation of a ► [supernova](#) blast wave into the ambient medium.

Cross-References

► [Interstellar Medium](#)

Shocked Quartz

Philippe Claeys
Earth System Science, Vrije Universiteit Brussel,
Brussels, Belgium

Definition

Shocked quartz refers to quartz grains displaying microscopic defects in crystalline structure that were produced by the passage of high-velocity and high-pressure (>5 GPa) shock waves. Shock metamorphism is commonly illustrated in quartz by the presence of fine lamellae of amorphous SiO₂ oriented parallel to two (or more) specific crystallographic planes and called planar deformation features, or PDF. Under extreme pressure, the whole quartz crystal transforms to glass. Shocked quartz is a diagnostic criterion to recognize hypervelocity impacts. Indeed, there are no other natural geological processes (tectonics,

volcanism, etc.) capable of producing the required high-pressure dynamic shock waves. Shock features are common in impact crater rocks and in some meteorites. Shock metamorphism is also known in zircon, feldspar, and olivine.

Cross-References

► [Crater, Impact](#)
► [Impactite](#)

Shooting Star

► [Meteor](#)

Short-Lived Radionuclides

► [Extinct Radionuclides](#)

Siderite

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the
Earth System, Université du Québec à Montréal,
Montréal, QC, Canada

Synonyms

[Iron carbonate](#); [Iron spar](#); [Spathose iron](#)

Chemical Formula

FeCO₃

Definition

Siderite is a carbonate mineral of the trigonal crystalline system. It forms mainly in sedimentary and hydrothermal environments and occasionally

in igneous pegmatite (pegmatite is an intrusive igneous rock with large, well-developed crystals). Siderite is found in banded iron formations of different ages, the oldest being at Isua, West Greenland (ca. 3.8 Ga). The occurrence of siderite is considered an index of intermediate oxidation conditions, compared to that in sulfide-facies (reducing conditions) and hematite- magnetite facies iron formations (oxidizing conditions). Being a carbonate, siderite is actively sought on planetary surfaces such as Mars as indirect evidence of the presence of water and mildly oxidizing conditions.

Cross-References

- ▶ [Banded Iron Formation](#)
- ▶ [Goethite](#)
- ▶ [Great Oxidation Event](#)
- ▶ [Hematite](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Iron](#)
- ▶ [Iron Cycle](#)
- ▶ [Iron Oxidation](#)
- ▶ [Iron Oxides, Hydroxides, and Oxyhydroxides](#)
- ▶ [Iron Reduction](#)
- ▶ [Jarosite](#)
- ▶ [Mars](#)
- ▶ [Oxygenation of the Earth's Atmosphere](#)

Siderophile Elements

Francis Albarède
Laboratoire de Géologie de Lyon, Ecole Normale Supérieure de Lyon, Lyon Cedex 7, France

Definition

In the Berzelius-Goldschmidt classification, siderophile elements alloy with metallic iron (sideros), most notably in planetary cores. Transition elements such as Ni, Co, Mn, Mo, Au, and the ▶ [platinum-group elements](#) (Os, Pd, Pt, Re, Rh, Ru) are highly siderophilic. Under reducing

conditions, carbon, silicon, and phosphorus become moderately siderophilic. Likewise, under high pressure, some ▶ [lithophile elements](#) tend to fractionate into the core and become siderophilic. The question of which elements behave in this way is hotly debated for K, Pb, and Nb for the implication it has on the evolution of planetary interiors.

Cross-References

- ▶ [Chalcophile Elements](#)
- ▶ [Lithophile Elements](#)

SiH₄

- ▶ [Silane \(SiH₄\)](#)

Silane (SiH₄)

William M. Irvine
Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Synonyms

SiH₄; [Silicane](#); [Silicon tetrahydride](#)

Definition

Silane (SiH₄) is the silicon analog of methane (CH₄). The symmetry of its tetrahedral shape, with four equivalent hydrogen atoms, results in a zero electric dipole moment and hence no pure rotational transitions. Silane is a gas under standard laboratory conditions, where it is extremely flammable.

History

Astronomically, silane is observed in the envelopes of some evolved stars by means of infrared

transitions at a wavelength of about 11 μm . It is expected by chemical equilibrium arguments to be present in the deep atmospheres of Jupiter and other gas [▶ giant planets](#) (Visscher et al. 2010). The related molecular species methyl silane (CH_3SiH_3) and silyl cyanide (SiH_3CN) have been detected in the envelope of the carbon-star IRC+10216 (Cernicharo et al. 2017).

Cross-References

- ▶ [IRC+10216](#)
- ▶ [Stellar Evolution](#)
- ▶ [Thermodynamical Chemical Equilibrium](#)

References

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Silica Metal Oxide Vesicles

- ▶ [Mineral Vesicles](#)

Silicane

- ▶ [Silane \(\$\text{SiH}_4\$ \)](#)

Silicate

- ▶ [Silicate Minerals](#)

Silicate Minerals

José Carlos Gaspar

Institute of Geosciences, University of Brasília, Brasília, DF, Brazil

Keywords

Earth's crust · Earth's mantle · Silica · Silicate classification · Silicate structure · Silicium

Synonyms

[Silicate](#)

Definition

Silicate minerals are those minerals that contain $[\text{SiO}_4]^{-4}$ as the fundamental unit of their chemistry and structure. Any other chemical element may occur in silicate minerals. $[\text{SiO}_4]^{-4}$ is a tetrahedron containing the four oxygen atoms in the apices and the silicium atom in the center. Up to all four oxygen atoms may be shared with other tetrahedrons. The number of shared oxygen atoms and the final space distribution are used to classify the silicate minerals.

Overview

Despite the fact that silicate minerals may accommodate any chemical element in their structures, the most common elements found are Al, Mg, Fe, Ca, Na, and K. Al is a common substitute for Si in the silica tetrahedron. Table 1 shows the classification of silicates, including their basic tetrahedral structure and most common minerals.

The Earth's [▶ crust](#), upper [▶ mantle](#), and transition zone are essentially composed of silicate minerals. The crust is mainly composed of silicate minerals containing mostly Al, Ca, Na, and K, as quartz $[\text{SiO}_2]$, feldspar [alkali-feldspar (K, Na)(Al, Si) $_3\text{O}_8$, and plagioclase $\text{Na}(\text{AlSi}_3\text{O}_8)$ - $\text{Ca}(\text{AlSi}_2\text{O}_8)$]. Much less abundant but still widespread and important in the Earth's crust are Ca-, Fe-, and Mg-silicates,

Silicate Minerals, Table 1 Classification scheme of silicate minerals

Name	Basic Si-tetrahedra structure	Number of shared oxygens	Example of common minerals
Nesosilicates	Independent tetrahedra	0	Olivine
Sorosilicates	2 tetrahedra	1	Epidote
Cyclosilicates	Rings of 3, 6, and 4 tetrahedra	2	Tourmaline
Inosilicates	Single tetrahedra chain	2	Pyroxene
	Double tetrahedra chain	2 or 3	Amphibole
Phyllosilicates	Tetrahedra sheet	3	Mica
Tectosilicates	Tridimensional framework	4	Quartz, feldspar

for example, mica $[K_2(Al, Mg, Fe)_{4-6}(Al, Si)_8O_{20}(OH,F)_4]$, amphibole $[(Ca, Na)_{2-3}(Mg, Fe, Al, Ti)_5(Si, Al)_8O_{22}(OH)_2]$, and pyroxene $[(Ca, Na)_{1-p}(Mg, Fe)_{1+p}(Al, Si)_2O_6(0 < p < 1)]$. Earth’s upper mantle and the transition zone are largely composed of the following Ca-, Mg-, Fe-bearing silicate minerals: olivine $[(Mg, Fe)_2SiO_4]$, pyroxene (see above), and garnet $[(Ca, Mg, Fe)_3Al, Fe, Cr, Ti)_2Si_3O_{12}]$. Chemical elements inside parenthesis in the chemical formulas occupy the same structural site and may vary in proportion one to another in a replacement process. Whenever valences are different, a conjugate elemental substitution occurs to compensate charge imbalance. The chemical element substitutions characterize these minerals as solid solutions. Extreme chemical compositions are called “end members.” Each end member has a specific name, as for example “diopside” for the pyroxene end member $CaMgSi_2O_6$.

Cross-References

- [Crust](#)
- [Mantle](#)
- [Quartz](#)
- [Zircon](#)

References and Further Reading

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Silicon Isotopes

Luc André¹ and Damien Cardinal²
¹Department of Earth Sciences, Royal Museum of Central Africa, Tervuren, Belgium
²LOCEAN-IPSL, Sorbonne Université, Paris, France

Keywords

Solar system · Meteorites · Bulk silicate Earth · Archean cherts · Early life · Crustal growth · Silicification · Siliceous organisms · Life diversity · Desilication · Weathering

Definition

Silicon (Si) is an element present in all natural environments, including the biosphere. It has three stable isotopes of mass 28, 29, and 30, respectively. Its isotopic composition is expressed in the delta notation $\delta^{30}Si$ ($^{30}Si/^{28}Si$) and $\delta^{29}Si$ ($^{29}Si/^{28}Si$) in per mil units normalized to a standard reference (see “► [Delta, Isotopic](#)”). The $\delta^{30}Si$ and $\delta^{29}Si$ vary in the solar system by up to 14‰ and 7‰, respectively. These isotopic changes in Earth and extraterrestrial materials are used to constrain diverse processes such as the origin of the ► [solar system](#), the protosolar nebula condensation, the core-mantle segregation, the appearance of life, the origin and growth of continental crust, the temperatures of early oceans, the weathering of silicate rocks, or the role of siliceous organisms in C-Si cycles.

Overview

The potential role of silica (SiO_2) in the emergence of life has been often questioned, especially because SiO_2 -rich deposits (cherts) host the oldest putative evidence for life. This view is reinforced by a recent experiment that demonstrates a drastic enhancement in the appearance of prebiotic molecular components in a triphasic system adding silicates to water and reduced Miller-Urey atmosphere (Criado-Reyes et al. 2021). Due to the chemical analogies between Si and C, others have wondered about the biological essentiality of silicon for life (e.g., Exley 2009; Petkowski et al. 2020), but silicon-based life that uses Si exclusively as a scaffold element is very likely impossible (Petkowski et al. 2020). The biologically reactive Si form is its most common dissolved form, silicic acid $\text{Si}(\text{OH})_4$, which is massively present in natural waters. Most biological compartments may have been therefore visited by silicic acid since organisms rarely exclude it. This was likely the case for primitive forms of life because of the extensive Si mobilization at the surface of the early Earth caused by conspicuous Hadean-Archean seafloor-seawater hydrothermal interactions and intense Middle to Late Archean continental weathering. However, the potential role, if any, of silicon in these early biogeochemical cycles was probably complex because it certainly involved numerous Si reservoirs and processes: primary and secondary silicates, adsorption on nonsilicates, biogenic silica, and aqueous $\text{Si}(\text{OH})_4$. These multiple Si components have been shown to bear contrasted Si isotopic signatures, which may in turn potentially trace the various vectors involved in the early biogeochemical cycles. This is one way by which Si isotopes represent a timely tool in the quest for the earliest archives of life.

Silicon has three stable isotopes: ^{28}Si , ^{29}Si , and ^{30}Si with respective abundances of 92.23%, 4.67%, and 3.1%. ^{28}Si is a primary nucleus that exists owing to the nuclear oxygen-burning processes within stars whose initial compositions are hydrogen and helium rich, the two left elements from the Big Bang. Secondary nuclei ^{29}Si and ^{30}Si derive from ^{28}Si by neutron capture or by

conversion of $^{25,26}\text{Mg}$ to $^{29,30}\text{Si}$. Because they require initial carbon and oxygen in the stars, the yield of ^{29}Si and ^{30}Si production should increase with time in the universe as the interstellar gas becomes increasingly enriched in C and O. However, recent silicon isotopic measurements in space find potential gaps in such a theory because both $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ vary much less than predicted on the basis of O and C isotope ratio gradients across the Milky Way (Monson et al. 2017).

The Si isotopic variations in natural samples are expressed in the delta notation per mil units (‰): $\delta^x\text{Si} = 1,000 \times [({}^x\text{Si}/^{28}\text{Si})_{\text{sample}}/({}^x\text{Si}/^{28}\text{Si})_{\text{reference}} - 1]$, where x refers to the atomic mass number 29 or 30. The large Si isotopic changes (>100‰) observed in presolar grain are commonly referred to as the solar abundances (e.g., $\delta^{30}\text{Si}_{\text{Sol}}$). The Earth, Moon, and meteorite abundances, with much smaller isotopic range of variations (<14‰), are normalized relative to a quartz standard, most often the NBS28 (NIST RM8546) silica sand reference material (e.g., $\delta^{30}\text{Si}_{\text{NBS28}}$).

Si isotopes fractionate following mass-dependent laws (isotopic changes about twice larger for $\delta^{30}\text{Si}$ than for $\delta^{29}\text{Si}$) except for stellar nucleosynthesis, which is so far the sole known process by which Si isotopes are fractionated along non-mass-dependent laws. Samples whose isotopic composition derives from a mass-dependent isotopic effect will fit two near-superimposed straight lines on a three-isotope graph according to the equilibrium ($\delta^{29}\text{Si} = 0.5178 \times \delta^{30}\text{Si}$) or kinetic ($\delta^{29}\text{Si} = 0.5092 \times \delta^{30}\text{Si}$) conditions of fractionation. All solar system and terrestrial materials appear to follow these “solar-terrestrial” lines because both mechanisms cannot be distinguished within the current analytic capabilities (best present-day precision at about ± 20 –30 ppm).

Basic Methodology

Four analytic methods are available to measure Si isotopes. Two are adapted for bulk sample determination, gas source isotope ratio mass

spectrometry (IRMS), and multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS, while two are dedicated for in situ micromass measurements: secondary ion mass spectrometry (SIMS) and laser ablation. Precise determinations have been gradually carried out by Si fluorination in combination with gas source IRMS (De La Rocha et al. 1996). Despite its accuracy and precision, this technique is not widely used because of its long and potentially hazardous procedures (making use of F_2 gas). The developed MC-ICP-MS methodology (e.g., Cardinal et al. 2003) is less contamination prone, quicker, and safer with similar or better precision and accuracy as shown by an interlaboratory comparison exercise ($2\sigma_M < \pm 0.15\%$, Reynolds et al. 2007). This methodology has been extended for in situ measurements using UV femtosecond laser ablation systems coupled to MC-ICP-MS (Chmieleff et al. 2008).

Key Research Findings

Significant silicon isotopic variations have been detected in ten major groups of samples, spreading different time periods, from presolar events to the modern biogeochemical Si cycle. All these isotopic fractionations were used to get new insights into the processes from which they were derived.

The major group of silicon carbide (SiC) grains preserved in the most primitive meteorites defines a non “solar-terrestrial” trend line within the three-isotope diagram, showing larger $\delta^{29}\text{Si}$ changes compared to $\delta^{30}\text{Si}$ (slope of 4/3) (Nittler et al. 2005). Their extrasolar isotopic composition suggests that they condensed outside the solar system in dense winds leaving the surface of a presolar carbon-rich asymptotic giant branch star.

Condensation stages of the solar nebula gas are recorded within the Si isotopic features of the three major components of the primitive carbonaceous meteorites: calcium-aluminum-rich inclusions (CAIs), chondrules, and matrix components. Si isotopes in high-temperature (CAIs) trace a process of partial Si evaporation-condensation at an early stage of the solar nebula

evolution. Their $\delta^{29}\text{Si}$ - $\delta^{30}\text{Si}$ plot defines a good correlation line with a mass-dependent slope of 0.5 with $-3.5\% < \delta^{30}\text{Si}_{\text{NBS28}} < +5\%$. This line includes the mean solar system composition ($\delta^{30}\text{Si}_{\text{NBS28}} = -0.5\%$) showing that the CAIs are fractionated products of the solar nebula. The lighter isotopes are preferentially lost during sublimation of the solid or evaporation from a liquid phase (Richter et al. 2009). So the CAIs enriched in heavy Si isotopes are likely residues of rapid Si evaporation while they were molten ($\sim 1\text{--}70$ days, Shahar and Young 2007). In contrast, those depleted in heavy isotopes may represent lasting-years condensates from a gas phase containing previously evaporated light Si. The much lower Si isotopic differentiations found in *chondrules* and the *matrix* components ($-1.0\% < \delta^{30}\text{Si}_{\text{NBS28}} < +0.4\%$) records the following steps of fractional condensation within the gaseous nebula (Martins et al. 2021).

The bulk meteoritic compositions were found to be homogeneous for ordinary (O) and carbonaceous (C) chondrites, at about $\delta^{30}\text{Si}_{\text{NBS28}} = -0.48 \pm 0.10\%$ (Georg et al. 2007; Savage and Moynier 2013), in good agreement with the solar wind values. In contrast, the enstatite (E) chondrites were shown to bear lighter isotopic signatures at $\delta^{30}\text{Si}_{\text{NBS28}} = -0.59\%$ and -0.77% , for low-Fe and High-Fe E-chondrites, respectively. Their lighter Si isotopic compositions are most likely due to the presence of light Si in the kamacites (Savage and Moynier 2013).

The bulk silicate Earth (BSE) composition was deduced from mantle-derived peridotitic and basaltic rocks at $\delta^{30}\text{Si}_{\text{NBS28}} = -0.29 \pm 0.08\%$ (Georg et al. 2007; Savage et al. 2010; Moynier et al. 2020). The small but resolvable difference ($\Delta^{30}\text{Si} \sim +0.2\%$) between the BSE and the O and C chondrites demonstrates that the BSE is non-chondritic with respect to Si isotopes. This is interpreted as resulting from two successive differentiation processes: (1) some light isotope Si loss by volatility during the very first stages of the Earth accretion (Moynier et al. 2020); (2) the incorporation of a significant proportion of light isotope Si (2–9 wt. %) along with metals into the Earth’s core during its segregation (Georg et al. 2007).

The strong Si oversaturation of early Earth seawater generated both Archean ► **chert** deposits and silicifications of Eo-Paleoarchean oceanic seafloors. Cherts display a very large range of Si isotopic signatures ($-2.5\text{‰} < \delta^{30}\text{Si}_{\text{NBS28}} < +2.5\text{‰}$), with an apparent secular increase in their proportion of ^{30}Si from 3.8 to 2.5 Ga. This secular change can be interpreted either as a gradual decrease of the oceanic temperature (Robert and Chaussidon 2006) or a progressive change in the Si source (Van den Boorn et al. 2010), from dominant pristine hydrothermal fluid in the early Archean ($\delta^{30}\text{Si}_{\text{NBS28}} \approx -0.3\text{‰}$) to pure seawater precipitations in the late Archean ($\delta^{30}\text{Si}_{\text{NBS28}} \gg 0\text{‰}$). Whatever the mechanism, it reflects the ^{30}Si -enriched residual character of the late Archean seawater composition consecutive to previous massive silica precipitations. In parallel this seawater-derived heavy silicon isotopic signature is massively transferred to the Archean mafic-ultramafic seafloors during their low-temperature (100–150 °C) silicifications consecutive to the seawater percolation within the oceanic seafloors (Abraham et al. 2011).

The early blocks of the continental crust (Paleo-Mesoarchean Na-rich and K-rich granitoids) display uncommon heavy Si isotopic signatures ($-0.14\text{‰} < \delta^{30}\text{Si}_{\text{NBS28}} < +0.15\text{‰}$). This requires that a notable supracrustal component in the form of seawater-derived silica had been added to their protoliths, suggesting that they formed by melting of recycled Eo-Paleoarchean silicified seafloors (André et al. 2019).

Loess samples, which are a good proxy of the bulk upper continental crust (UCC) composition, define a narrow range of Si isotopic composition ($\delta^{30}\text{Si}_{\text{NBS28}} = -0.22 \pm 0.07\text{‰}$, Savage et al. 2013), identical to average post-Archean granite and felsic rock compositions ($\delta^{30}\text{Si}_{\text{NBS28}} = -0.23 \pm 0.15\text{‰}$, Savage et al. 2012). The slightly heavier isotopic signature of the UCC ($\Delta^{30}\text{Si} \sim +0.1\text{‰}$) relative to the BSE results of two balanced processes: (1) the magnitude of isotopic fractionation ($\Delta^{30}\text{Si} \sim +0.2\text{‰}$) observed between the mafic minerals and the felsic melts during the magmatic differentiation and partial melting processes, (2) the lighter signatures

generated by the weathering processes which are transferred to the secular sedimentary mass.

Weathering conditions generate mass-dependent fractionation of Si isotopes with more negative values of $\delta^{30}\text{Si}$ in secondary soil minerals by clay desilication (Opfergelt et al. 2011) or Si adsorption onto Fe oxides (Delstanche et al. 2009) and heavier values in the percolating soil water compared to the original mineral Si source. Clays become isotopically lighter with the increase of soil weathering and clay desilication from polar to equatorial climatic zones (Bayon et al. 2018).

Siliceous organisms, such as diatoms, radiolarians, and sponges, along with amorphous silica stored in plants (phytoliths), have been well-documented as an important pool of light silicon relative to the residual heavy silicon from their ambient fresh or marine water reservoirs. Combined with clay formation and silicification, they contribute to generate the large range of Si isotopic differentiation observed in various compartments of the *modern global silicon cycle* ($-7\text{‰} < \delta^{30}\text{Si}_{\text{NBS28}} < +6\text{‰}$, Sutton et al. 2018).

The early Cambrian Explosion of Life diversity is marked by a divergence in chert $\delta^{30}\text{Si}$ which is interpreted as the consequence of the appearance of dominant forms of large silica-secreting organisms (sponges, radiolarians) which reduced oceanic dissolved Si concentrations (Ye et al. 2021). This might have removed the threat of harmful Si precipitation in organismal cytoplasm and permit energy expenditure on new metabolic functions, ultimately promoting the main stage (~ 520 Ma) of Cambrian Explosion in functional and ecological diversification (Ye et al. 2021).

Future Directions

The probability exists that a long-term record of continental weathering might be preserved in $\delta^{30}\text{Si}$ from fine-grained sediments. Considering the resistance of Si isotopes to post-emplacement metamorphic redistributions (André et al. 2006), these $\delta^{30}\text{Si}$ archives could be useful in solving the debate about the strength of soil weathering under the reducing conditions of the Archean

Eon (e.g., Delvigne et al. 2016). Better estimations of biogenic versus inorganic silica fractionation factors relative to dissolved silicic acid would also be a potential advance toward a more accurate constraint on the processes involved in the Si cycle. Significant improvements of both $\delta^{29}\text{Si}$ - $\delta^{30}\text{Si}$ analytic precision (<10 ppm) could allow to discriminate between kinetic and equilibrium isotopic fractionations. Such a progress would be essential to (1) better decipher primary and secondary processes at the origin of rock Si isotopic variations and (2) distinguish kinetically controlled biogenic Si incorporation from temperature-controlled equilibrated Si partitioning between minerals with or without fluid phases. This is another way by which Si isotopes might be a helpful tracer in exploring the rise of life.

Cross-References

- ▶ [Archaean Traces of Life](#)
- ▶ [CAIs](#)
- ▶ [Chert](#)
- ▶ [Oceans, Chemical Evolution of](#)

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Definition

Radio astronomers have found that the diatomic molecule SiS, containing silicon and sulfur, is quite abundant in the gas phase in the envelope expelled by the evolved star IRC + 10,216, and it has also been identified in warm gas in star-forming regions of our Galaxy. In the stellar envelope, some seven rare isotopic variants have been detected, involving ^{29}Si , ^{30}Si , ^{34}S , ^{33}S , and ^{36}S , as well as the principal isotopes ^{28}Si and ^{32}S . The abundance of SiS relative to SiO in warmer molecular clouds seems to be roughly in the ratio of the cosmic abundance of sulfur relative to oxygen.

Cross-References

- [Hot Core](#)
- [Isotope](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Silicon Monoxide \(SiO\)](#)
- [Stellar Evolution](#)

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Silicon Monosulfide (SiS)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[SiS](#)

Silicon Monoxide (SiO)

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[SiO](#)

Definition

This diatomic molecule is the simplest oxide of silicon. Silicon monoxide, SiO, has been detected in the gas phase in both interstellar molecular clouds and in the envelopes of evolved stars. In addition to the principal isotopic species, $^{28}\text{Si}^{16}\text{O}$, the rarer forms $^{29}\text{Si}^{16}\text{O}$ and $^{30}\text{Si}^{16}\text{O}$ are also observed. Maser emission is frequently observed from various transitions of SiO. Not surprisingly, SiO is not detected in cold, dark interstellar clouds or in the diffuse ► [interstellar medium](#), where the silicon is thought to be primarily in the ► [interstellar dust](#) grains. However, it is detected in the shocks associated to molecular outflows emanating from newly formed stars.

History

Interstellar SiO was first detected in 1974 by L. Snyder and D. Buhl at millimeter wavelengths. The maser emission from stellar envelopes is often strong enough to provide useful sources for evaluating the pointing accuracy of radio telescopes.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Maser](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)

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Silicon Nitride (SiN)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

[SiN](#)

Definition

The diatomic radical SiN is referred to by astronomers as silicon nitride, although that nomenclature is used by chemists for Si_3N_4 , which is a solid at room temperature and which has been found in ► [meteorites](#). Gas phase SiN has been detected by radio astronomers in both the envelopes expelled by evolved stars and in the ► [molecular clouds](#) toward the center of our Milky Way galaxy. It has been suggested that the SiN in the ► [interstellar medium](#) is produced by gas phase chemistry after silicon has been released from ► [interstellar dust](#) grains by ► [sputtering](#) in shocks.

Cross-References

- [Interstellar Dust](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Sputtering](#)

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Silicon Tetrahydride

- [Silane \(\$\text{SiH}_4\$ \)](#)

Simple Sugar

► [Monosaccharide](#)

Simulation Chambers

Nisha K. Ramkisson¹ and Mickaël Baqué²

¹Faculty of Science, Technology, Engineering and Mathematics, The Open University, Milton Keynes, UK

²Institute of Planetary Research, Planetary Laboratories Department, German Aerospace Center (DLR), Berlin, Germany

Keywords

Planetary environments · Simulations · Habitability

Synonyms

[Environmental chamber](#); [Exoplanet simulation chamber](#); [Icy moons chamber](#); [Mars chamber](#); [Reaction vessels](#)

Definition

Simulation chambers are vessels that aim to imitate multiple environmental properties that can be found on planetary bodies in the Solar System and beyond.

Overview

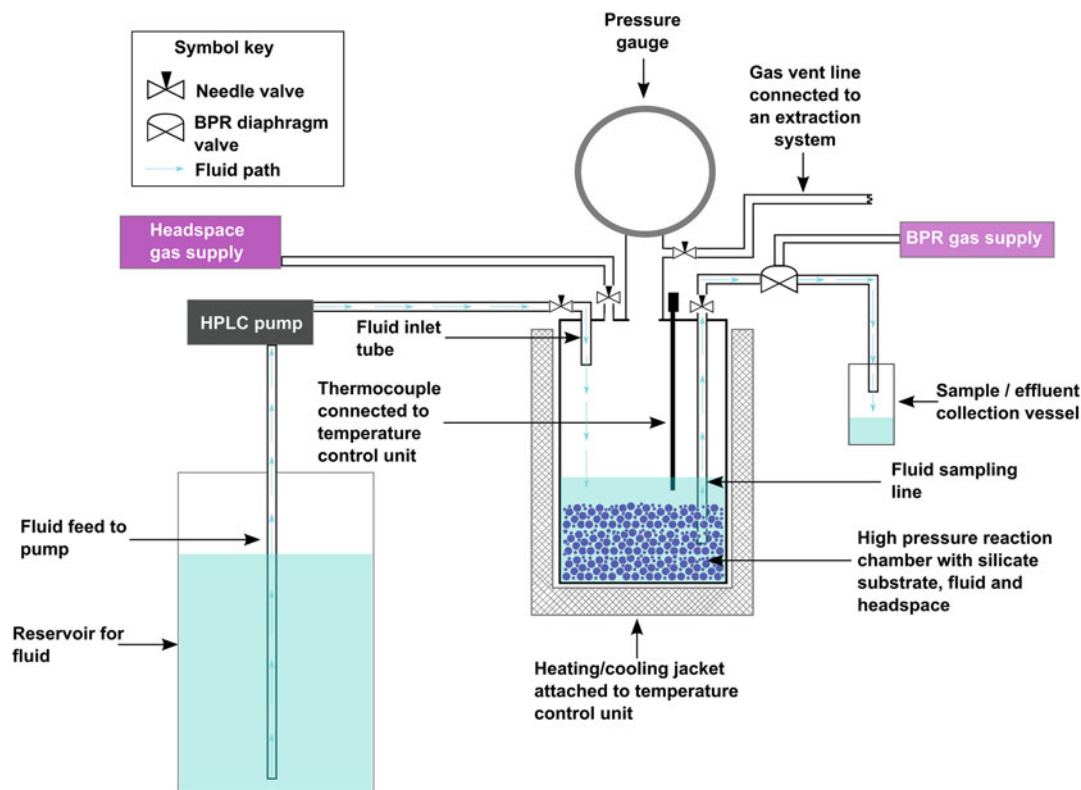
Celestial bodies within, and outside, the Solar System host a wide range of environments that vary significantly to those found on Earth today. Examples of this include, the subsurface of Europa where a temperature of 0 °C and a pressure of 1500 bar exist at the seafloor-ocean interface, or on Mars where the surface temperature

and pressure are on average −63 °C and 6 mbar, respectively, and the atmosphere is dominated by carbon dioxide. In addition, with the discovery of hundreds of planets orbiting other stars, the range of environments different to Earth's is potentially limitless. Such dissimilarities in conditions makes it difficult to understand how natural processes would proceed on these worlds and how these processes can influence their evolution or assess their habitability. Simulation chambers are an invaluable resource that are commonly used in space science and exploration. They have the ability to mimic multiple physical conditions, such as pressure, gas composition, irradiation, temperature, or humidity, as well as replicating aqueous systems under controlled settings, such as lacustrine environments. In addition to scientific investigations, simulation chambers are also used to assess the performance and function of spacecraft, including landers, exploration rovers, and their instruments under environments found in open space or on other planets and satellites. A wide variety of simulation chamber have been developed and optimized for specific conditions and environments, which have either been measured by spacecraft or are expected on planetary bodies.

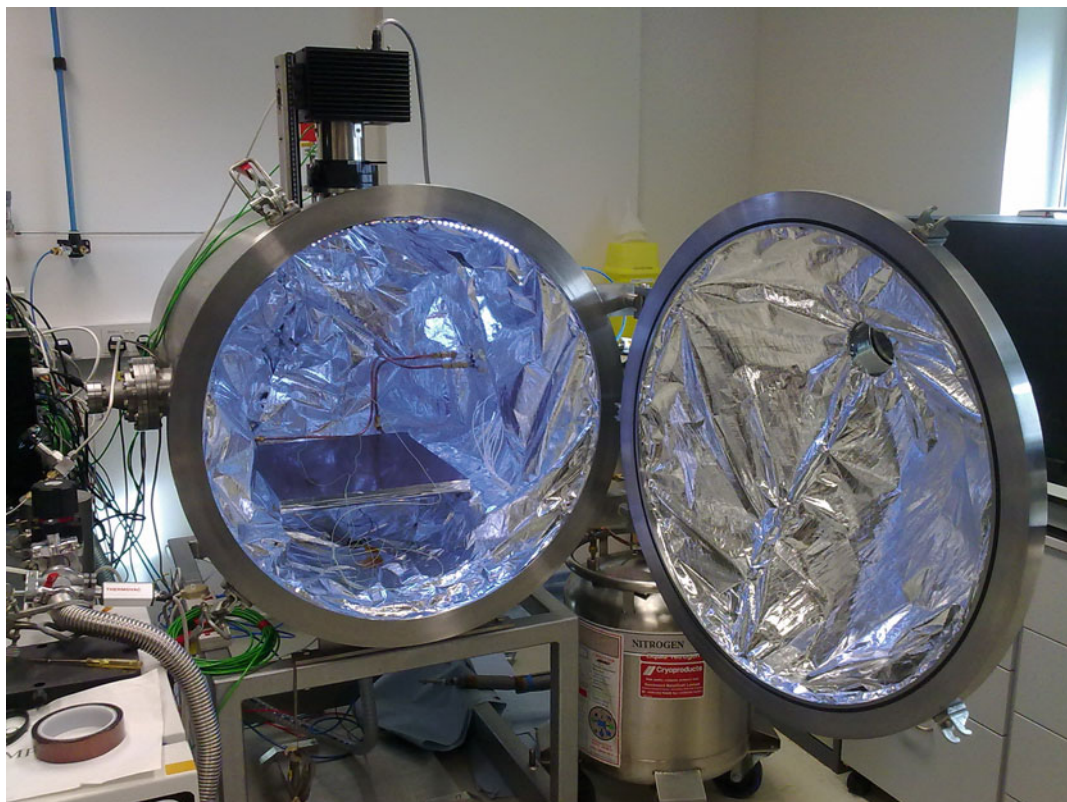
High pressure chambers are used to replicate the conditions identified on the surface of Venus (e.g., Lessis et al. 2019; Santos et al. 2021), and subsurface aqueous environments of bodies such as Mars and the icy moons, Enceladus or Europa (e.g., Olsson-Francis et al. 2020; Taubner et al. 2018), which are generally characterized by elevated temperatures and pressures. Such simulation chambers can use either an electric heating jacket or a fluid circulating thermal collar attached to a heater/chiller unit to maintain a constant temperature within the sample chamber (between −40 °C and +430 °C). While high pressures are achieved using either inert gases or gas mixtures, for example, a mixture of carbon dioxide, nitrogen, water vapor, carbon monoxide, and hydrogen chloride gas have been used to simulate the Venusian atmosphere (Llessis et al. 2019). Aqueous subsurface environments can be simulated either under static conditions to reflect

systems closed to incoming fluids (using the chambers described previously), or to allow the continuous flow of fluids through the reaction chamber, to reflect open aqueous systems that are commonly found in nature, such as river fed lakes or hydrothermal circulation. These open system chambers use a high-pressure pump to inject fresh fluid (from an external stock bottle) into the thermally controlled high pressure reaction chamber. An air-articulated back pressure regulator (BPR) is used to maintain a constant pressure within the chamber. As fresh fluid is added, the internal pressure of the chamber increases and causes the BPR to open and release the excess fluid, which is collected in an external effluent bottle (Fig. 1). These systems can be run under anaerobic and sterile conditions for long-term experimental runs (28 days; e.g., Ramkissoon et al. 2020), which are useful for exploring water-rock-atmosphere interactions and examining habitability.

Low pressure chambers are used to mimic the low atmospheric pressures observed on the surface of planets, such as Mars, in addition to those found on airless bodies, such as the Moon or asteroids. These types of bodies also experience variable temperatures (between -73°C and $+430^{\circ}\text{C}$) and exposure to UV radiation, which have also been incorporated into chambers to fully simulate surface conditions (Fig. 2). Chambers are evacuated using a vacuum pump to pressures between 1 and 1×10^{-10} bar, analogue atmospheric gases can be re-introduced to the chamber for low pressure environments. Sample holders are commonly cooled using liquid nitrogen to achieve temperatures as low as -180°C (e.g., Conway et al. 2011; dos Santos et al. 2016; Jensen et al. 2008; Richards et al. 2021; Sobrado et al. 2014), and heating jacket can also be applied to chambers to generate high temperature low pressure environments (e.g., Ramachandran et al. 2020). The attachment of a solar simulator or a



Simulation Chambers, Fig. 1 Schematic of a high pressure flow-through reaction chamber, which is used to simulate subsurface extra-terrestrial aqueous environments. (Source: Olsson-Francis et al. 2020))



Simulation Chambers, Fig. 2 Low pressure chamber for simulating the environmental conditions found on the surface of Mars. (Image credit: Manish Patel)

high-power UV lamp to the chamber exposes samples to high UV conditions that would be experienced on these planets, satellites, and asteroids. Other kinds of irradiation sources can also be used to simulate other stars than our Sun such as M-dwarfs (e.g., Claudi et al. 2016). In addition to allowing the exposure of different samples and taking measurements before and after, more and more chambers are also facilitate in situ monitoring of the samples via different devices (e.g., photosynthetic activity via fluorescence measurements; de Vera et al. 2014). Chambers have also been developed to simulate low pressure aqueous environments (Martin and Cockell 2015), which are similar to their high pressure counterparts. A high-performance peristaltic pump is used to feed fluid from an external stock bottle into the chamber, with excess fluid released via side arms on the chamber that connects to effluent bottles. Heater and chiller units are used to sustain a constant temperature within the chamber.

Cross-References

- [Enceladus](#)
- [Europa](#)
- [Exobiologie Experiment](#)
- [Exposure Facilities](#)
- [Mars](#)
- [Planetary and Space Simulation Facilities](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [UV Radiation, Biological Effects](#)

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SiN

- [Silicon Nitride \(SiN\)](#)

Single-Column Model

- [Atmospheric Modeling: 1D Model](#)

SiO

- [Silicon Monoxide \(SiO\)](#)

SIRTF

- [Spitzer Space Telescope](#)

SiS

- [Silicon Monosulfide \(SiS\)](#)

Skumanich Law

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

An empirical relationship, discovered by Andrew Skumanich in 1972, between the rotation rate of a star and its age is referred to as the Skumanich Law. The equatorial speed of a star at its equator falls as the inverse square root of the star's age, for ages between 100 Myr and 10 Gyr. This law has only been established for solar-type objects, i.e., main-sequence stars of spectral type G. Along

with the rotation rate, the surface activity of such stars, such as their X-ray emission, also declines in a similar manner. This activity arises ultimately from the star's surface magnetic field. Slowing of the rotation rate occurs because solar-type stars also emit winds. Such magnetized outflows carry off angular momentum.

Cross-References

- ▶ [Rotational Velocity](#)
- ▶ [Stellar Winds](#)

Slope Lineae, Recurrent

Alessandro Airo
Institut für Geologische Wissenschaften Tektonik
und Sedimentäre Geologie, Freie Universität
Berlin, Fachbereich Geowissenschaften, Berlin,
Germany

Synonyms

[Recurring slope lineae](#); [Seasonal dark flows](#);
[Warm season flows](#)

Definition

Recurring slope lineae (RSL) are seasonal dark markings on steep slopes (25–40°) that appear and progressively grow throughout the warm season and subsequently fade in the cold season (McEwen et al. 2011). RSL generally originate at rocky bedrock outcrops on slopes and are frequently associated with small channels. RSL have been found between 50 and 30°S latitude on slopes facing the equator and reaching surface temperatures during summer of up to 300 K. At these temperatures, liquid brines could develop close to the surface and percolate downhill through the subsurface pore space resulting in dark surficial “water tracks” that are known from Antarctic environments (Levy 2012). However,

the origin of these seasonal features on Mars remains debated.

Cross-References

- ▶ [Dark Streaks \(Mars\)](#)
- ▶ [Gullies](#)
- ▶ [Slope Streaks \(Mars\)](#)

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Slope Streaks (Mars)

Alessandro Airo
Institut für Geologische Wissenschaften Tektonik
und Sedimentäre Geologie, Freie Universität
Berlin, Fachbereich Geowissenschaften,
Berlin, Germany

Definition

Slope streaks are dark features extending usually a few hundred meters downslope in a fan-shaped fashion and are prevalent in equatorial, high-albedo, dust-covered regions on Mars. They were first identified on images taken by the Viking Orbiters in 1977 and more than two decades later the appearance of new slope streaks was discovered (Edgett et al. 2000). New slope streaks appear to form sporadically and independent of the season (Schorghofer and King 2011). Various mechanisms of their formation have been proposed, ranging from dry dust avalanches (Sullivan et al. 2001) to wet mass wasting (Kreslavsky and Head 2009).

Cross-References

- [Dark Streaks \(Mars\)](#)
- [Slope Lineae, Recurrent](#)

replaces the term “minor planet” which has been very often used as a synonym for asteroid but does not exist as an official term anymore.

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Cross-References

- [Asteroid](#)
- [Centaurs \(Asteroids\)](#)
- [Comet](#)
- [Dwarf Planet](#)
- [Kuiper Belt](#)
- [Near-Earth Objects](#)
- [Planet](#)
- [Satellite or Moon](#)
- [Trans-Neptunian Object](#)

Small Solar System Body

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Synonyms

[Minor planet](#)

Definition

According to IAU (International Astronomical Union) resolutions five and six (Resolution GA26-5-6), all objects that are neither a satellite, a ► [planet](#), nor a ► [dwarf planet](#) are to be considered a small solar system body (SSSB). This definition covers most of the ► [asteroids](#), ► [near-Earth objects](#) (NEO), ► [comets](#), ► [trans-Neptunian objects](#) (TNO) or ► [Kuiper belt](#) objects (KBO), and other small bodies. Small bodies are bare objects without stable atmospheres. Some of the icy small bodies (in particular the comets and the distant asteroids named Centaurs) have transient atmospheres when they come sufficiently close to the Sun. The temporary atmospheres are caused by sublimation of ices heated by the solar radiation. The term “small solar system body”

SNC Meteorites

Frank Sohl¹ and Tilman Spohn²
¹DLR, Institute of Planetary Research, Berlin, Germany
²International Space Science Institute, Bern, Switzerland

Synonyms

[Martian meteorites](#)

Definition

The SNC Meteorites are a group of petrologically similar ► [Achondrites](#) named after the locations where examples of these meteorites were first found – Shergotty (India), Nakhla (Egypt), and Chassigny (France). Subgroups are the shergottites, nakhlites, and chassignites. The term SNC meteorites is sometimes restricted to the shergottites, nakhlites, and chassignites but many times includes meteorites from other findings as well. SNC meteorites are basalts, and most of them are much younger than other meteorites – with an apparent age of 1.3 Ga or younger. Together, these findings suggest that the meteorite parent body was a planetary size object. The only

undisputed example of an old SNC meteorite is ► [ALH 84001](#) – found in the Allan Hills, Antarctica, in 1984 – which is 4.1 Ga old (Bouvier et al. 2009). Most researchers accept that SNC meteorites were part of the regolith layer of ► [Mars](#), as their composition is similar to that of the Martian regolith analyzed by space probes. Gas inclusions found in some SNC meteorites resemble the Martian atmosphere in isotopic composition. It is believed that these ► [Igneous Rocks](#) probably reached escape velocity (5.4 km/s) when a body impacted Mars and thus could leave its gravity field. Later, some of these ► [Rocks](#) got captured by *Earth's* gravity field and ended up as meteorites on Earth's surface.

Cross-References

- [Achondrite](#)
- [ALH 84001](#)
- [Basalt](#)
- [Chassigny](#)
- [Earth](#)
- [Igneous Rock](#)
- [Mars](#)
- [Meteorites](#)
- [Nakhlites](#)
- [Rock](#)
- [Shergotty](#)

References and Further Reading

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Snow Line

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Synonyms

[Frost line](#); [Ice line](#)

Definition

The snow line is the radial position within a ► [protoplanetary disk](#) where the conditions in the disk allow the existence of water ice. It implies in particular that the temperature is low enough and, equally important, that water (vapor or ice) is present in the same region. The snow line marks the transition between the inner region of the disk where water exists in the gaseous phase and the outer region of the disk where water condenses into solid ice particles. The position of the snow line changes with time and with the viscous dissipation assumed for the disk. In the ► [solar nebula](#) and other protoplanetary disks, this position is of great importance for understanding the formation and evolution of both giant and ► [terrestrial planets](#), due to the role of water as both a major constituent of the solid material in the disk and as the primary liquid medium on planetary surfaces and within planetary interiors.

Overview

The temperature structure of a protoplanetary disk is determined by both the accretion history of the disk as it forms from the stellar birth cloud and accretes onto the central star and the ongoing radiative heating from the central star itself. Viscous heating caused by accretion is mostly constrained to the midplane of the disk, so the radial temperature structure is primarily driven by heating from the central star and decreases from the inner disk to the outer disk. The inner regions of the disk can be heated by the central star to more than 5,000 K, while the outer regions of the disk beyond 50 AU can have gas and grain temperatures as low as 10 K, based on studies of comets in our own Solar System.

This substantial range in temperature encompasses the sublimation temperatures for many chemical species within the protoplanetary disk, leading to “condensation fronts” where a specific chemical constituent transitions from the gaseous phase to the solid phase. Refractory materials such as silicates have very high condensation temperatures and condense out in the inner disk, while volatile materials such as water and methane

condense out at larger distances from the central star. The condensation temperature for water in a low-pressure environment such as a protoplanetary disk is ~ 150 K; early models of the minimum-mass solar nebula suggested that this transition temperature would occur at 2.7 AU in our own Solar System, but since then the location and evolution of the snow line has been a topic of debate (see below).

The location of the snow line during the formation of planets in a circumstellar disk is important for several reasons. First, H_2O is thought to comprise at least half of the available solid material in a protoplanetary disk, based on thermochemical models of the solar nebula. Therefore, the density of solid material beyond the snow line will be much greater than the density of solid material within the snow line, leading to faster growth of planets and larger planetary cores beyond the snow line. This enhancement has been invoked to explain the fact that all the giant planets in our Solar System orbit beyond 5 AU – the larger planetary cores beyond the snow line were able to reach the critical mass for runaway gas accretion, while smaller planetary cores within the snow line never accreted significant gaseous atmospheres.

The location of the snow line is also important for constraining the source and abundance of water on the terrestrial planets, particularly Earth. If all the source material for the terrestrial planets formed within the snow line where the water content of planetesimals would be very low, there should be very little water on the surfaces or in the interiors of planets in the inner system. We clearly know of only one planet with a significant water fraction today (Earth), the Moon is essentially dry, and there may have been significant amounts of water on both Venus and Mars at the time of their formation; the origin of the water on Earth and the potential for water-rich terrestrial planets in other planetary systems are therefore an active area of research (see below).

Key Research Findings

The location of the snow line during the formation of the Solar System, and by extension other

planetary systems, is an area of active research. Hayashi (1981) first calculated the location of the snow line in the minimum-mass solar nebula to be at 2.7 AU; however, the calculation was only an energy balance between the solar radiation absorbed and re-emitted from a ► [blackbody](#) absorber. Since then our knowledge of the various heating and cooling processes in the solar nebula has advanced significantly, improving our ability to determine the temperature structure of the disk over time. Calculations by Sasselov and Lecar (2000) and Lecar et al. (2006) incorporated more recent models of protoplanetary disk structure and included heating from accretion and solar radiation and variations in condensation temperature with gas density. They found that for a minimum-mass solar nebula with low levels of accretion similar to observed protoplanetary disks, the snow line would lie between 1.6 and 1.8 AU; however, increasing the mass, the accretion rate, or the opacity of grains in the disk could move the snow line out as far as 3.5 AU.

The role of the snow line in aiding the formation of giant planets is also still under debate. The obvious increase in planet mass beyond 5 AU naturally correlates with the enhancement of solid material beyond the snow line, but this increased mass has been thought to be insufficient to overcome the long dynamical timescales for accretion in the outer Solar System; estimated timescales for unaided core accretion in the giant planet region were 10^7 – 10^8 years, much longer than the lifetime of gas in the solar nebula. Beginning with Stevenson and Lunine (1988), who postulated that water vapor in the disk would be redistributed to the snow line by eddy diffusion and lead to core formation at the condensation front, various researchers have invoked processes that could lead to a buildup of material at or near the snow line and lead to rapid core formation. Recent hydrodynamic simulations of giant ► [planet formation](#) with a more accurate treatment of the role of the expanding planetary atmosphere seem to suggest that no additional mechanism is necessary (Lissauer et al. 2009), but this does not rule out other enhancement processes.

The other active area of research relating to the snow line concerns the delivery of water

and other volatile material to the terrestrial planets. If the snow line was located beyond the orbit of Mars, as would be expected based on models and the water content of asteroids in the asteroid belt, then the bulk of the material that formed the terrestrial planets should have been very water poor. However, we know that the Earth has a water mass fraction of $\sim 0.1\%$, and there is evidence of significant past water flow on the surface of Mars over geologic time-scales. Researchers have debated whether the Earth's water was delivered primarily by comets from the Jupiter-Saturn region (e.g., Delsemme 2000) or by hydrated asteroids from the outer asteroid belt (e.g., Morbidelli et al. 2000), relying primarily on comparisons between the deuterium-to-hydrogen ratio (D/H) for Earth's water and that of different classes of Solar System bodies. More recent simulations of the final stages of the accretion of terrestrial planets have shown that water-rich asteroid-type planetesimals from 2 to 3 AU are naturally incorporated into terrestrial planets during the late stages of formation (Raymond et al. 2007; Bond et al. 2010).

Cross-References

- [Core Accretion, Model for Giant Planet Formation](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)
- [Solar Nebula](#)
- [Water, Delivery to Earth](#)

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Snowball Earth

Paul Felix Hoffman

School of Earth & Ocean Sciences, University of Victoria, Victoria, BC, Canada

Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA, USA

Keywords

Albedo · Atmospheric oxygenation · CO₂ hysteresis · Energy balance models · Fe-Mn ore deposits · Greenhouse effect · Ice grounding line · Ice sheet · Paleomagnetism · Radiative forcing · Geochemical carbon cycle · Silicate-weathering feedback · Volcanic-metamorphic outgassing · Multicellular animals

Synonyms

[Hard snowball](#); [Ice-albedo bifurcation](#); [Large ice-cap instability](#); [Panglacial](#)

Definition

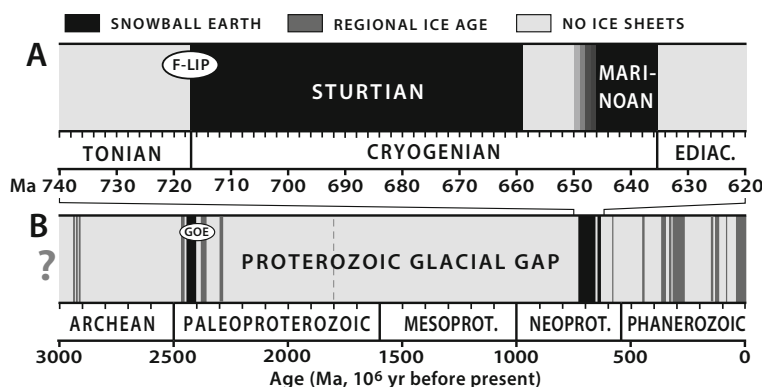
Planets with surface oceans are vulnerable to run-away glaciation due to a bifurcation in ice-line latitude caused by ice-albedo feedback. In the stable panglacial state, the oceans are covered everywhere by equatorward-flowing ice shelves

(sea glaciers) and continents are partially covered by slow-moving ice sheets fed by sublimation off the equatorial sea glacier. If such a planet is tectonically active, feedback in the geochemical carbon cycle may allow volcanogenic atmospheric CO_2 to slowly accumulate, in the absence of rainfall, to the point where greenhouse radiative forcing overcomes the high planetary albedo, leading to rapid total deglaciation and a transient hyperthermal aftermath, in which high CO_2 coexists with low surface albedo. Snowball Earth (Kirschvink 1992; Hoffman et al. 2017) postulates that the scenario just described occurred on Earth (Fig. 1), twice in rapid succession less than a billion years ago – 717–661 Ma (Sturtian) and 645(±5)–635 Ma (Marinoan) – and ~2.43 billion years ago (Makganyene), based on more fragmentary evidence.

History

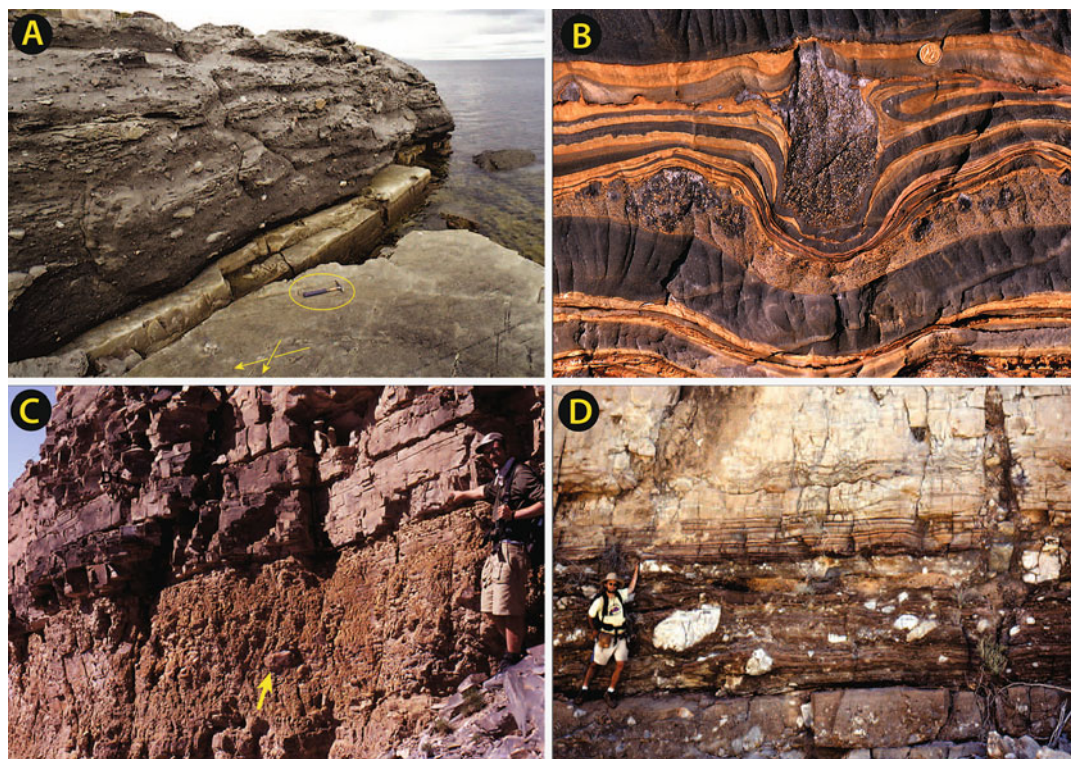
The globally widespread occurrence of “Eo-Cambrian” glacial deposits (Fig. 2) was first

recognized by Swedish geologist Oskar Kulling (1934), and their stratigraphic association in certain areas with nonskeletal marine carbonate rocks (Fig. 2b, d), which form preferentially in the warmest parts of the surface ocean. The ice-albedo bifurcation (Fig. 3a–b) was revealed at the end of 1960s by physical climatologists. The panglacial state was initially assumed to be irreversible and therefore not geologically relevant. This changed when planetologists Walker et al. (1981) pointed out that a panglacial state on Earth would likely be self-reversing due to negative feedback in the geochemical carbon cycle (Fig. 3c–d). American paleomagnetist J.L. Kirschvink (1992) was the first to apply the concept of a self-reversing ice-albedo bifurcation to the geologic record, inspired by paleomagnetic evidence of low paleolatitude for Marinoan tidewater glacial deposits in South Australia. Kirschvink (1992) coined the term Snowball Earth, alluding to its appearance from space, and posited three occurrences in the geologic record (Fig. 1): Marinoan, Sturtian and Makganyene (Kirschvink et al. 2000); each being represented by non-Alpine



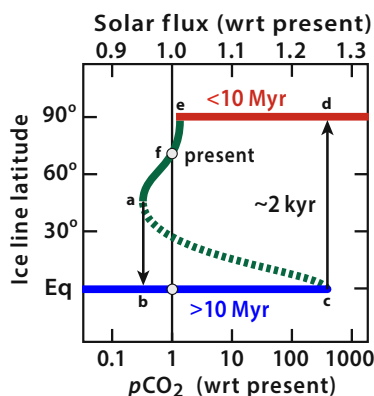
Snowball Earth, Fig. 1 Climate states on Earth since 3.0 Ga, the limit of the quasi-continuous sedimentary record (Hoffman et al. 2017). Three equilibrium states are (1) Snowball Earth (see Definition in the text), (2) regional high-latitude ice sheets, ice shelves, and sea ice, (3) absent non-alpine glaciers and ice sheets. (a) 740–620 Ma (10^6 year before present). Black bands indicate radiometrically determined durations of Sturtian and Marinoan Snowball Earths (Rooney et al. 2015; Zhou et al. 2019). Graded start to Marinoan denotes chronometric uncertainty, not gradual onset. Ellipse F–LIP (Franklin Large Igneous Province, NW Canada) shows possible age span of flood-basalt volcanism on the paleo-equator, coincident with Sturtian onset

(Macdonald et al. 2010, 2018) and postulated as a climate-change driver (Cox et al. 2016b; Macdonald and Woodward 2017). (b) Climate states on Earth since 3.0 Ga: Snowball Earths (black), regional ice sheets (medium grey), no ice sheets (light grey). Ellipse GOE is centered on the Great Oxidation Event, as recorded by the disappearance of mass-independent S isotope fractionations ≥ 0.3 per mil in non-detrital sedimentary sulfide and sulfate minerals (Farquhar and Wing 2003). Dashed gray line at 1.8 Ga indicates possible glaciation (Williams 2005) within a 1.5-Gyr non-glacial interval. (Modified after Hoffman et al. 2017)



Snowball Earth, Fig. 2 The sedimentary record of Snowball Earth. (a) Evidence of dynamic glacial action: classic exposure described and interpreted by Reusch (1891) as a glacial moraine (upper left), deposited on a subglacial bedrock (quartzite) pavement on which two intersecting sets of striations (arrows) indicate successive ice flow directions at Bigganjar'ga, Varanger Peninsula, Finnmark, North Norway. View looking eastward with 0.33-m-long hammer (circled) for scale. The glacial features here were later shown to be Marinoan in age (Edwards 1984; Rice et al. 2012) and indicate that net snow accumulation was sufficient to generate glaciers that flowed by meltwater-lubricated basal sliding. Sturtian and Marinoan glaciation was recognized early on in the North Atlantic region, where geologists were familiar with Quaternary and active glaciers and glacial products. (b) Evidence of glacial action in tropical seas. Marinoan carbonate turbidites and debrite with an ice-rafted dropstone (center) composed of oolitic limestone that depressed the underlying layers upon impact, ejected the doubly-folded layer (below 2-cm-diameter coin) at the surface when impact occurred, and was subsequently draped and buried by post-impact layers (under coin). These subaqueous deposits are composed of glacially-eroded carbonate detritus that accumulated near the grounding line of a floating ice shelf (Domack and Hoffman 2011), which melted basally releasing trillions of dropstones. The oolitic limestone was eroded from a falling-stand carbonate wedge formed during sea-level fall due to ice buildup at higher latitudes during the Marinoan glacial inception. Ghaub Formation (Otavi Group) on the foreslope of a long-lived

marine carbonate platform, near Fransfontein, Kunene Region, Namibia. In this area, both Sturtian and Marinoan glacial deposits occur within a thick shallow-water carbonate succession that accumulated in a relatively warm part of the ancient surface ocean. If the warmest areas were glaciated, colder regions must have been frozen as well. (c) Sturtian cap carbonate in Zavkhan terrane west of Taishir, western Mongolia (Bold et al. 2016; Rooney et al. 2015). Orange-weathering stratified glacial marine deposits (Maikhan Uul Formation) with ice-rafted debris (arrow) are sharply overlain without evident hiatus by dark gray, organic-rich, fossiliferous limestone (basal Taishir Formation). Abrupt onset of carbonate sedimentation is typical of Sturtian and Marinoan glacial terminations. Geologist at right for scale. (d) Marinoan cap carbonate in Namibia (Hoffman 2011). Drape of stratified carbonate debris with ice(berg?)-rafted dropstones (Ghaub Formation, Bethanis Member), recording terminal deglaciation, is sharply overlain without evident hiatus by pale pinkish to buff colored micropeloidal dolostone (Keilberg Member of Maieberg Formation). Note abrupt termination of carbonate debris at the base of the cap dolostone (by geologist's left hand). The cap dolostone extends far beyond the area of glacial deposits, which are mainly localized on the narrow foreslope of a vast ($>2.10^8$ m²) glacially-eroded marine carbonate platform. Average depth of Marinoan glacial erosion was <10 m. Cap carbonates are products of slow snowball ocean acidification and buffering, followed by rapid ocean warming, shelf flooding, loess weathering, and deacidification. (Images taken by author PF Hoffman)

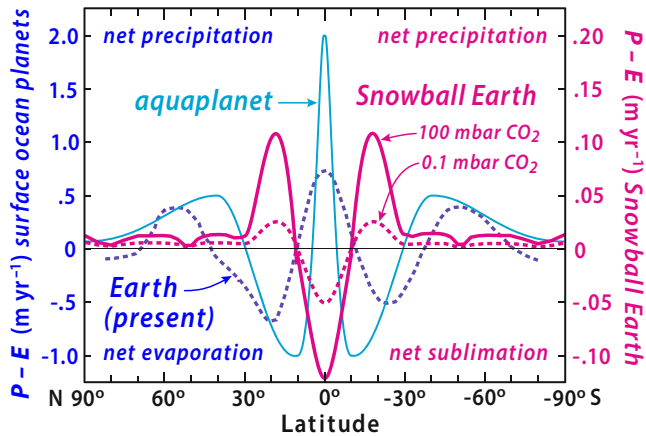


Snowball Earth, Fig. 3 Generic bifurcation diagram illustrating the Snowball Earth hysteresis loop (Hoffman et al. 2017). Ice-line latitude as a function of solar or equivalent CO_2 radiative forcing in one-dimensional (meridional) energy-balance models (Budyko 1969; Sellers 1969; North et al. 1981). Three stable branches (red, green, and blue) are separated by an unstable regime (dashed). Yellow dots are stable climates possible with present-day forcing. Black arrows indicate non-equilibrium transitions. In response to lower forcing, ice line migrates equatorward to the ice-albedo instability threshold (a), whereupon the ice line advances uncontrollably to the equator (b). With reduced sinks for carbon, normal volcanic outgassing drives atmospheric CO_2 higher over millions to tens of millions of years (Le Hir et al. 2008b) until it reaches the deglaciation threshold (c). Once the tropical ocean begins to open, ice-albedo feedback drives the ice line rapidly poleward to (d), where high radiative forcing combined with low surface albedo creates a transient hyperthermal climate with global mean sea-surface temperature ~ 323 K (Yang et al. 2017). Intense silicate weathering and organic burial lower atmospheric CO_2 in $\sim 10^7$ years (Mills et al. 2011) to (e) the threshold for reestablishment of a polar ice cap. The hysteresis loop (a→f) predicts that Snowball Earth epochs were long-lived (b→c), began synchronously at low latitudes (a→b), and ended synchronously at all latitudes (c→d) under extreme CO_2 radiative forcing. The ocean is predicted to undergo severe acidification and deacidification in response to the CO_2 hysteresis (Higgins and Schrag 2003; Le Hir et al. 2008b). Qualitatively similar hysteresis is found in three-dimensional general circulation models. $p\text{CO}_2$, partial pressure of CO_2 ; wrt, with respect to. (Modified after Hoffman et al. 2017)

glacial deposits formed at low paleomagnetic latitudes. Geologists broadly accepted the snowball Earth concept after radiometric geochronology established that the postulated glaciations were long-lived and globally synchronous (Rooney et al. 2015; Zhou et al. 2019).

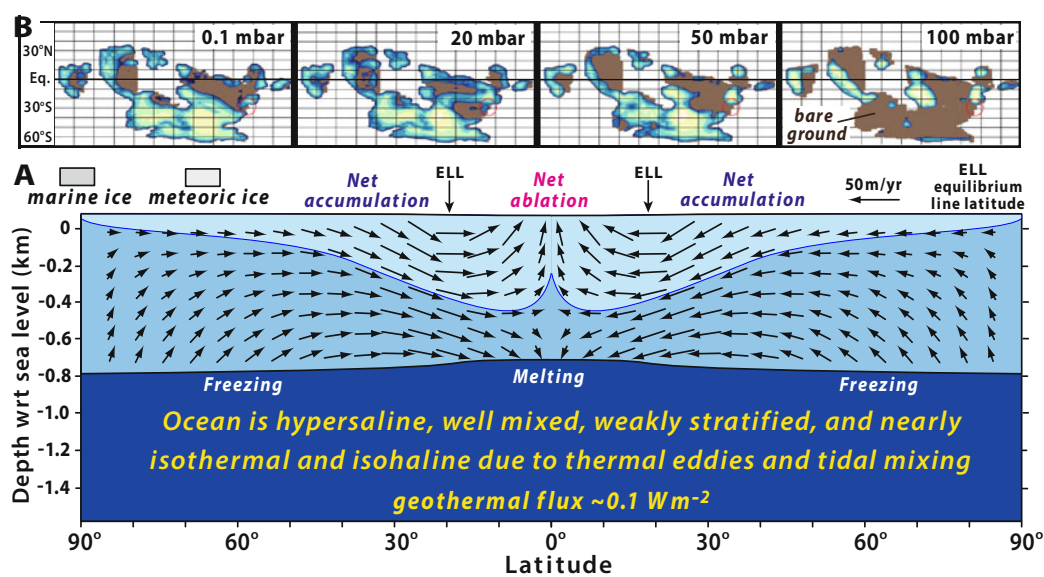
Basic Methodology

Since postulated climatic boundary conditions during a Snowball Earth and its hyperthermal aftermath lie far outside geologic norms, improved theory is needed to properly ascertain the predicted consequences, and intelligently investigate the geologic record (Pierrehumbert et al. 2011; Hoffman et al. 2017). The basic bifurcation has been investigated in coupled atmosphere–ocean–sea ice general circulation models (see Abbot et al. 2013; Hoffman et al. 2017), as have the viabilities of low-latitude marine ice margins (Rose 2015). The low temperature and solid surface of the panglacial state dictate a shallow troposphere and vigorous Hadley circulation above a surface with little thermal inertia (Pierrehumbert 2005; Voigt and Abbot 2012; Voigt 2013). The result is a weak hydrologic cycle in which net equatorial sublimation in the annual mean drives net meteoric accumulation elsewhere (Fig. 4), principally in the subequatorial zones (Abbot et al. 2013). Thus, the water balance between the equatorial and subtropical zones is reversed, relative to any climate state with liquid surface water. Tropical surface winds are strong, but boundary-layer inversions, due to surface heat loss by radiation, decouple the winds from the surface in the winter hemisphere (Pierrehumbert 2005; Pierrehumbert et al. 2011). Atmospheric aerosols and clouds have net warming effects that make deglaciation possible and may dictate its timing once CO_2 levels are high (Abbot 2014). After the tropical ocean becomes ice covered at a panglacial onset, marine ice thickens to roughly 10^3 m within a few 10^4 years (Fig. 5a), with as little as 10% difference between polar and equatorial ice thickness, due to sea-glacier flow (Tziperman et al. 2012). Thin ice is generally precluded by glacial inflow, but may occur in constricted seaways and silled basins where situated in the equatorial zone of net ablation. The sea glacier becomes thinner in response to CO_2 rise, but the change may be smallest at the equator if thickness gradients flatten as the ice warms and softens (Tziperman et al. 2012; Abbot et al. 2013). Continental ice sheets thicken more slowly after panglacial onset, depending on topography, but



Snowball Earth, Fig. 4 Zonal mean precipitation minus evaporation/sublimation as a function of latitude on present Earth (blue dashed), an aquaplanet (blue solid) under the same boundary conditions, and Snowball Earth (magenta) with 94% Solar luminosity and 0.1 (dashed) or

100 (solid) mbar CO₂ (generalized from Abbot et al. 2013). Note equatorial desert in Snowball Earth, with subtropical maxima in net precipitation and absence of polar deserts. Note scale difference for Snowball Earth. (Original figure by author PF Hoffman)



Snowball Earth, Fig. 5 The cryosphere on Snowball Earth. (a) Sea glacier steady-state thickness and flow lines in a prescribed Snowball aquaplanet that is relatively warm (i.e., high CO₂) and has a spatially uniform surface dust flux of 1 m Myr⁻¹ and uniform ice albedo (Li and Pierrehumbert 2011, Goodman and Pierrehumbert 2003). The sea glacier consists of meteoric ice (compressed snow) and marine ice (frozen seawater): exposure of lower-albedo marine ice causes warming and thinner ice. Adjusting surface albedo for dust accumulation results in thinner ablation-zone ice (Fig. 7b) and non-steady state pulses of

equatorial sea-glacier invasion (Goodman and Strom 2013). (b) Changes in ice-sheet mass balance in response to variable CO₂ radiative forcing in an ice-sheet-atmosphere general circulation model with Marinoan paleogeography and a totally ice covered ocean (Benn et al. 2015). Note the increase in ice-free land area as CO₂ rises, and its concentration in areas where intense Hadley cells generate strong seasonal surface winds and dust plumes (Voigt 2013; Pierrehumbert et al. 2011). (Modified after Hoffman et al. 2017)

reach dynamic steady state within a few 10^5 years (see Benn et al. 2015). This implies that glacial erosion and sedimentation were ongoing through 99% and 96% of the Sturtian and Marinoan epochs, respectively. Net sea-level falls of $\sim 5 \cdot 10^2$ m occur on most continental margins, despite the countervailing effects of ice gravity and isostatic adjustments (Benn et al. 2015, among others). As CO_2 rises, ice-sheet mass balance becomes sensitive to orbital forcing, causing ice-margin migrations of $\leq 5 \cdot 10^5$ m on a precessional ($2 \cdot 10^4$ year) time scale (Benn et al. 2015). Although ice sheets flow faster as CO_2 rises, their area and mass contract (Fig. 5b), leaving increasingly large fractions of tropical land area free of glacial ice (Benn et al. 2015). The only heat received by the subglacial ocean is geothermal: heat is lost at the top by diffusion through the ice cover (Jansen 2016). The Snowball ocean is consequently well mixed by eddies and is nearly isothermal and isohaline (Ferreira et al. 2011; Ashkenazy and Tziperman 2016; Jansen 2016). It is weakly stratified because isopycnal surfaces incline toward the poles, where heat dissipation is greatest through the nearly uniform-thickness ice shell (Jansen 2016). Tidal mixing is also strong in the absence of dissipation on continental shelves, which are ice covered or emergent. Zonal jets occur close to the equator at shallow depths beneath the sea glacier, and pulsating cavities of thinner ice develop on basin margins where such jets are directed offshore (Ashkenazy and Tziperman 2016). Whereas atmospheric dynamics on Snowball Earth have parallels with Mars, ocean dynamics have much in common with the Arctic Ocean. The role of seafloor weathering in CO_2 consumption on Snowball Earth, was investigated by Le Hir et al. (Le Hir et al. 2008a, b). Since basalt weathering rates are pH dependent at low temperature, seafloor weathering should not prevent early CO_2 rise on a Snowball Earth, but it could delay final deglaciation by limiting CO_2 rise (Le Hir et al. 2008b).

Key Research Findings

A key advance has been the development of a radiometric chronology (Fig. 1 and first paragraph) for Sturtian and Marinoan glaciation

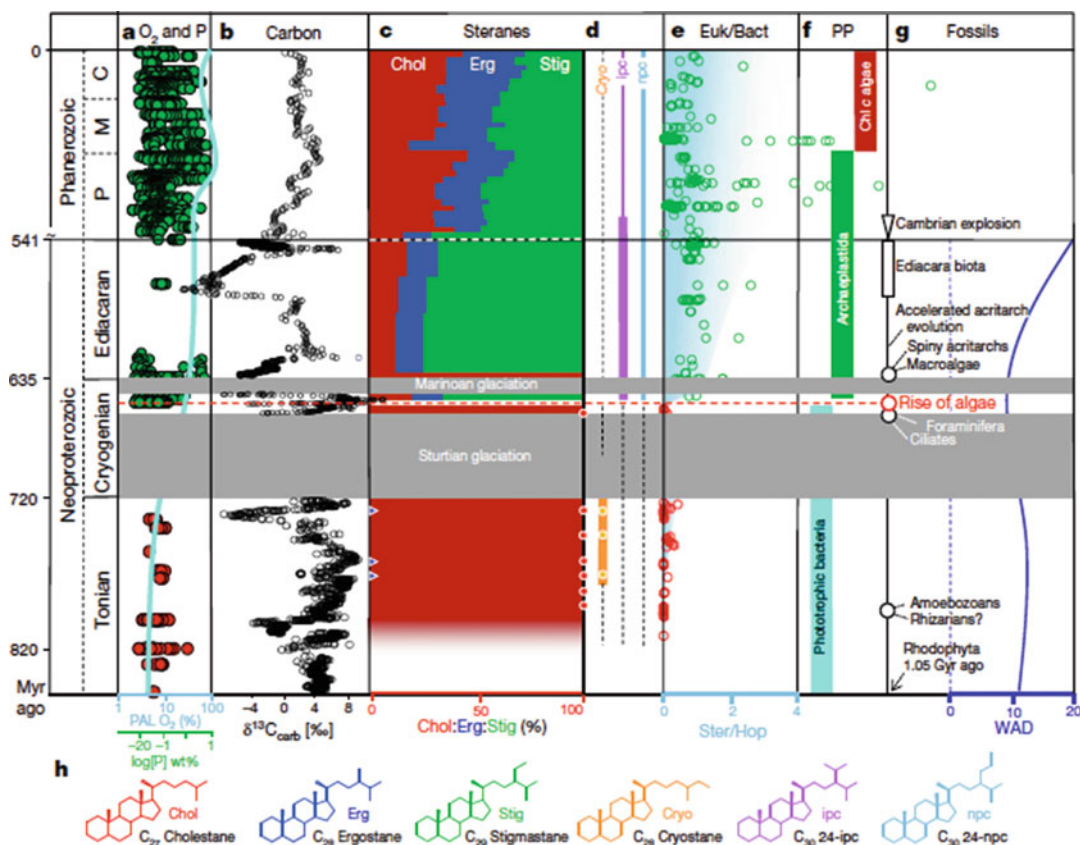
(Rooney et al. 2015; Prave et al. 2016; Zhou et al. 2019). Strong predictions of the Snowball scenario – prolonged (106–108 year) glaciation at low latitude (Fig. 3b–c) and synchronous deglaciation globally (Fig. 3c–d) – are supported for both (Rooney et al. 2015). The chronology permits comparison of their average sediment accumulation rates with younger high-latitude glaciations of comparable duration. Sturtian and Marinoan accumulation rates were 3–10 times slower, reflecting the weak hydrologic cycle and slow-moving ice sheets on Snowball Earth. Sturtian and Marinoan deglaciations are uniquely associated with globally extensive carbonate deposits called “cap carbonates” (Fig. 2c, d) having unusual sedimentological and geochemical attributes (Hoffman and Schrag 2002; Shields 2005; Hoffman et al. 2017). Severe ocean warming, meltwater production, terrestrial and seafloor weathering, shelf flooding and vertical mixing are all implicated in their origin and alteration (Shields 2005; Yang et al. 2017; Ahm et al., 2019). Sturtian and Marinoan cap carbonates are quite distinct. The latter contain barite (BaSO_4) of sea-floor and shallow-subsurface origin, in which sulfate-oxygen isotope anomalies produced by photochemical reactions in the stratosphere record extreme atmospheric CO_2 relative to (non-negligible) O_2 concentrations (Cao and Bao 2013) and rapid global deglaciation. Many workers assume that slow acidification of the subglacial ocean was buffered by dissolution of detrital carbonate delivered by tropical glaciers (Higgins and Schrag 2003; Le Hir et al. 2008a, b), but rapid ocean acidification upon deglaciation has been inferred from boron-isotope pH proxy data. Expanded meridional extent of cap carbonate and profuse crystallization of benthic aragonite (orthorhombic CaCO_3) at thermocline depths indicate anomalous carbonate oversaturation during Marinoan deglaciation. A comprehensive theory for cap carbonates is the supreme challenge and ultimate reward of the Snowball Earth hypothesis. Numerous occurrences of sedimentary iron formation imply that Sturtian oceans were anoxic and ferruginous (Kirschvink 1992; Cox et al. 2016a). Their co-occurrence with ice grounding-line deposits implicates subglacial meltwater discharge as an

oxidant source. The more ancient Makganyene event involved non-Alpine glaciation at low ($11\pm4^\circ$) paleolatitude around 2.43 Ga in South Africa, but the duration and extent of this glaciation remain to be determined. Multiple glaciations occurred between 2.2 and 2.5 Ga on different paleocontinents, but existing radiometric constraints do not require strict contemporaneity. The Makganyene glaciation appears to stratigraphically predate the Great Oxidation Event, contrary to suggestions that glaciation was caused by oxidative collapse of a methane-supported greenhouse, but potentially consistent with Snowball-induced oxygenation. Extreme isotopic depletions in oxygen and hydrogen, widely observed in 2.2–2.5-Ga crustal rocks in Arctic Europe, which then arguably lay in low latitudes, could be a record of subglacial recharge of groundwater on a Snowball Earth (Bindeman and Lee 2018). Existing chronology suggests that depleted groundwater existed in Arctic Europe around Makganyene time and again ~ 2.29 Ga (Zakharov et al. 2017), potentially correlative with the younger Rietfontein glaciation in South Africa.

Ongoing Research: Biological Consequences

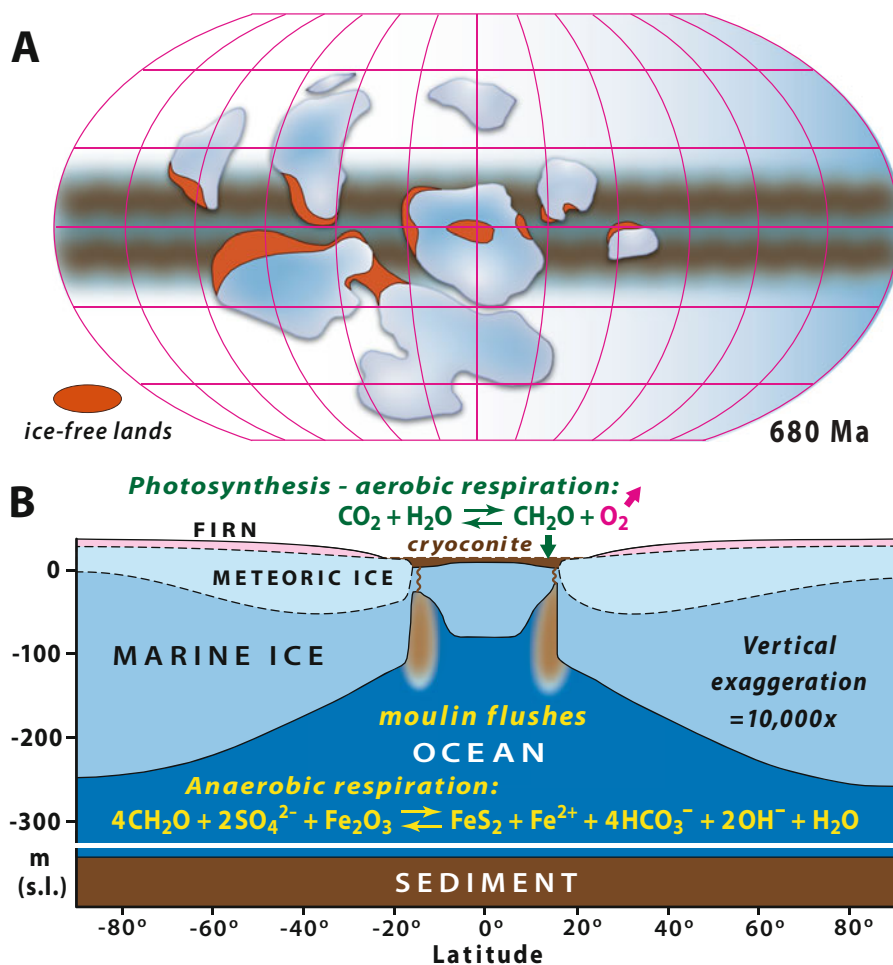
The biological consequences of any given Snowball Earth are not predictable from existing evolutionary theory. The physical microfossil record indicates a prolonged (10^8 year) minimum in within-assemblage diversity and age-scaled species richness that began $\leq 2.10^7$ year before Sturtian onset and ended $\leq 3.10^6$ year after Marinoan termination. The emerging molecular biomarker record from indigenous sediment-hosted bitumens and oils is revelatory (Fig. 6). A revolution in marine primary production occurred, not in the immediate Sturtian aftermath but within the 10–15 Myr nonglacial interlude before the Marinoan. It is recorded by a stepwise increase in sterane/hopane ratio (Fig. 6e) (i.e., algal versus bacterial production), in abrupt first appearances of stigmastane (C_{29}) and ergostane (C_{28}) as predominant steranes (Fig. 6c), and isopropyl- and n-propyl-cholestane (C_{30}) in trace amounts (Fig. 6d) (Brocks 2018; Gold 2018, among others). The major steranes record the ascendance of green algae as major marine primary producers, an hegemony among eukaryotes

they would retain until the Mesozoic rise of secondary endosymbiotic (chlorophyll *c*) algae (Brocks 2018; Gold 2018). Despite the exclusion of phototrophism beneath a sea glacier, supraglacial meltwater-associated cyanobacterial mats, made possible by surface-darkening dust (cryoconite), would have created oligotrophic ecosystems on Snowball Earth in which select eukaryotic (green) algae, fungi, protists and possibly even metazoans survived, grew and evolved (Vincent et al. 2004). Such freshwater ecosystems would have greatly expanded in response to Snowball Earth. Strong surface winds (Pierrehumbert 2005; Voigt and Abbot 2012) and orbitally-driven waxing and waning of ice sheets (Benn et al. 2015) ensured ample supplies of dust, which sea-glacier flow would have delivered to the ablative ice surface (Fig. 5a), creating an equatorial zone dotted by cryoconite holes, ponds and streams over $\sim 12\%$ of global surface area (Hoffman 2016). In addition, glacier-free land areas would have held ice-covered meromictic (salt-stratified) brine lakes, where oligotrophic phototrophs including benthic mat-forming cyanobacteria and planktonic picocyanobacteria (*Synechococcus*) now preside in polar deserts (Sumner et al. 2016). It is perhaps not surprising, therefore, that relaxed molecular clock analysis suggests that major groups of modern marine cyanobacteria, including nitrogen-fixers and the syn-pro clade of planktonic picocyanobacteria, which dominate the oligotrophic subtropical gyres of modern oceans and account for $\sim 5\%$ of total organic productivity (Zehr et al. 2017), have last common ancestors of roughly Sturtian–Marinoan age (Sanchez-Baracaldo 2015). Moreover, trait evolution analysis suggests that they stemmed from freshwater lineages (Sanchez-Baracaldo 2015). Nitrogen isotope fractionations in Marinoan glacial marine sediments indicate active nitrogen cycling, suggesting that cyanobacterial nitrogen cycling in modern polar and alpine environments (Fernandez-Valiente et al. 2001; Cameron et al. 2012) might not be a recent adaptation. More intriguingly, certain cyanobacterial clades appear on molecular phylogenetic grounds to have cold-tolerant basal groups and derived groups in other environments, the cosmopolitan genus *Nodularia* being a potential example (Christmas et al. 2015).



Snowball Earth, Fig. 6 Time chart for 850 Ma to present environmental, biomarker, and fossil data highlighting the position of the rise of algae (figure and caption from Brocks et al. 2017; data sources referenced therein). Note the condensed time scale after 541 Ma. (a) Speculative trajectory of atmospheric O_2 (turquoise) and P concentrations in shales before (red) and after (green) the rise of algae (dashed red line). (b) Marine carbonate C isotopes in permil relative to Vienna Pee Dee Belemnite. (c) Relative abundances of steranes: cholestane (red), ergostane (blue), and stigmastane (green) in 20-Myr-time bins. Red circles indicate average cholestane abundances and blue triangles denote isolated occurrences of ergosteroids before the algal rise, based on data from ten formations in Oman, Australia, USA, and Sweden. No reliable sterane record exists before 800 Ma. Note algal gap in each Snowball aftermath. (d) Occurrence of unusual steranes (see h for structures; dashed lines indicate absence). Cryostane (26-methylcholestane) is restricted to pre-Sturtian time and its biological source is unknown, but the only extant organisms that have the biosynthetic capacity to methylate sterol in the 26-position are demosponges (Brocks et al. 2015). 24-ipc is regarded as a biomarker for demosponges (Love et al. 2009; Gold et al. 2016 [but see Bobrovskiy et al.

2020]). It emerges after the Sturtian aftermath but before Marinoan onset (Love et al. 2009) and remains abundant throughout the Ediacaran (635–541 Ma). 24-npc also emerges before Marinoan onset, revealing the activity of rhizaria (a group that includes foraminifera and radiolarians). (e) The relative contribution of eukaryotic (Euk) and bacterial (Bact) lipids to sedimentary organic matter approximated by the sterane/hopane ratio (Ster/Hop) before (red) and after (green) the rise of algae. (f) Succession of dominant primary producers (PP) in the oceans: bacterial phototrophs were dominant before the rise of primary endosymbiotic algae (Archaeplastida), heralded by sharply increasing sterane/hopane ratios and the emergence of abundant ergostane and stigmastane. Archaeplastids were replaced as the dominant algae after the Permo–Triassic mass extinction by secondary endosymbiotic (chlorophyll c) algae as recorded by rising ergostane/stigmastane ratios. (g) First occurrences of eukaryotic groups in the fossil record, Blue line is the mean within assemblage diversity (WAD) of unique eukaryotic species or morphotypes per stratigraphic unit (Cohen and Macdonald 2015). (h) Color-coded sterane structures. (From Brocks et al. 2017)



Snowball Earth, Fig. 7 Supraglacial meltwater ecosystems on Snowball Earth (modified after Hoffman 2016). (a) Global paleogeography during the Sturtian Snowball Earth at 680 Ma. Continental ice sheets outlined. Reddish areas schematically indicate dry-valley dust sources (Abbot and Halevy 2010; Benn et al. 2015) and brownish areas indicate the sea-glacier ablation zone where glacially-advected dust accumulates as cryoconite (Abbot and Pierrehumbert 2010; Li and Pierrehumbert 2011; Goodman and Strom 2013), creating oligotrophic meltwater-associated ecosystems capable of supporting cold-tolerant cyanobacteria, green algae, fungi, unicellular heterotrophs, and even certain metazoans (Vincent et al. 2000, 2004; Christner et al. 2003; Hawes et al. 2018). (b) Snapshot of a two-dimensional ice flow model of Snowball Earth with a global dust accumulation rate of 10 m Myr^{-1} (Goodman and Strom 2013). Dark cryoconite (mineral dust suffused with deeply-pigmented extracellular polymeric substances copiously secreted by cyanobacteria) and exposed low-albedo marine ice make the sublimative

ice warm and thin. Hemispheric asymmetry at low latitudes reflects unsteady, quasi-periodic, reciprocal ice surges from the respective subtropics in the model (Goodman and Strom 2013). Flushing of meltwater through moulins is shown schematically. The apparent ice walls at 18° latitude have actual slopes of 1 m km^{-1} . Organic production and aerobic respiration are nearly balanced within cryoconite holes and pans. Flushed cryoconite organic matter (typically 10 wt%) is subject to anaerobic respiration in the water and sediment columns. Fe(III) and sulfate are sourced from the flushed cryoconite and oxidative sub-ice sheet weathering. Assuming coldwater anaerobic respiration is incomplete, organic matter is buried, and O_2 is added to the atmosphere, as is required to offset O_2 consumption by volcanic SO_2 and H_2S emissions and sea-floor weathering (Hoffman 2016). Redox proxy evidence supports transient oxygenation in the Sturtian aftermath (Pogge von Strandmann et al. 2015; Lau et al. 2017). (Modified after Hoffman et al. 2017)

Future Directions

An outstanding question concerns the grossly unequal durations of the Sturtian and Marinoan Snowballs, 58 and 5–15 Myr respectively (Fig. 1). Is this difference related in any way to their contrasting geochemical attributes – syn-glacial sedimentary iron-formations are (nearly?) all Sturtian, whereas barite and seafloor aragonite occur in cap carbonates only of Marinoan age (Hoffman et al. 2011)? The brief nonglacial interlude, 15 ± 5 Myr, is in the estimated range for post-Sturtian CO₂ drawdown. Was Marinoan onset simply the return to ambient conditions at Sturtian onset, 72 ± 5 Myr earlier? If so, why was post-Marinoan glaciation delayed for 55 Myr? How close did we come to a Carboniferous Snowball Earth (Feulner 2017), and how might that have changed the history of life? Also unresolved are the causal factors for each Snowball Earth inception. Paleogeographic factors like supercontinent breakup could cool the climate through enhanced weathering and organic burial (Donnadieu et al. 2004), but while Sturtian–Marinoan glaciation did accompany such a breakup (Zhang et al. 2013), supercontinents broke up at other times without severe glacial response. Contemporaneity of Sturtian onset (Fig. 1) with equatorial flood-basalt emplacement supports enhanced silicate weathering (Cox et al. 2016b; Godderis et al. 2003) and stratospheric aerosol injection (Macdonald and Wordsworth 2017) as potential factors, but the Marinoan and Makganyene are not known to have had volcanic outbursts at their inceptions. Biological innovations have been advanced as causal factors also (e.g., Feulner et al. 2015; Isson and Planavsky 2018), but correlation with unique events is frustratingly not subject to induction in nature.

Cross-References

- Cyanobacteria
- Glaciation
- Gondwana
- Great Oxidation Event
- Mass Extinctions

- Oceans, Chemical Evolution of
- Oxygenation of the Earth's Atmosphere
- Proterozoic Eon

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SO

- [Sulfur Monoxide \(SO\)](#)

Social Studies of Science and Technology

- [Social Study of Science](#)

Social Study of Science

Klara Anna Capova
Department of Anthropology, Durham University,
Durham, UK

Acronyms

STS Science and Technology Studies, also
Science, Technology and Society

Synonyms

[Anthropology of science](#); [Science and society studies](#); [Science studies](#); [Social studies of science and technology](#); [Sociology of science](#)

Definition

Social study of science, or science and technology studies (STS), also anthropology of science and technology, is an interdisciplinary field of social sciences concerned with the roles of sciences and technologies in society, conditions and context under which scientific knowledge and technological advancements are produced, and with social changes and societal impacts they make.

Overview

The social studies of science and technology developed from the tradition of sociology, history, and philosophy of science (i. e., Russell 1951; Kuhn 1962). Taking sciences and technologies as objects of a critical study, these new fields of social research approached sciences as historically, socially, politically, and culturally situated local practices rather than uniform, universal, and value-neutral processes of knowledge production (Jasanoff 1995; Martin 1998). The ethnographic and historical studies of science provide accounts of the works of scientific communities and social context of inventions (e.g., Latour 1987; Traweek 1988; Rabinow 1996), showing how science is socially embedded and positioned in the configuration of scientific, technological, cultural, social, economic, political, and legal elements.

As a newly formed interdisciplinary and multi-disciplinary field of scientific practice and knowledge production, astrobiology as a science presents new directions for the social study of science. Namely, the epistemological issue emerges regarding its disciplinary boundaries and the very status of astrobiology as a science. Astrobiology has contemporary societal implications and relates to topics of a cultural, ethical, educational, political, and legal importance. Those include societal reaction to the discovery of extraterrestrial life; role of astrobiology in primary, secondary, and tertiary education; science dissemination and outreach; commercial and industrial use of outer space; moral and legal

status of extraterrestrial life; environmental ethics in space, technological innovations, and commerce among other.

Cross-References

- [Astrobiology as Science](#)
- [Discovery of Extraterrestrial Life](#)

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Société Française d'Exobiologie

- [SFE, France](#)

Socioeconomic Benefits of Space

Klara Anna Capova
Department of Anthropology, Durham University,
Durham, UK

Synonyms

[Contribution of science to society](#); [Socioeconomic impact](#); [Value](#)

Acronyms

UN	United Nations
SDG	Sustainable Development Goals
UNOOSA	United Nations' Office for Outer Space Affairs

Overview

Since the Apollo program, space exploration has been recognized as a world-view shifting activity with undeniable inspirational and aspirational aspects and an accelerator of technological development and scientific advancements. The idea that the knowledge, technologies, and know-how developed to explore space can make life on Earth more productive, clean, and sustainable is becoming more prominent and articulated in numerous initiatives and policies. The United Nations' Sustainable Development Goals (UN SDGs) agenda was adopted by all UN Member States in 2015 as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. The 17 interlinked goals define global social, environmental, and economic sustainable development priorities (planet, people, prosperity, peace, and partnership) and are often referred to as existential importance for humanity.

Space has been recognized as a driver for sustainable development by the UN Office for Outer Space Affairs (UNOOSA) that as such promotes the utilization of space science and technology for sustainable economic and social development. According to UNOOSA (2018), space technologies in general have an impact on almost all aspects of development: agriculture, global health, environment, education, research and development, human settlements, transportation, communication, humanitarian assistance, and security.

In relation to astrobiology, the broader societal benefits of the Martian missions rest in its immense inspirational, cultural, educational, and science dissemination potential and ability to engage wide audiences globally (Capova et al. 2018). Technologies developed for astrobiological research on Mars may have unique potential to leverage innovative solutions and

further contribute to sustainable socioeconomic development on Earth in the near future (e.g., robotics, energy solutions, and sample analysis).

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Socioeconomic Impact

- [Socioeconomic Benefits of Space](#)

Sociology of Science

- [Social Study of Science](#)

Soda Lake

Daniele L. Pinti
GEOTOP, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montreal, QC, Canada

Keywords

Alkaline environments · Extreme environments · Natron · Rift Valley lakes · Thermonatrite

Synonyms

[Alkaline lake](#); [Carbonate lake](#); [Hypersaline lake](#)

Definition

Soda lakes are lakes with pH up to 12 and high alkalinity. They are enriched in HCO_3^- and CO_3^{2-} (carbonate ions) and borates. Soda lakes are usually saturated in sodium carbonate (Na_2CO_3), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4). Soda lakes form in arid and semiarid areas of tropical and subtropical deserts of North America, continental Asia, and East African Rift Valley. Despite the extreme caustic conditions, soda lakes are the most productive aquatic environments on Earth, mainly because unlimited amount of CO_3^{2-} in solution. Microbial communities are studied in soda lakes as a possible analogue for ancient life on Earth, while soda lake chemistry is studied as an alternative model for the early ocean chemical evolution.

Overview

As the name indicates, soda lakes are characterized by the occurrence of large deposits of sodium in the form of carbonates such as trona ($\text{Na}_3\text{H}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$), natron ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$), thermonatrite ($\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$), halite (NaCl), and thenardite (Na_2SO_4). They are very alkaline with pH never below 10.5, with the highest values of pH = 12 recorded at Magadi Lake, Kenya. These conditions derive from a peculiar mixture of geographical, geological, and climatic conditions. Soda lakes are formed in very arid environments, often in depressions located above sea level and formed by continental rifting and with few or no freshwater inflow. Soda lakes occur worldwide but occur predominantly in the desert environments of Western North America (Soda Lake, Mojave Desert), inland Asia (North Tibet, Mongolia, Siberia), and the East African Rift Valley (Magadi and Natron Lakes, Kenya). The geology of the surrounding rocks, particularly the presence of rocks very depleted in Ca^{2+} and Mg^{2+} ions, plays a key role in the development of alkalinity. In most lacustrine environments, water rapidly becomes saturated with respect to Ca^{2+} , resulting in the precipitation of calcite (CaCO_3), magnesite (MgCO_3), and dolomite ($\text{MgCa}(\text{CO}_3)_2$) and preventing alkalinity. If the

CO_3^{2-} concentration exceeds that of Mg^{2+} and Ca^{2+} , alkalinity increases, and rock-available Na precipitates as halite and sodium carbonate.

Soda lakes are extreme environments for the strong alkalinity and high salinity of the waters. They are studied in astrobiology for three main reasons. Though living in caustic waters, a prolific ► [prokaryote](#) life develops in soda lakes, because of the high luminosity, high temperatures, and mostly unlimited supply of nutrients in form of dissolved CO_2 (CO_3^{2-}). Grant (2006) listed more than 60 species of living prokaryotes among ► [cyanobacteria](#), ► [archaea](#) (► [methanogens](#), thermophiles, and halobacteria), sulfur oxidizers, and anoxygenic phototrophs.

The possible occurrence of similar soda lake habitats on Mars in the past (Kempe and Kazmierczak 1997) makes these prokaryote communities an analogue for ancient life on Mars. Studying the chemistry of these lakes is also important because it has been proposed that ancient oceans were alkaline, as a consequence of the relative high amount of CO_2 in the atmosphere (e.g., Kasting 2011) and dissolved in the ocean, which promoted weathering of the basaltic crust of the early Earth, where Na^+ ions dominated over Ca^{2+} (Kempe and Degens 1985). Weathering of basalt plagioclase promotes precipitation of sodic carbonates, rendering alkaline the ocean. Although the hypothesis of Kempe and Degens (1985) on alkaline early oceans has been progressively dropped, very recently Toner and Catling (2020) proposed the existence of early carbonate-lakes which could have provided phosphorus for first living organisms. Phosphate is central to the origin of life because it is a key component of nucleotides, phospholipid cell membranes, and energy transfer molecules such as ATP (adenine triphosphate) which might be one of the candidates among the first metabolic pathways developed by LUCA (Last Universal Common Ancestor). Yet, in natural environments phosphorous is very rare because tend to precipitate as apatite in the geological record. In contrast, soda lakes contain large amounts of phosphorus making carbonate-rich lakes as plausible settings for the origin of life (Toner and Catling 2020).

Finally, the alkaline Lake Magadi, Kenya, contains chert deposits (Magadi chert), which are likely formed inorganically from sodium silicate

precursors (magadiite $\text{NaSi}_7\text{O}_{13}(\text{OH})_3 \cdot 3\text{H}_2\text{O}$ and/or kenyaite $\text{NaSi}_{11}\text{O}_{20.5}(\text{OH})_4 \cdot 3\text{H}_2\text{O}$). They have been often cited as modern analogues for inorganic-produced Precambrian ► [cherts](#) found in iron formations (Schubel and Bruce 1990).

Cross-References

- [Alkaliphile](#)
- [Archaea](#)
- [Banded Iron Formation](#)
- [Chert](#)
- [Cyanobacteria](#)
- [Evaporite](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [LUCA](#)
- [Natron](#)
- [Oceans, Chemical Evolution of](#)
- [Phosphorus chemistry](#)
- [Thermonatrite](#)
- [Trona](#)

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Soil

- [Regolith, Terrestrial](#)

Sol

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

A sol is a solar day on another ► [planet](#) or other body orbiting the sun. It is the time between two successive returns of the ► [Sun](#) to the same local meridian.

Cross-References

- [Planet](#)
- [Sun \(and Young Sun\)](#)

Solar Constant

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Total solar irradiance](#); [TSI](#)

Definition

The solar constant is the amount of total solar electromagnetic power that crosses a unit area perpendicular to the rays, at the mean distance from the Sun to the Earth. Its average value is $1,367.7 \text{ W m}^{-2}$. Despite its name, the solar constant is not exactly a constant and its fluctuations, most accurately measured since 1978, are of the order of one part in a thousand and are correlated with the 11-year cycle of the solar activity. They are also correlated with climate variations; however, they are too weak by a factor 3–6 to explain the

temperature variations on Earth. A planet-dependent solar constant has also been defined in the case of other solar system planets such as Mars.

Solar Luminosity

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The solar luminosity is defined as the total power emitted by the Sun in the form of electromagnetic radiation. The currently accepted value is $3.839 \times 10^{26} \text{ W}$. This is the most common unit used to express the luminosities of other stars or bigger objects such as galaxies or clusters of galaxies. Note that the Sun is a weakly variable star, with its luminosity fluctuating periodically by about a part in a thousand over the 11-year solar (sunspot) cycle.

Cross-References

- [Bolometric Magnitude](#)

Solar Mass

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The solar mass is defined as the total mass of the Sun. The currently accepted value is $1.99 \times 10^{30} \text{ kg}$. This is the unit commonly used to express the mass of huge astrophysical objects: stars, galaxies, black holes, dark matter.

Solar Nebula

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

The solar nebula is the original ► [protoplanetary disk](#) from which the Solar System formed. The solar nebula itself formed from a pre-stellar cloud during the collapse phase of the Sun's formation. The solar nebula had an initial composition similar to that of the outer layers of the present Sun and had a minimum mass sufficient to form the current planets. The latter model nebula is known as the “minimum-mass solar nebula” (MMSN), which is estimated by adding enough light elements to the masses of all the planets to bring them to solar composition.

Cross-References

- [Planet Formation](#)
- [Protoplanetary Disk](#)
- [Protoplanetary Disk, Chemistry](#)
- [Protosolar Nebula, Minimum Mass](#)
- [System Solar Formation, Chronology of](#)

Solar Neighborhood

Leticia Carigi

Instituto de Astronomía, Universidad Nacional
Autónoma de México, Ciudad de México,
Mexico

Keywords

Milky Way · Stellar populations · Exoplanets

Synonyms

[Solar vicinity](#)

Definition

The solar neighborhood is the space associated with a cylinder centered at the Sun and perpendicular to the Milky Way disk. This solar cylinder is located at 8.2 kpc from the galactic center, with a radius of ~ 1 kpc. Hence, the solar vicinity includes diverse physical entities that belong to the galactic disk and halo, such as planets and moons; stars of different masses, ages, chemical elements, and evolutionary stages; interstellar medium of different properties: HII regions, neutral gas, molecular gas, and dust; among others.

Overview

The solar neighborhood contains baryonic matter (stars and gas) and dark matter. The total mass surface density is roughly $70 M_{\odot} \text{ pc}^2$, of which the stars take 50%, 20% is in gaseous material, and 30% is in dark matter.

The solar cylinder contains two main baryonic structures: first, a *disk component* where approximately 98% of the total stellar mass of the solar neighborhood is found in Population I stars embedded in metal-rich gas. They are located between ~ 1400 pc above and below the central plane of the disk, and secondly, a *halo component* formed by the older Population II stars and no gas, located beyond the disk.

The first component (*disk*) in turn shows two subcomponents. One is a thin disk of 350 pc formed by a young stellar population with an average age of 3.8 Gyr and an average metal content around the solar metallicity ($Z_{\odot}$), and interstellar gas with $1.2 Z_{\odot}$. Another is a thick disk of ~ 1000 pc thickness and formed by an older stellar population with age ~ 10.4 Gyr and a metallicity of $0.3 Z_{\odot}$. The mass of the thick disk is $\sim 12\%$ of the mass in the thin disk.

The solar neighborhood stars show basic relations to understanding the chemical evolution of galaxies: (1) an age-metallicity relation, such that low age correlates with high metallicity; (2) a metallicity distribution function that exhibits different peaks, as a combination of Gaussian curves (Bell curves), corresponding to the halo and disk stellar populations.

However, the relation presents a spread in ages for a fixed value of Z and the Gaussian functions show skewness (asymmetries). The main causes for these are not clear yet, but the explanation could be outside the solar vicinity: some stars could have migrated from other places of the Milky Way and some would have belonged to satellites galaxies accreted to the Milky Way.

Moreover, those stars show another important evolutionary relation, involving α/Fe versus Fe/H , where α represents an alpha-chemical element (e.g., O, Mg, Si, S, Ca, and Ti). This relation has led to elucidating several questions, such as the chemical contribution in time by massive stars (the main producers of α elements) and by thermonuclear supernovae (the main producers of Fe), the star formation efficiency, and the different scenarios for galactic formation for the Milky Way. The thick disk stars exhibit overabundances of α elements compared to the thin disk stars with the same Fe abundance, and the halo stars show a large scatter in α/Fe , reaching up to the extreme ratios of the thick and thin disk stars.

Due to the current methods for exoplanet detection, most of the extrasolar planets have been found in stars at distances from the Sun closer than 1.5 kpc, and mainly in the disk component of the solar vicinity.

The solar neighborhood is the astronomical laboratory for studying the properties of the stellar populations and of the interstellar medium.

There are other definitions of the solar neighborhood in the literature, for instance, (1) the region within 0.2 pc, where the planets, minor bodies, and the Oort cloud of the solar system are; (2) the region up to 100 pc from the Sun, where the closest stars are; and (3) the region up to 20 Mpc from the Milky Way, where the galaxies of the local cluster are.

Cross-References

- [Galactic Archaeology](#)
- [Metallicity](#)
- [Milky Way](#)
- [Stellar Populations](#)

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Solar Particle Events

M. A. Shea
Air Force Research Laboratory (Emeritus),
Bedford, MA, USA

Keywords

Solar activity · Solar composition · Solar cosmic rays · Solar cycle · Solar protons

Synonyms

SPE

Definition

Ions and electrons that are accelerated by major solar activity and propagate through the interplanetary medium.

History

Major high energy events were first detected by ground-based detectors in 1942. Routine measurements of lower energy protons by spacecraft instrumentation commenced in 1965.

Overview

Solar particle events occur when activity on the Sun such as a solar flare and/or a coronal mass ejection accelerates and releases particles into the interplanetary medium. The actual process of solar particle acceleration is still under debate although it is most likely some type of shock acceleration process.

The frequency of solar particle events is correlated with the solar activity cycle although there is a large variance in the distribution. Major solar particle events consist primarily of sizable fluxes of energetic electrons and energetic protons with a small and variable flux of heavier elements. Protons are the most abundant ions. While most solar protons have energies less than 100 MeV, energies greater than 25 GeV have been identified. The flux and spectrum of solar particle events are not well correlated with solar activity parameters. Typical spectral slopes of solar particle events have values of -3 , with a large variation between events. Simple power laws or exponentials are generally not adequate to depict spectra over many orders of magnitude.

There are two general types of solar particle events frequently delineated by the duration of the associated solar X-ray emission. Solar particle events associated with solar flare impulsive X-ray events are generally small events detectable only over a limited range of heliolongitudes from the solar active region site. The elements in these events have an ionization state that is consistent

Solar Particle Events, Table 1 Normalized “average” solar particle composition

Charge	Species	Normalized abundance
$Z = 1$	Protons	1.0
$Z = 2$	Alpha particles	$1.5 \times 10^{-2} \pm 50\%$
$Z = 6$	Carbon	1.3×10^{-4}
$Z = 7$	Nitrogen	3.7×10^{-5}
$Z = 8$	Oxygen	2.4×10^{-4}
$Z = 26$	Iron	3.4×10^{-5}

with a ten million Kelvin plasma source. Solar particle events associated with fast coronal mass ejections are much larger events and can be detected over a range of heliolongitudes often in excess of 180° . As the coronal mass ejection driven shock moves outward from the sun through the interplanetary medium, additional acceleration of the ambient particle flux occurs, and this is often observed as a particle increase as the fast interplanetary shock moves past an observation position. These larger events with a proton flux that can exceed $100 \text{ particles cm}^{-2} \text{ s}^{-1} \text{ ster}^{-1}$ with energies $>10 \text{ MeV}$ have an elemental composition and charge state of the accelerated ions similar to that of the one million Kelvin solar corona. Table 1 gives the normalized “average” composition of these large events.

Cross-References

- [Cosmic Rays in the Heliosphere](#)
- [Radiation Biology](#)
- [Space Environment](#)
- [Stellar Winds](#)

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Solar Radius

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The solar radius is defined as the mean radius of the Sun. The currently accepted value is 6.955×10^8 m. This is the unit most frequently used to express the radius of other stars. Note that the Sun is very slightly oblate because of its rotation, by about 10 ppm.

Solar System

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Definition

The solar system may be defined as a system including all celestial objects which are subject to the gravitational field of the Sun. According to this definition, the solar system extends over a distance of about 2 light-years, or 0.65 pc, or about 120,000 AU. The most distant frontier that we know is the ► [Oort cloud](#), a spherical shell that extends beyond about 40,000 AU from the Sun, and is a reservoir for nonperiodic ► [comets](#). The solar system contains two main regions, the inner solar system between the Sun and the main asteroidal belt and the outer solar system beyond this limit. The inner solar system contains the ► [terrestrial planets](#) and their satellites and several families of ► [asteroids](#). The outer solar system contains the ► [giant planets](#) and their systems, distant asteroids (► [Centaurs](#)), and ► [trans-Neptunian objects](#). Most comets reside in the outer solar system

but some enter the inner solar system as they approach the Sun.

The solar wind is a flow of plasma emitted by the solar corona that fills the heliosphere and extends up to the heliopause, the frontier where the pressure from the solar wind equals the interstellar pressure. The heliopause has been detected by the ► [Voyager 1](#) spacecraft at a distance of about 120 AU from the Sun.

Cross-References

- [Asteroid](#)
- [Centaurs \(Asteroids\)](#)
- [Comets, History of](#)
- [Oort Cloud](#)
- [Solar System, Inner](#)
- [Solar System, Outer](#)
- [Trans-Neptunian Object](#)

Solar System, Inner

François Forget¹ and Tilman Spohn²
¹Institut Pierre Simon Laplace, Laboratoire
de Météorologie Dynamique, BPParis,
France

²International Space Science Institute, Bern,
Switzerland

Definition

The inner solar system is the region of the solar system that stretches between the Sun and the asteroid belt. It contains the ► [terrestrial planets](#) ► [Mercury](#), ► [Venus](#), ► [Earth](#), and ► [Mars](#) (in order of distance to the Sun), as well as the Earth's ► [Moon](#) and ► [Phobos](#) and ► [Deimos](#), which orbit Mars. In addition, the inner solar system is home to an unknown number of small bodies, ► [asteroids](#), and comet nuclei. Furthermore, the inner solar system contains the ► [habitable zone](#) of our solar system.

Cross-References

- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [Comet \(Nucleus\)](#)
- [Deimos](#)
- [Earth](#)
- [Habitable Zone](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Phobos](#)
- [Sun \(and Young Sun\)](#)
- [Terrestrial Planet](#)
- [Venus](#)

Solar System, Outer

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

The informal phrase “outer Solar System” normally refers to the region of the ► [giant planets](#) and beyond, corresponding to distances from the Sun ≥ 5 AU. The outer Solar System thus also includes almost all ► [comets](#) during most of their orbital periods, as well as centaurs and objects in the ► [Kuiper Belt](#) and ► [Oort Cloud](#). As a result of the low temperatures in this region, solid objects contain a much higher percentage of volatiles such as water and other ices than the rocky objects closer to the Sun.

Cross-References

- [Centaurs \(Asteroids\)](#)
- [Comet](#)
- [Giant Planets](#)
- [Kuiper Belt](#)
- [Oort Cloud](#)
- [Snow Line](#)

Solar UV Radiation, Biological Effects

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Keywords

Early Earth · Solar extraterrestrial UV
radiation · Space experiments · Stratospheric
ozone layer · Survival

Synonyms

[Solar UV rays](#)

Definition

Solar ► [UV radiation](#) is the ultraviolet (UV) component of the solar extraterrestrial electromagnetic radiation that amounts to about 7% of the whole spectrum. Space experiments have shown that UVC (200–280 nm) is mainly responsible for the high lethality of extraterrestrial solar radiation to microorganisms exposed to it. Due to absorption by stratospheric ozone, only UV at wavelengths longer than 290 nm reaches the surface of the Earth. Several effects on human health and the integrity of ► [ecosystems](#) are caused by this UV range. In the Archean, before the buildup of the stratospheric ozone layer, UV at wavelengths shorter than 290 nm would have reached the Earth’s surface with the associated severe biological consequences.

Overview

The ultraviolet (UV) component of the extraterrestrial ► [electromagnetic spectrum](#) of our Sun can be divided into three spectral ranges: UVC (200–280 nm) contributing 0.5%, UVB (280–320 nm) contributing 1.5%, and UVA

(320–400 nm) contributing 6.3% to the whole solar electromagnetic spectrum, respectively. Although the UVC and UVB regions make up only 2% of the entire solar extraterrestrial irradiance, they are mainly responsible for the high lethality of extraterrestrial solar radiation to microorganisms exposed to it. This is due to the high absorption of those wavelengths by DNA, the decisive target within that UV range for inactivation and mutation induction. Experiments in space, such as on board of Apollo, Spacelab, LDEF, Foton, MIR, and ► [EURECA](#), as well as at space simulation facilities on ground, have shown that extraterrestrial solar UV radiation is biologically a thousand times more efficient than UV at the surface of the Earth and kills 99% of bacterial spores within a few seconds. In addition, a synergistic effect was observed in spores of *Bacillus subtilis* that were simultaneously exposed to solar UV radiation and space vacuum (Nicholson et al. 2000; Horneck et al. 2010).

Solar UV radiation undergoes absorption and scattering as it passes through the Earth's atmosphere, with the absorption by ozone being the most important process. As a result, no UV radiation at wavelengths shorter than 290 nm reaches the surface of the Earth. Several deleterious effects of sunlight on human health and ecosystem integrity are due to the Sun's UV emission that does reach the surface of the Earth. In addition, concern of an increase in solar UVB radiation has arisen in view of a gradual reduction in stratospheric ozone concentration, as already visualized by the ozone hole during austral spring. In humans, mainly the skin, the eye, and the immune system are influenced by increased UVB radiation; at the ecosystem level, most important effects are expected on aquatic ecosystems as marine primary producers (Diffey 1991; Häder 1997; Horneck and Baumstark-Khan 2002; Björn 2008). Without the stratospheric ► [ozone layer](#), as assumed to be the case for the Archean, UVC and UVB would have reached the Earth's surface with biologically effective doses three orders of magnitude higher than today (Cockell and Horneck 2001). A similar high biological effectiveness is assumed for UV at the surface of

► [Mars](#), which is bombarded with solar UV radiation of wavelengths longer than 200 nm (Cockell et al. 2000; Patel et al. 2004).

Solar UV radiation and its biological effects are important factors for considering the following astrobiological questions:

- How did solar UV radiation affect chemical evolution and biological evolution on the early Earth?
- How does solar UV radiation influence the habitability of other planets, for example, the surface of Mars?
- What is the impact of solar UV radiation on viable interplanetary transport of life by natural or anthropogenic processes?

Cross-References

- [Aerobiology](#)
- [Apollo Mission](#)
- [Archean Traces of Life](#)
- [Biological Efficacy](#)
- [DNA Damage](#)
- [Ecosystem](#)
- [Electromagnetic Spectrum](#)
- [EURECA](#)
- [Exposure Facilities](#)
- [Lithopanspermia](#)
- [Mars](#)
- [Ozone Layer](#)
- [Panspermia](#)
- [Photobiology](#)
- [Planetary Protection](#)
- [Space Environment](#)
- [Spore](#)
- [UV Radiation](#)
- [UV Radiation Dose](#)

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Solar UV Rays

- [Solar UV Radiation, Biological Effects](#)

Solar Vicinity

- [Solar Neighborhood](#)

Solid-State Greenhouse Effect

François Forget
 Institut Pierre Simon Laplace, Laboratoire de
 Météorologie Dynamique, BPParis, France

Definition

A quasispecies is a distribution of ► [mutant](#) genomes centered around one dominant or master

sequence. Quasispecies theory was developed by M. Eigen as a general model to understand the dynamics of the first replicative molecules in the context of the origin of information and the early evolution of life (Eigen [1971](#)). Although they were initially conceived as steady-state distributions of infinite size in equilibrium, quasispecies dynamics – characterized by a continuous process of mutant generation, competition, and selection – have also provided an interpretation of the great adaptive potential of RNA viruses (Domingo and Holland [1997](#)). Indeed, experimental evidence has shown that, due to their error-prone replication, different current biological entities behave as quasispecies: ► [viroids](#), RNA viruses, and DNA viruses that use RNA as an intermediate molecule during their replicative cycle. The response of the evolving viral quasispecies to selective pressures, e.g., immune response of the infected host or antiviral treatment, is influenced by the ensemble of mutants that compose the population (Lauring and Andino [2010](#)).

Cross-References

- [Error Rate](#)
- [Evolution, Molecular](#)
- [Hypercycle](#)
- [Mutant](#)
- [Origin of Life](#)
- [RNA](#)
- [RNA World](#)
- [Viroid](#)
- [Virus](#)

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Solidus

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Meguro-ku, Tokyo,
 Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry and geology, a solidus is the set of temperatures below which a substance is completely solid or crystallized. The solidus defines the temperature at which a substance begins to melt, but not necessarily when the substance is completely melted. A solidus may be contrasted with a ► [liquidus](#). The solidus and liquidus may not be the same in all cases. When a difference exists between the solidus and liquidus temperatures, then in the intervening region, the system consists of a mixture of solid and liquid phases. In eutectic systems, solidus and liquidus temperatures are the same: The mixture melts completely at the eutectic point.

Cross-References

► [Liquidus](#)

Sour Damp

► [Hydrogen Sulfide](#)

South Indian Shield

► [Dharwar Craton](#)

Space Biology

Ruth Hemmersbach
 German Aerospace Center (DLR), Institute of
 Aerospace Medicine, Cologne, Germany

Synonyms

[Space Life Sciences](#)

Definition

The ► [space environment](#) is characterized by an intense radiation field of solar and galactic origin and by high vacuum, extreme temperatures, and – induced by orbital space flight – reduced gravity (► [microgravity](#)) conditions. Thus, the interdisciplinary field of space biology includes all basic disciplines in ► [Life Sciences](#) by investigating the impact of space environmental factors on all organizational levels (from subcellular to organismal) of living matter.

History

The beginnings of the discipline “space biology” may be set with the start of orbital flights that means ballistic flights (1948–1957) and early orbital missions (1957–1961) with animals, followed in 1961 by human flights. This opened a new experimental field by enabling the investigation of the influence of the space environment (mainly microgravity and radiation) on living systems.

Cross-References

- [Astrobiology](#)
- [Cosmic Rays in the Heliosphere](#)
- [Gravitational Biology](#)
- [International Space Station](#)
- [Life](#)

- [Microgravity](#)
- [Radiation Biology](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [Space Vacuum Effects](#)

Space Environment

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Galactic cosmic radiation · Solar extraterrestrial UV radiation · Space radiation · Space vacuum · Temperature in space

Definition

Space environment is the large void which occupies the (relatively) empty areas of the universe outside the atmosphere or surface of any planet or other celestial body. It is a vacuum that contains a low density of particles, as well as electromagnetic radiation, magnetic fields, and neutrinos. Based on our own perspective from planet Earth, the space environment is defined as the area beyond the atmosphere of the Earth. It is also considered as a branch of astronautics that addresses conditions of space that might affect the operations of spacecraft, the health of astronauts, and any other living being during space flight.

Overview

The space environment is characterized by a high vacuum, an intense radiation of galactic and solar origin, and extreme temperatures (Table 1).

Space Vacuum

In interplanetary space, vacuum reaches pressures down to 10^{-14} Pa. Within the vicinity of a body,

the pressure may significantly increase due to outgassing. In a low Earth orbit of an altitude below 450 km, which is the average altitude of the ► [International Space Station](#), pressure reaches 10^{-7} – 10^{-4} Pa. The major constituents of this environment are hydrogen, molecular oxygen, and molecular nitrogen as well as highly reactive oxygen and nitrogen atoms. In the vicinity of a spacecraft, the pressure further increases, depending on the degree of outgassing of the spacecraft itself. In the Space Shuttle cargo bay, a pressure of 3×10^{-5} Pa was measured.

There is no definite boundary between the atmosphere of the Earth and outer space. With increasing altitude, the atmosphere becomes thinner and eventually fades away into space (Fig. 1). The Kàrmàn line, at an altitude of 100 km, is often regarded as the “official” boundary for space human flights between the Earth’s atmosphere and space.

Space Radiation

The planets, moons, and small bodies in our solar system are continuously bombarded by charged particles coming from sources outside our solar system and from the Sun. The radiation field in interplanetary space is composed primarily of two types of radiation: galactic cosmic radiation (GCR) and solar cosmic radiation (SCR). GCR originates outside the solar system in cataclysmic astronomical events, and the particles are accelerated by supernova shock waves. They are composed of energetic particles, i.e., nuclei with all their orbital electrons stripped off, and have traveled for several million years through the galaxy before entering the solar system. GCR covers a broad spectrum of energy and mass values (Fig. 2). About 98% are atomic nuclei and 2% electrons and positrons. The nuclear component consists of about 87% protons, about 12% α -particles (He nuclei), and about 1% nuclei of an atomic mass $Z > 2$, the so-called ► [HZE particles](#). When these charged particles enter the solar system, they interact with the outbound streaming of the solar wind and its embedded interplanetary magnetic field which varies with the solar activity. In interplanetary space, the annual ► [radiation dose](#) amounts to ≤ 0.1 Gy depending on mass

Space Environment, Table 1 Parameters of interplanetary space and in low Earth orbit (LEO)

Space parameter	Interplanetary space	Low Earth orbit
Space vacuum		
Pressure (Pa)	10 ^{−14}	10 ^{−7} –10 ^{−4}
Residual gas (part/cm ³)	1 H	10 ⁴ –10 ⁵ H
		10 ⁴ –10 ⁶ He
		10 ³ –10 ⁶ N
		10 ³ –10 ⁷ O
Solar electromagnetic radiation		
Irradiance (W/m ²)	Different values ^a	1,370 ^b
Spectral range (nm)	Continuum from 0.01 (X-rays) to 10 ⁶ (IR)	Continuum from 0.01 (X-rays) to 10 ⁶ (IR)
Cosmic ionizing radiation		
Dose (Gy/a)	≤0.1 ^c	0.1–10,000 ^d
Temperature (<i>K</i>)	>4 ^a	Wide range (153–393) ^e
Microgravity (<i>g</i>)	<10 ^{−6}	10 ^{−3} –10 ^{−6}

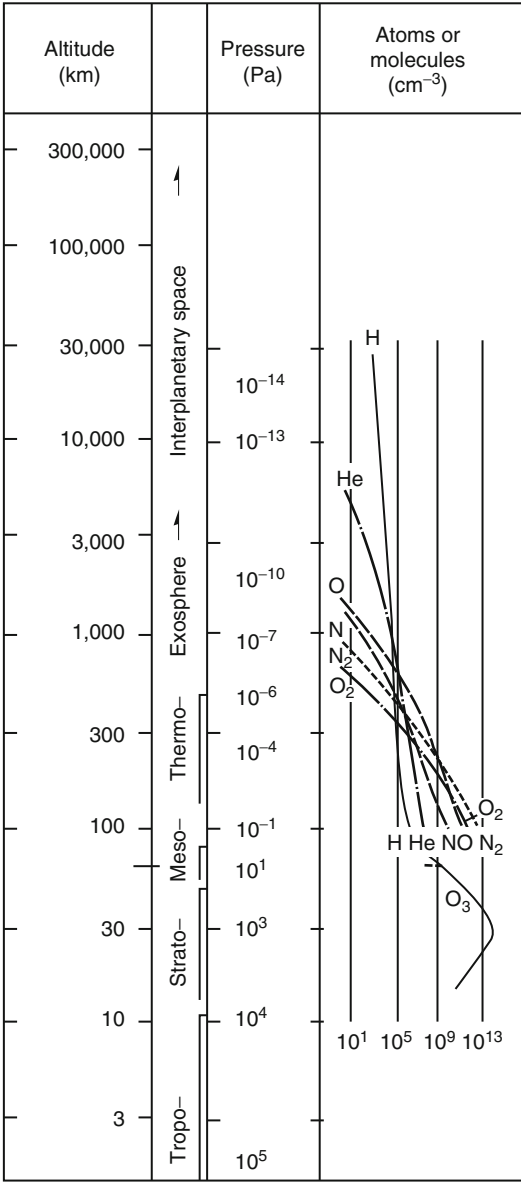
^aDepending on orientation and distance to the Sun
^bAbove the Earth atmosphere
^cDepending on shielding, highest values at mass shielding of 0.15 g/cm²
^dDepending on altitude, orbit, and shielding, highest values at high altitudes, during frequent passages through the SAA of the radiation belts and through the polar horns, and shield of 0.15 g/cm²
^eDepending on orientation to the Sun and albedo of the body

shielding with the highest dose at 0.15 g/cm² shielding due to built-up radiation (Table 1). With increasing solar activity, the interplanetary magnetic field increases, resulting in a decrease of the intensity of GCR of low energies. Hence, the GCR fluxes vary with the solar cycle and differ by a factor of approximately three between solar minimum and solar maximum with a peak level during minimum solar activity and the lowest level during solar maximum activity.

SCR consists of the low-energy solar wind particles that flow constantly from the Sun and the so-called ► [solar particle events](#) (SPEs) that originate from magnetically disturbed regions of the Sun and sporadically emit bursts of charged particles with high energies (up to several GeV). These events are composed primarily of protons and electrons with a minor component (5–10%) of α -particles and an even smaller component (1%) of heavy ions. SPEs develop rapidly and generally last for no more than a few hours at energies >100 MeV and up to a few days at low MeV energies.

In low Earth orbit (LEO), which reaches up to an altitude of 450 km, the Earth’s magnetic field provides a latitude dependent shielding against GCR and SPE particles, so they are primarily

experienced in high-inclination orbits. In LEO, the radiation field includes an additional component: the radiation belts, the so-called Van Allen belts (Fig. 2). These Van Allen belts in the vicinity of the Earth are a result of the interaction of GCR and SCR with the Earth’s magnetic field and atmosphere. They consist of two radiation belts that are comprised of electrons and protons as well as some heavier particles trapped in closed orbits by the Earth’s magnetic field. The main production process for the inner belt particles is the decay of neutrons produced in cosmic particle interactions with the atmosphere. The outer belt consists mainly of trapped electrons and low-energy protons. In each zone, the charged particles spiral around the geomagnetic field lines and are reflected back between the magnetic poles that act as mirrors. Electrons reach energies of up to 7 MeV and protons up to about 200 MeV (Fig. 2). Of special importance for LEO missions is the so-called South Atlantic Anomaly (SAA), a region over the coast of Brazil, where the radiation belt reaches as low as 200 km above the Earth’s surface. This behavior is due to an 11° offset of the Earth’s magnetic dipole axis from its rotation axis and a 500 km displacement toward the Western



Space Environment, Fig. 1 Altitude profile of the Earth's atmospheric components and pressure

Pacific, with corresponding significantly reduced field strength values. The inner fringes of the inner radiation belt come down to the altitude of LEO, which results in a thousand times higher proton flux than in other parts of the orbit. Almost all radiation received in LEO is due to passages through the SAA. This complex radiation field experienced in outer space cannot be simulated

by any ground-based facility. The ► [radiation doses](#) in low Earth orbit and on Earth-Moon transfer have been measured since the beginnings of space flight activities (Swenberg et al. 1993; Reitz et al. 2009). Figure 3 reflects the increase of the space radiation dose with altitude of the Earth. At the surface of the Earth, the atmosphere provides a shielding of 1,000 g/cm².

► [Mars](#) has currently no planetary magnetic field and therefore also no radiation belts. The only radiation shielding is due to the Martian atmosphere, the thickness of which varies with surface altitude from 16 to 8 g/cm². Higher altitudes are less shielded; low altitudes such as Hellas Planitia are more shielded. Dose rates range from 200 to 300 mSv/year. The ► [radiation doses](#) expected during Earth-Mars transfer have been measured during the 2001 NASA Mars Odyssey mission (Zeitlin et al. 2004).

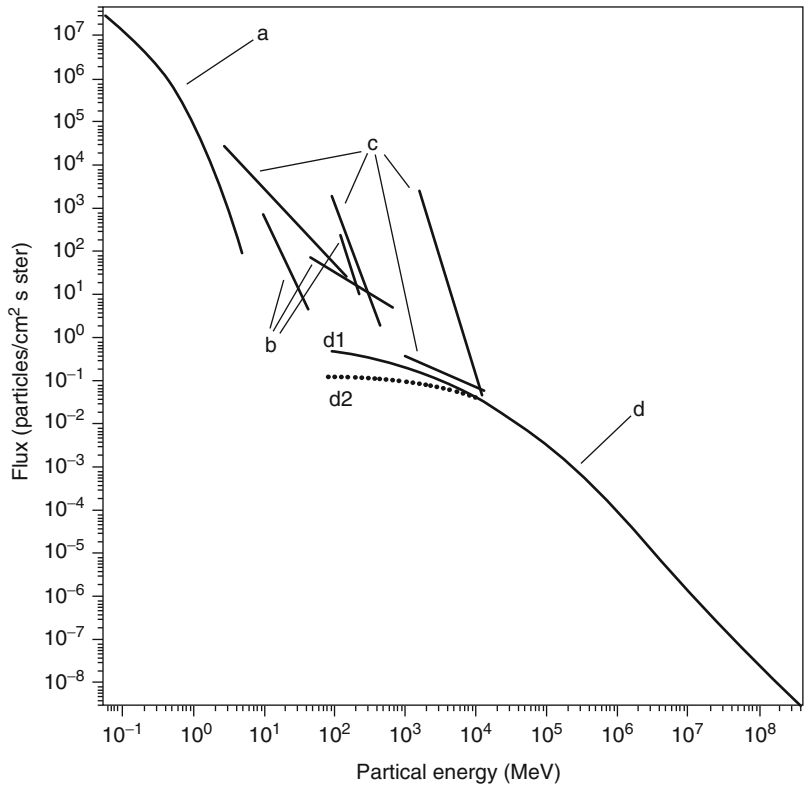
Jupiter has a strong global magnetic field. The Galilean satellites Io, ► [Europa](#), Ganymede, and Callisto are embedded within Jupiter's magnetosphere, and Io is known as a source of ions and neutral particles. Jupiter's inner radiation belt is analogue to the Earth's Van Allen belts, but about 10,000 times more intense. Europa is therefore continually bombarded by magnetically trapped ionizing radiation reaching an electron dose rate at its surface of several gray per minute (Baumstark-Khan and Facius 2002).

Solar Electromagnetic Radiation

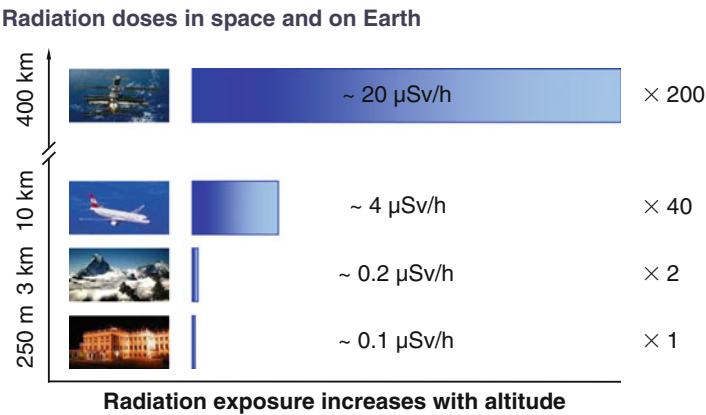
The spectrum of solar electromagnetic radiation spans over several orders of magnitude, from short wavelength X-rays at 0.01 nm to radio frequencies at mm wavelengths. At the average distance of the Earth (1 AU), solar irradiance amounts to 1,370 W/m², which is the ► [solar constant](#). Of this radiation, 45% is attributed to the infrared fraction, 48% to the visible fraction, and 7% to the ultraviolet range. The extraterrestrial solar spectral UV irradiance has been measured during several space missions, such as Spacelab 1 and ► [EURECA](#) (Labs et al. 1987).

On its way through the Earth atmosphere, solar electromagnetic radiation is modified by scattering and absorption processes. Numerous lines of isotopic and geologic evidence suggest that the

Space Environment,
Fig. 2 The energy spectra of the components of the radiation field in space in the vicinity of the Earth: (a) electrons (belts); (b) protons (belts); (c) solar particle events; (d) heavy ions of galactic cosmic radiation; (d1) during solar minimum; (d2) during solar maximum



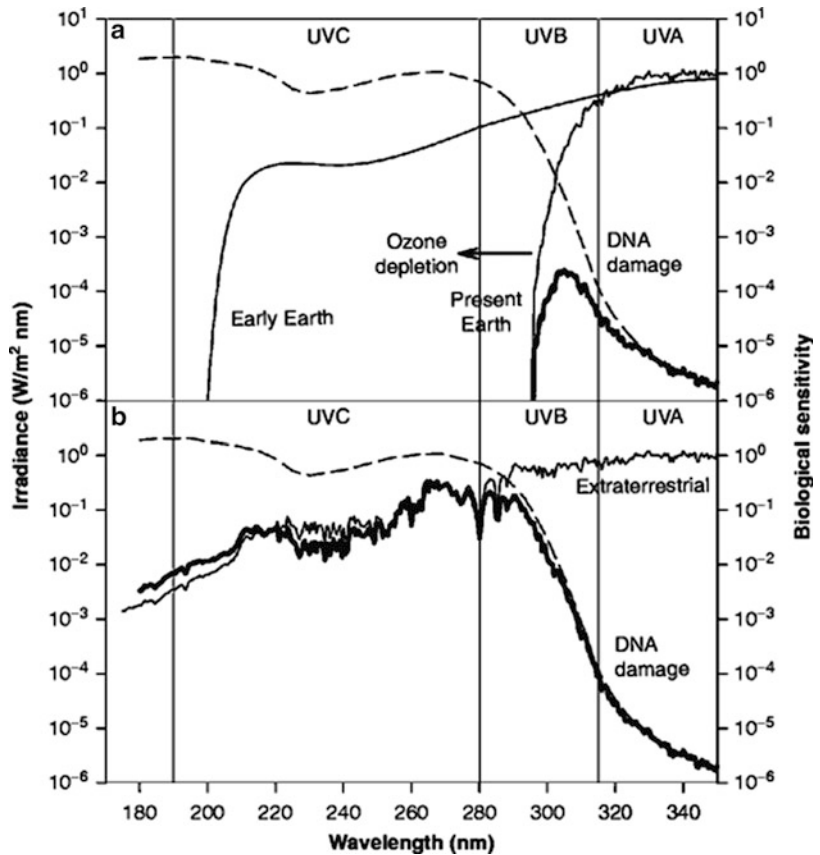
Space Environment,
Fig. 3 Increase of the environmental radiation dose with altitude of the Earth



Archean atmosphere was essentially anoxic. As a result, the amount of ozone in the stratosphere, if any, would have been insufficient to affect the surface UV radiation environment. Thus, UV radiation at wavelengths >200 nm would have penetrated to the Earth’s surface with its associated biological consequences (Cockell and Horneck 2001). It took more than 2 billion years, until about 2.2 billion years ago, when as a consequence

of oxygenic photosynthesis, the Earth’s atmosphere was subject to rapid oxidation, and hence a stratospheric ► **ozone layer** was photochemically formed. This UV screen allowed life to colonize the surface of the Earth. Today, the stratospheric ozone layer effectively absorbs UV radiation at wavelengths shorter than 290 nm (Fig. 4).
For Mars, the solar constant is only 43% of that for Earth. However, the very low concentrations

Space Environment,
Fig. 4 Solar terrestrial
 (a) and extraterrestrial
 (b) UV irradiance spectra,
 action spectrum for DNA
 damage as example for the
 biological sensitivity
 (dashed line) and biological
 effectiveness spectra (bold
 line) for present terrestrial
 and for extraterrestrial
 conditions (Modified from
 Horneck et al. 2010)



of oxygen in its atmosphere prevent the formation of a stable UV-absorbing planetwide ozone layer. The energy-rich short wavelengths of solar UV radiation penetrate the Martian atmosphere and lead to high surface fluxes of UV radiation with wavelengths longer than 200 nm in contrast to the conditions on Earth, where only wavelengths longer than 290 nm reach the surface. Therefore, the biologically effective dose rate of UV irradiation on the surface of Mars is up to three orders of magnitude higher than on the surface of the Earth (Cockell et al. 2000; Patel et al. 2002, 2004). The actual UV irradiance at a certain location on the surface of Mars varies depending on factors like dust cover, season, local time, and altitude (Patel et al. 2003).

Temperature of Bodies in Space

The temperature of a body in interplanetary space depends on its position and distance to the Sun and also on its albedo, surface, size, and mass. It is

determined by the absorption and emission of energy. In Earth orbit, the energy sources are the solar radiation (1,370 W/m²), the effects of Earth's albedo (480 W/m²), and terrestrial thermal radiation (230 W/m²). In Earth orbit, the temperature of a body can reach extreme values. In different space exposure experiments, the samples were subjected to temperatures in the range of 243–318 K (Horneck 1998; Rabbow et al. 2009).

Cross-References

- [Aerobiology](#)
- [Albedo](#)
- [Cosmic Rays in the Heliosphere](#)
- [Desiccation](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Environment](#)
- [EURECA](#)
- [Europa](#)

- [Extreme Ultraviolet Light](#)
- [Giant Planets](#)
- [HZE Particle](#)
- [International Space Station](#)
- [Mars](#)
- [Mars Odyssey](#)
- [Ozone Layer](#)
- [Photochemistry, Atmospheric](#)
- [Radiation Biology](#)
- [Radiation Dose](#)
- [Solar Constant](#)
- [Solar Particle Events](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Vacuum Effects](#)
- [Space Weathering](#)
- [Supernova](#)
- [UV Climate](#)
- [UV Radiation](#)
- [UV Radiation, Biological Effects](#)
- [UV Radiation Dose](#)
- [Wavelength](#)

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Space Infrared Telescope Facility

- [Spitzer Space Telescope](#)

Space Life Sciences

- [Space Biology](#)

Space Studies Board

- [SSB, USA](#)

Space Tourism

► [Commercial Use of Space](#)

Space Vacuum Effects

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Definition

The vacuum of interplanetary space reaches pressures down to 10^{-14} Pa. Within the vicinity of a body, the pressure significantly increases due to outgassing (e.g., in low Earth orbit, pressure reaches 10^{-6} – 10^{-4} Pa). Pressures below the vapor pressure of a certain material cause vaporization of atoms or molecules from the material's surface. In addition to water, sealants, lubricants, and adhesives are the main substances that outgas from spacecraft. However, even metals and glasses can release gases from cracks and impurities. For biological samples in space, vacuum dehydration is the main process affecting their integrity.

Cross-References

- [Desiccation](#)
- [Space Biology](#)
- [Space Environment](#)

Space Voyages

- [Imaginary Voyages \(from Antiquity to the Eighteenth Century\)](#)

Space Weathering

Harald Hoffmann
DLR, Institute of Planetary Research, Berlin,
Germany

Keywords

Cosmic rays · Exospheres · Micrometeorite impacts · Optical alteration · Solar wind · Sputtering

Definition

Space weathering describes all the effects caused by the interaction between the surface of an airless planetary body and the space environment.

Overview

The term space weathering summarizes alteration processes on an atmosphereless planetary surface due to the interaction of the surface material or regolith with the ► [space environment](#). As the direct contact layer between the planetary body and space, the surface is permanently reworked and physically and/or chemically modified by micrometeorite impacts, galactic and solar cosmic rays, solar irradiation, and the solar wind. These weathering processes may strongly affect the optical properties of the surface material and have to be taken into account in the analysis of remotely sensed observations.

The planetary surface is pulverized and turned over by a continuous micrometeorite bombardment. Depending on the kinetic energy involved, micrometeorite impacts may result in the melting of material and the formation of glass-welded aggregates (agglutinates), known as a major constituent of the lunar regolith, as well as glass splashes on single grains. Impact-related vaporization and sputtering due to the interaction with highly energetic particles can generate thin rims on individual grains. The reduction of iron in

silicates like olivine or pyroxene can result in the formation of metallic nanophase (single-domain) iron within these rims or glassy materials. Collisions with cosmic rays and the solar wind can also form tracks and result in the implantation of particles like ► [hydrogen](#), helium, and other rare gases. Space weathering processes result in the maturation of a planetary regolith over time until a steady-state equilibrium is reached and as long as fresh material is not excavated by a large impact.

Optical alterations due to space weathering of terrestrial planetary surfaces are mainly associated with the formation of single-domain iron and of glassy material. The spectral signature becomes darker, diagnostic absorption features weaker, and the spectral curvature redder. Similar effects have been reported not only for the ► [Moon](#) but also for ► [Mercury](#), the Martian ► [satellites](#), and some ► [asteroids](#). Pulverization and gas implantation are more effective for determining the spectral characteristics of icy satellites.

Space weathering processes are also responsible for the formation of the tenuous atmospheres (exospheres) found around, e.g., the Moon or Mercury, which consist mainly of Na^+ and K^+ ions.

Cross-References

- [Asteroid](#)
- [Crater, Impact](#)
- [Hydrogen](#)
- [Mercury](#)
- [Moon, The](#)
- [Regolith, Planetary](#)
- [Satellite or Moon](#)
- [Space Environment](#)

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Spall

- [Spallation Zone](#)

Spallation

- [Spallation Zone](#)

Spallation Reaction

Nikos Prantzos

Institut d'Astrophysique de Paris, Paris, France

Definition

Spallation reactions are ► [nuclear reactions](#) where a high-energy projectile (usually a proton, neutron, or alpha particle) fragments a heavy nucleus, removing one or more nucleons from it and producing lighter nuclei. Such reactions occur during the propagation of cosmic rays in the galaxy's ► [interstellar medium](#). Spallation of abundant CNO nuclei is the main nucleosynthesis mechanism producing the light and fragile nuclides of Li, Be, and B, which are destroyed by thermonuclear reactions in stars (notice that ^7Li is also produced in the Big Bang and in stars, while some ^{11}B is, perhaps, produced through neutrino-induced nucleosynthesis). The abundance of particular spallation products on the surface of a meteorite provides a means of measuring the duration of its exposure to cosmic rays.

Cross-References

- [Cosmic Rays in the Heliosphere](#)
- [Interstellar Medium](#)
- [Nuclear Reaction](#)
- [Nucleosynthesis, Neutrino](#)

Spallation Zone

H. Jay Melosh

Departments of Earth, Atmospheric and Planetary Sciences, Physics and Aerospace Engineering, Purdue University, West Lafayette, IN, USA

Keywords

High-speed ejection · Lithopanspermia · Meteorite impact

Synonyms

[Cavitation zone](#); [Interference zone](#); [Spall](#); [Spallation](#)

Definition

Spallation zones are regions adjacent to the free surface of a solid where the reflection of a strong incident stress wave induces tensile stresses and ejects material at high speed. The tensile stresses add to the compressive stresses in the incident wave and partially cancel its compression, leading to high-speed ejection of lightly compressed (“shocked”) material.

History

Spallation of the surface following impingement of a strong shock wave was first observed in association with underground nuclear explosions. During the 1980s, accumulated evidence indicated that the SNC suite of ► [meteorites](#) originated on a large planet, probably ► [Mars](#). Their

launch raised the conundrum of how intact rocks could be ejected at high enough speed to escape from Mars (a minimum of 5 km/s) and yet escape melting or vaporization. Melosh (1984) first suggested that spallation could provide the answer. Furthermore, Melosh (1988) suggested that the launch conditions might be gentle enough that microbes could survive interplanetary transfer inside the ejected rocks. This suggestion renewed modern interest in the ► [panspermia](#) idea.

Overview

The process of “spallation” is responsible for the high-speed ejection of rocks (often denoted “spalls” when produced by this process) from the surface of a planet near the site of a meteorite impact. While the ejection speed of the rocks may suggest that large compressive pressures are required by the Hugoniot equations that express the conservation of mass, momentum, and energy across a sharp shock front, the presence of a free surface drastically reduces the pressure in the incident wave near the surface (boundary conditions require that the normal stress on the free surface itself is exactly zero). This zone in which the reflected tensile wave adds destructively to the incident compressive wave is sometimes described as an “interference zone.” In a liquid, the same process produces an opaque “cavitation zone” that forms on the surface near underwater explosions. Away from the free surface, pressures rise rapidly to the level required by the Hugoniot equations. The distance over which this rise occurs is comparable to the diameter of the projectile but also depends on the distance from the impact site.

The existence of a spallation zone explains how nearly intact rocks can be ejected from the surfaces of such bodies as Mars (escape velocity 5 km/s) and the Moon (escape velocity 2.4 km/s), whose large escape velocities would normally imply that escaping material is melted or vaporized (Melosh 1984, 1985). Such rocks are the progenitors of the many dozens of meteorites that are now known to originate on Mars or the

Moon, some of which show little sign of the forces that ejected them (Head et al. 2002). Antarctic meteorite ► [ALH 84001](#) not only shows no sign of shock damage upon launch but, between its formation on Mars and its recovery on the Earth, did not experience temperatures greater than about 40 °C (Weiss et al. 2000). The spallation process has now been observed in the ejecta of large impact craters on Earth, in laboratory experiments, and in very high-resolution numerical simulations of impact.

The process of spallation allows viable microbes or microbial spores to survive launch from the surface of a planet into interplanetary space (Stöffler et al. 2007; Horneck et al. 2008; Fajardo-Cavazos et al. 2009). It may thus initiate interplanetary exchange of living organisms between planets in our solar system (Mileikowsky et al. 2000), although interstellar exchange seems very unlikely (Melosh 2003; Valtonen et al. 2009). This process of meteorite exchange between planets has variously been called panspermia or ► [lithopanspermia](#).

Cross-References

- [ALH 84001](#)
- [Crater, Impact](#)
- [Lithopanspermia](#)
- [Mars](#)
- [Meteorites](#)
- [Moon, The](#)
- [Panspermia](#)
- [SNC Meteorites](#)

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Spark Discharge

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Keywords

Cavendish · Electrodes · Miller

Synonyms

[Electric discharge](#)

Definition

A spark discharge is an electrical discharge between two electrodes that is used to simulate atmospheric lightning and coronal discharges. It

occurs when the electric field strength between the two electrodes exceeds a certain threshold value in volts per cm. This leads to a momentary increase in the concentration of ions between the two points, temporarily allowing the gases between the electrodes to serve as an electrical conductor.

Overview

Henry Cavendish did one of the first spark discharge chemistry experiments in the late eighteenth century. His investigations were designed to study aspects of atmospheric chemistry and showed that the action of a spark discharge in air resulted in the production of nitrous acid (Cavendish 1788). In Stanley Miller's classic 1953 experiment, a spark discharge acting on a mixture of hydrogen, methane, ammonia, and water produced HCN, aldehydes, and ketones, which in turn reacted by the Strecker reaction to form ► [amino acids](#).

Cross-References

- [Amino Acid](#)
- [Atmosphere, Organic Synthesis](#)
- [Corona Discharge](#)
- [Electric Discharge](#)
- [Miller, Stanley](#)
- [Strecker Synthesis](#)

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Spathose Iron

- [Siderite](#)

SPE

- [Solar Particle Events](#)

Special Region (Mars)

Catharine A. Conley
NASA Headquarters, NASA Ames Research
Center, Washington, DC, USA

Definition

“Special Region” are locations on Mars that could be habitable for Earth life or be a habitat for Martian life. Currently, Special Regions are defined using the parameters of temperature and water activity. The specification as of 2020 is a location where (concurrently) the temperature reaches above $-28\text{ }^{\circ}\text{C}$ and the water activity is above 0.5 (relative humidity above 50%).

In accordance with the planetary protection policy maintained by the COSPAR, these Special Regions define a new category (Category IVc) of Martian mission. For those missions that investigate Martian Special Regions, even if they do not include life detection experiments, all of the requirements applicable to a surface mission to Mars (Category IVa) apply, along with the following requirements:

- Case 1. If the landing site is within the Special Region, the entire landed system is restricted to a surface bioburden level of $\leq 30^1$ spores.
- Case 2. If the Special Region is accessed through horizontal or vertical mobility, *either*

¹This figure takes into account the occurrence of hardy organisms with respect to the sterilization modality. This specification assumes attainment of Category IVa surface cleanliness, followed by at least a four order-of-magnitude reduction in viable organisms. Verification of bioburden level is based on pre-sterilization bioburden assessment and knowledge of the bioburden reduction factor of the sterilization modality.

the entire landed system is restricted to a surface bioburden level of $\leq 30^1$ spores, *or* the subsystems which directly contact the Special Region are sterilized to these levels, and a method of preventing their recontamination prior to accessing the Special Region shall be provided.

If an off-nominal condition (such as a hard landing) would cause a high probability of inadvertent biological contamination of the Special Region by the spacecraft, the entire landed system must be sterilized to a surface bioburden level of $\leq 30^1$ spores and a total (surface, mated, and encapsulated) bioburden level of $\leq 30 + (2 \times 10^5)^1$ spores.

At the present time, there are no areas accessible to spacecraft at the surface of Mars that are known to be Special Regions. However, recent surface features associated with fluid flow, particularly in low latitudes, have the potential to be Special Regions and are treated (under the precautionary principle) as though they are.

Further Reading

http://cosparhq.cnes.fr/assets/uploads/2020/07/PPPolicy_June-2020_Final_Web.pdf

http://mepag.jpl.nasa.gov/reports/MEPAG_SR-SAG_final1.pdf

http://www.nap.edu/catalog.php?record_id=11381

Species

Ramon Rosselló-Móra
IMEDEA (CSIC-UIB), Esporles, Mallorca,
Balearic Islands, Spain

Keywords

Pattern of recurrence · Taxonomic category ·
Unit of biodiversity

Synonyms

Lowest taxonomic category

Definition

In biology, species is the basic rank (category) supporting the taxonomic hierarchy that attempts to embrace all of the biological diversity present in the biosphere.

Overview

Aristotle first enunciated the idea of species about 2,400 years ago (fourth century before Christ). Linnaeus, in the eighteenth century, consolidated its use within a scientific framework and initiated the modern binomial classification. Since then, it has been used to identify each of the different biological units that can be observed in nature. As Jody Hey states, “species are categories motivated by recurrent observations about the world, and as humans are great observers of patterns of recurrence they devise categories as a response.” However, such patterns of recurrence are necessarily different for different kinds of organisms that exhibit distinct levels of morphological and/or physiological complexity. The idea of what a species may be depends on the type of organisms under study and the ability of the taxonomists to identify the phenotypic, genetic, and ecological singularities that make a unit different from its closest relatives. For organisms exhibiting complex morphologies such as plants and animals, the circumscription of the unit is mainly based on simple, easily recognizable, observable traits requiring no experimentation on living specimens. However, for morphologically simpler organisms such as prokaryotes and some microscopic eukaryotes, simple ocular examination is insufficient. In such taxonomies, there is a need to experiment with living specimens in the laboratory in order to retrieve enough genetic and phenotypic information to establish the taxa boundaries.

Over the years, philosophers and taxonomists have insistently tried to formulate the essence of what this biological unit could be. However, the search for a universal concept that describes the basic taxonomic rank soon became the focus of strong debates. Hitherto, more than 25 different concepts have been formulated. The most widely

known is the “biological species concept” (BSC) by Ernst Mayr who understood “species as groups of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups.” However, while this concept works for most animals, it is not applicable to the vast majority of the biological entities that do not reproduce sexually. Among the different concepts formulated, scientists debate between the use of those of high theoretical load (such as “evolutionary” (ESC) or “cohesive” (CSC) species concepts, both considered synonyms) and those that can be considered theory-free (such as the “phenetic” (PhSC) or the “polythetic” (PtSC) species concepts, both considered synonyms). The former formulates that species is “an entity composed of organisms which maintains its identity from other such entities through time and over space, and which has its own independent evolutionary fate and historical tendencies”; the latter is formulated as “a similarity concept based on statistically co-varying characteristics which are not necessarily universal among the members of the taxa.” The success of the PhSC or PtSC is mainly based on the achievement of as many independent characters as possible. However, neither concept is well accepted. The ESC or CSC is very difficult to apply, and the PhSC or PtSC lacks a theoretical background.

Each discipline in biology creates its own classification and especially tailors its species circumscriptions in a manner that best fits the patterns of recurrence that they observe. Either we admit that biological diversity is so vast and evolutionary constraints are so varied among different biological lines of descent that a variety of species concepts are necessary to accurately capture the complexity of variation patterns in nature (pluralistic view) or if we want to achieve a universal concept that takes into account all biological diversity (monistic view), we have to admit that the concept of species may lack applicability and may not be operative.

As a final remark, we can consider species as each of the recurrence patterns that humans observe in nature, each of them having a different evolutionary fate. The ability to recognize species depends on the biological complexity of the

organisms under observation and the technological capacities available to recognize their unique properties. The final circumscription of a species will depend on the scientists’ abilities to recognize genetic and/or phenotypic complexities.

Cross-References

- [Darwin’s Conception of the Origins of Life](#)
- [Evolution, Biological](#)
- [Phylogeny](#)
- [Taxonomy](#)

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Species (Prokaryote)

Antonio Ventosa and Cristina Sánchez-Porro
Department of Microbiology and Parasitology,
Faculty of Pharmacy, University of Sevilla,
Sevilla, Spain

Keywords

Classification · Phylogeny · Average Nucleotide Identity · Digital DNA-DNA hybridization · Genomic indexes · Taxonomy

Definition

A species is a category that circumscribes a (preferably) monophyletic and genomically coherent group of individual isolates/strains sharing a high degree of similarity in (many) independent features, comparatively tested under highly standardized conditions (Rosselló-Mora and Amann 2001).

Overview

Species is the basic unit and most important taxonomic rank in prokaryote classification, represented by a group of microorganisms that share a common ancestor (monophyly) and have a genotypic relationship and coherent phenotypic features. The concept of species in prokaryotes is quite complex, since it is based on the premises of the species adopted for higher organisms, which are differentiated by the inability of reproduction among the organisms. However, this concept cannot be applied to prokaryotes, which is able to exchange genetic material easily among different species. Besides, morphologically they are not so diverse, and thus the relative morphologic simplicity of most prokaryotic microorganisms implies that morphology is, in general, of little importance in contrast with the classification of higher organisms. A species is represented by a type strain, a designated strain that is used as a reference specimen and as a permanent example of the species.

Traditionally, the definition of species in prokaryotes was based on the determination of the DNA-DNA hybridization values and ΔT_m . It was generally accepted that strains with approximately 70% or greater DNA-DNA relatedness and with 5 °C or less ΔT_m should be considered as members of the same species (Wayne et al. 1987). However, certain drawbacks with respect to reproducibility, workability, and rigid application of DNA-DNA hybridization were reported (Stackebrandt et al. 2002). For those reasons, the prokaryote species delimitation has been based on a polyphasic approach which included phenotypic, genotypic, chemotaxonomic, and

phylogenetic features. Phenotypic characteristics should agree with DNA-DNA hybridization values, and it was recommended that a distinct genospecies that cannot be differentiated from another genospecies on the basis of any known phenotypic property not be named until they could be differentiated by some phenotypic properties.

In recent years, new methods and techniques have been proposed to supplement or supplant the experimental DNA-DNA reassociation technique. The most extensively used is the 16S rRNA gene sequence analysis, a molecular marker to establish relationships among nucleotide sequences in the definition of prokaryotic species. On that basis, it was proposed that strains sharing 16S rRNA gene similarities below 97% could be considered as different genospecies (Stackebrandt and Goebel 1994). More recently, this percentage has been fixed on a 98.7%, (Kim et al. 2014; Chun et al. 2018), requiring a high quality of the 16S rRNA gene sequences under investigation (Chun et al. 2018). However, comparative studies clearly reveal the limitations of the sequence analysis of this highly conserved gene in the determination of relationships at the strain level. To overcome these limitations, MultiLocus Sequence Analysis (MLSA) based on conservative protein-coding genes, called housekeeping genes, had been developed for its applicability to genomically circumscribe the taxon species and differentiating it from neighboring species. Such genes should be at diverse chromosomal loci and widely distributed among taxa.

A more recent approach that advances the species definition for prokaryotes, as it is currently widely accepted, is based on the whole-genome sequence analysis, by using the Overall Genome Related Indexes (OGRI). The Average Nucleotide Identity (ANI) and digital DNA-DNA hybridization (dDDH) are the most widely used. It has been estimated that ANI values of approximately 95–96%, and dDDH 70%, respectively, corresponded to the traditional 70% DNA-DNA reassociation standard of the current species definition (Konstantinidis and Tiedje 2005; Goris et al. 2007; Richter and Rosselló-Móra 2009; Meier-Kolthoff et al. 2013; Chun et al. 2018).

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Specific Activity

Dionysis Foustoukos

Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Definition

Specific activity is a measure of the reactivity of a compound per unit mass under specific physico-chemical conditions. For example, the specific activity of an enzyme, used to assess enzyme purity, is defined as the amount of substrate converted through enzymatic processes per unit of time and mass of the total protein (e.g., $\mu\text{mol min}^{-1} \text{mg}^{-1}$). For a system containing a specific number of radionuclides, specific activity describes the number of decay events per unit time per mass or, equivalently, the product of the number of nuclides by the decay constant (Becquerel or counts per second).

Cross-References

- [Enzyme](#)
- [Radioactivity](#)

Spectral Analysis

- [Spectroscopy](#)

Spectral Classification of Embedded Stars

Philippe André

Laboratoire AIM, IRFU/Service d'Astrophysique, CEA Saclay, Gif-sur-Yvette, France

Keywords

Circumstellar disk · Infrared excess · Pre-main-sequence stars · Protostars · Spectral

energy distributions · Star formation ·
Submillimeter · Young stellar objects

Synonyms

Evolutionary sequence of young stellar objects

Definition

Young stars and their protostellar precursors are referred to as “young stellar objects” (YSOs) (Strom 1972), by astronomers since they are often deeply embedded in circumstellar dust and invisible at optical wavelengths. While most of them cannot be placed in the Hertzsprung-Russell diagram, YSOs can be organized along an empirical evolutionary sequence based on the shape of their spectral energy distributions (SEDs) from near-infrared to submillimeter wavelengths. Four broad classes of YSOs are distinguished (Class 0 → Class I → Class II → Class III) as the peak of the SED shifts from the submillimeter to the optical domain.

History

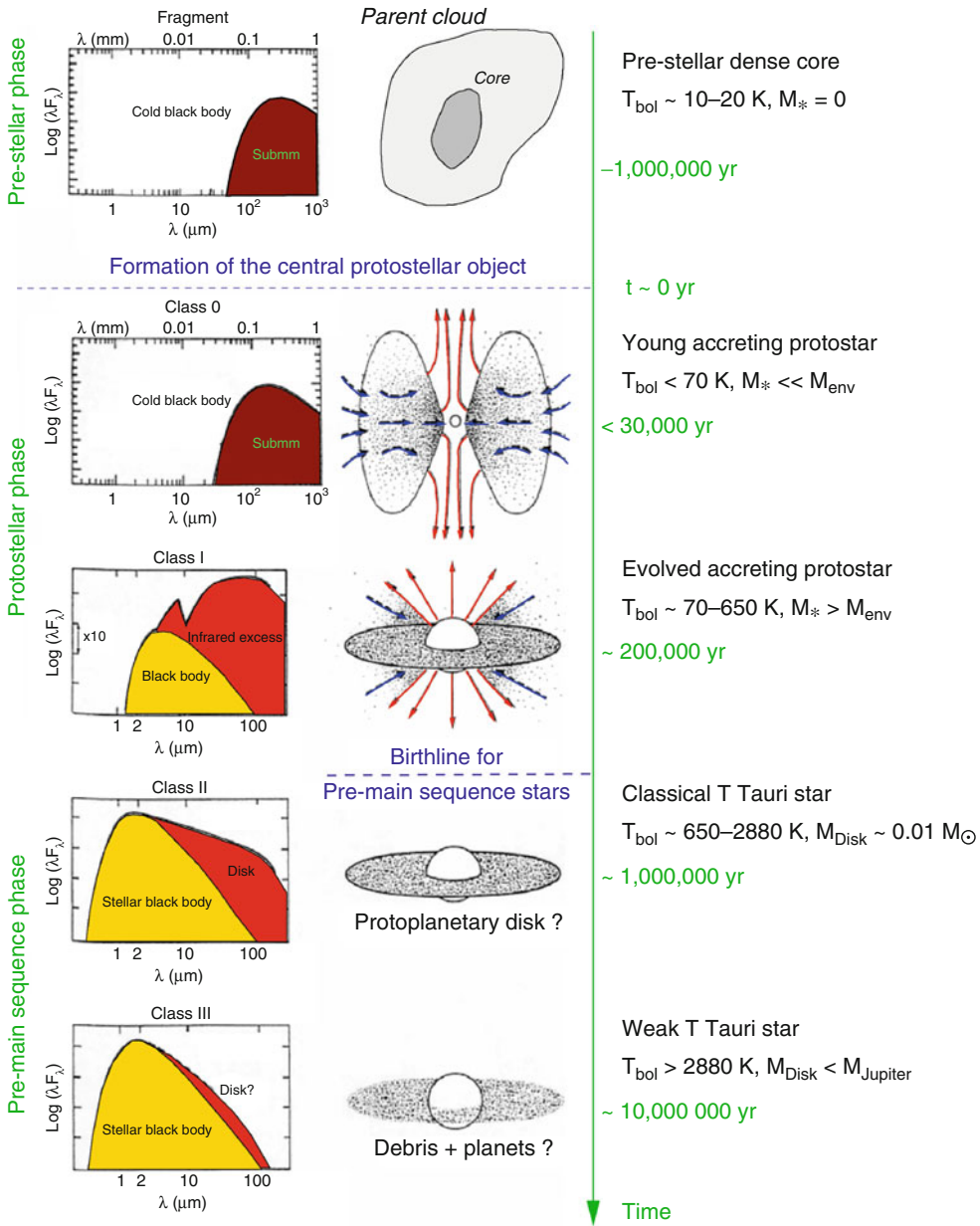
With the development of near-► [infrared astronomy](#) in the 1970s, many YSOs heavily obscured by dust at optical wavelengths were discovered in nearby star-forming clouds (e.g., Strom 1972). In the 1980s, the launch of the infrared satellite *IRAS* and the advent of near-infrared detectors allowed extensive surveys for embedded YSOs to be carried out and nearly complete spectral distributions of radiated energy to be constructed. Lada and Wilking (1984) and Lada (1987) proposed to divide the observed YSOs into three distinct morphological classes (I–III), depending on the slope $\alpha_{IR} = d \log (\lambda F_{\lambda}) / d \log \lambda$ of their near-infrared to far-infrared spectral energy distributions (energy flux λF_{λ} vs. wavelength λ). Adams et al. (1987) suggested that this infrared classification scheme could be interpreted in terms of an evolutionary sequence. With the development of millimeter and submillimeter observations, a fourth class (Class 0) was

then added to accommodate the discovery of YSOs so deeply embedded that they radiate large amounts of far-infrared and submillimeter emission relative to their total luminosities (André et al. 1993).

Overview

Classification of Spectral Energy Distributions

It is convenient to describe the spectral evolutionary classification of YSOs (cf. Fig. 1) by going backward in time, starting from objects detected in the near-infrared and ending with objects only (or mostly) visible at far-infrared and submillimeter wavelengths. In the near-/mid-infrared, three broad classes of YSOs can be distinguished based on the index $\alpha_{IR} = d \log (\lambda F_{\lambda}) / d \log \lambda$ of the spectral energy distributions (SEDs) between ~ 2.2 and $\sim 10\text{--}25 \mu\text{m}$ (Lada 1987). Class III sources have $\alpha_{IR} < -1.5$ and display reddened starlike or blackbody-like energy distributions. Class II sources have $-1.5 < \alpha_{IR} < 0$, reflecting the presence of significant near-► [infrared excess](#) emission superposed on a typical stellar blackbody. Class I sources have $\alpha_{IR} > 0$ and thus rising SEDs toward long wavelengths, implying a huge excess of far-infrared emission compared to that expected from a stellar photosphere. When optically visible, Class III and Class II objects correspond to pre-main-sequence stars (“weak” and “classical” T Tauri stars, respectively). The SEDs of Class I sources are successfully modeled in the framework of the “classical” theory of isolated protostars (e.g., Adams et al. 1987), in agreement with the view that a substantial fraction of their luminosity arises from accretion of circumstellar material (e.g., Greene and Lada 1996). Using millimeter and submillimeter observations, younger protostars, corresponding to a fourth class of YSOs (Class 0), have been identified. Class 0 objects, whose SEDs peak longward of $100 \mu\text{m}$ in the submillimeter domain, are very weak and often even undetected at near- and mid-infrared wavelengths shortward of $25 \mu\text{m}$. These objects are characterized by high ratios of submillimeter to bolometric luminosity ($L_{\text{submm}}/L_{\text{bol}} > 1\%$) and overall SEDs



Spectral Classification of Embedded Stars, Fig. 1 Empirical sequence for the formation and circumstellar evolution of a single star from a prestellar cloud core to a Class III young stellar object, based on the shape of the

spectral energy distribution (*left*), the bolometric temperature, and the mass of circumstellar (envelope + disk) material indicated on the *right* (From Lada (1987), André et al. (1993, 2000), and Myers et al. (1998))

resembling 15–30 K blackbodies (André et al. 1993). The full sequence of SEDs from Class 0 to Class III objects is in fact quasi-continuous and may be conveniently parameterized by a

single parameter, the average or “bolometric” temperature (T_{bol}), defined as the temperature of a blackbody having the same mean frequency as the observed YSO SED (Myers et al. 1998).

Circumstellar Evolution

YSOs are composite objects made up of a growing central star, a circumstellar disk, a circumstellar envelope, and a bipolar outflow. The SED classification described above primarily tracks the evolution of the circumstellar components. The strong submillimeter emission of Class 0 sources relative to their total luminosity indicates that the circumstellar envelope is the dominant component at the Class 0 stage, with a mass that exceeds the mass of the central stellar object ($M_{\text{env}} \gg M_*$; André et al. 2000). Class 0 objects are thus excellent candidates for being very young accreting protostars in which a hydrostatic protostellar embryo has formed within a dense cloud core but not yet accreted the majority of its final mass. They represent a pivotal evolutionary stage in the path leading from interstellar cloud matter to solar systems like our own. Class I objects are still associated with dense molecular gas and derive their large infrared excesses from the presence of both a disk and a circumstellar envelope (Adams et al. 1987). Mapping at millimeter wavelengths confirms the presence of a significant envelope at the Class I stage but shows that this envelope is no longer very massive and often only a remnant of the parent prestellar core ($M_{\text{env}} < M_*$; André and Montmerle 1994). Class II and Class III objects lack a dense circumstellar envelope component and are only surrounded by a circumstellar disk (optically thick and optically thin at $\lambda < 10 \mu\text{m}$, respectively). While the disk is still massive enough to be protoplanetary in nature at the Class II stage ($M_{\text{disk}} \sim 0.01 M$ on average; Beckwith et al. 1990), it has evolved to an optically thin debris disk by the Class III stage.

Bipolar Outflows and Gravitational Infall

Class 0 sources are associated with powerful, highly collimated bipolar outflows (Bontemps et al. 1996; Bachiller 1996), which provide indirect evidence of the presence of a central protostar and distinguish Class 0 YSOs from prestellar cores, i.e., starless dense fragments within molecular clouds.

As a whole Class 0 objects drive much more powerful outflows than Class I sources of

comparable bolometric luminosities (Bontemps et al. 1996). Furthermore, the **bipolar flows** from Class 0 objects are much better collimated than those from Class I (and Class II) sources.

Class 0 protostars were the first YSOs for which convincing spectroscopic signatures of gravitational infall motions could be obtained, confirming their protostellar nature (see Evans 1999 for a review). While some infall is still present at the Class I stage, the outflow is so broad in Class I sources that there often appears to be little transfer of mass to the inner 2,000 AU radius region around these objects.

Although the accretion/ejection phenomenon is believed to be episodic, the observed outflow and infall properties are suggestive of a global decline in the mass accretion rate onto the central protostar from $\sim 10^{-6} - 10^{-5} M_{\odot}/\text{year}$ at the Class 0 stage to $\sim 10^{-7} - 10^{-6} M_{\odot}/\text{year}$ at the Class I stage. Despite substantial scatter, a general decline in mass accretion rate as a function of age is similarly observed among T Tauri stars from $\sim 10^{-7} M_{\odot}/\text{year}$ for the youngest Class II objects to less than $\sim 10^{-9} M_{\odot}/\text{year}$ for Class III sources (e.g., Hartmann 1998).

Time Evolution and Approximate Timescales

To summarize, combining observations at near-infrared to millimeter wavelengths makes it possible to distinguish two classes of protostars (Class 0 and Class I) and two classes of pre-main-sequence stars (Class II and Class III), which are interpreted as an evolutionary sequence (Class 0 $\rightarrow$ Class I $\rightarrow$ Class II $\rightarrow$ Class III). Statistical arguments based on the numbers of sources observed in the various classes suggest that the corresponding lifetimes run from $\sim 1-5 \times 10^4$ years for Class 0 protostars to $\sim 1-5 \times 10^7$ years for Class III young stars, increasing by roughly a factor of ~ 10 from one evolutionary stage to the next (e.g., André and Montmerle 1994; Greene et al. 1994; Evans et al. 2009). These lifetimes also provide very rough estimates of the typical ages of YSOs according to their SED class. This is only true in a statistical average sense, however, since the above-described classification corresponds to an

evolutionary sequence only for the circumstellar material and is not directly related to the evolution of the underlying stellar objects. For instance, when placed in the Hertzsprung-Russell diagram, a significant fraction of weak T Tauri stars (Class III objects) appears to be not older than, but coeval with, Class II objects (e.g., Stahler and Walter 1993). These relatively young Class III objects may have dissipated their circumstellar disks and infalling envelopes particularly early, as a result of, e.g., unusually strong fossil magnetic fields and/or the tidal effects of a close companion. To some extent, therefore, the circumstellar evolution of YSOs is decoupled from their purely stellar evolution.

Basic Methodology

The practical diagnostics that one uses to order YSOs and cloud cores along the evolutionary sequence sketched in Fig. 1 are the infrared spectral index α_{IR} or shape of the infrared SED (Lada 1987), the “bolometric” temperature T_{bol} of a source (Myers et al. 1998), and the mass of circumstellar (envelope + disk) material (e.g., André and Montmerle 1994). Independently of the details of any protostellar theory, and in a statistical sense at least, one expects young stellar objects to become warmer and to be surrounded by progressively smaller amounts of circumstellar material as they evolve. Accordingly, the peak of the SED moves from the submillimeter for prestellar cores and (cold, deeply embedded) Class 0 protostars, to the far-IR for Class I protostars, to the near-IR and the optical for pre-main-sequence stars (Class II and Class III sources) (see Fig. 1). In the case of embedded protostars, the decrease of circumstellar mass with time results from the progressive dissipation of the protostellar envelope through accretion and outflow. For instance, in all self-similar isothermal models of collapse, including the classical Shu et al. (1987) model, the mass enclosed within a given radius R of the infalling envelope scales approximately as $M_{\text{env}}(r < R) \propto t^{-1/2}$ with time.

Future Directions

While ground-based near-IR surveys, coupled with infrared and X-ray observations from space with the *IRAS*, *ISO*, *Spitzer*, *XMM-Newton*, and *Chandra* satellites, have provided a fairly complete census of YSOs from Class I to Class III in nearby clouds, no such census exists yet for Class 0 protostars and cold prestellar cores. Only about 30 Class 0 protostars are known to date and only four in the nearest clouds ($d < 150$ pc) (cf. André et al. 2000). Consequently, the ages and lifetimes of prestellar cores and Class 0 objects are very uncertain compared to those of pre-main-sequence stars and remain a matter of lively debate in the star formation community (e.g., Ward-Thompson et al. 2007; Evans et al. 2009). Wide-field imaging at far-infrared and submillimeter wavelengths (70–500 μm) with the *Herschel* Space Observatory, successfully launched by ESA in May 2009, will soon remedy this unsatisfactory situation by providing complete samples of prestellar cores and Class 0 protostars in nearby Galactic molecular clouds. The first results of *Herschel* are extremely promising and suggest that more than 5,000 prestellar cores and more than 500 Class 0 protostars will be identified by the end of the space mission (see Astronomy and Astrophysics Vol. 518, special feature on *Herschel*).

Cross-References

- [Bipolar Flow](#)
- [Birthline](#)
- [Debris Disk](#)
- [Dense Core](#)
- [Fragmentation of Interstellar Clouds](#)
- [Hertzsprung-Russell Diagram](#)
- [Infrared Astronomy](#)
- [Infrared Excess](#)
- [Pre-Main-Sequence Star](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Protostellar Envelope](#)
- [Star Formation, Observations](#)

- [Star Formation, Theory](#)
- [T Tauri Star](#)

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Spectral Line

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A spectral line is a deficiency or excess of radiation at a precise wavelength in the spectrum of a source because of a quantum effect (transition between two energy states) in an atom, molecule, ion or functional group (in the case of a solid) present in the source. The terminology originated with the slit spectrometers used by physical scientists to display a spectrum. Each spectral line is very specific to a given species, so that it can be used to identify the chemical composition of the object emitting or transmitting the light analyzed with a ► [spectrometer](#). Comparing the intensities of different spectral lines provides information on physical conditions such as temperature and density. The displacement of spectral lines under the Doppler Effect allows astronomers to derive the velocity of the emitter (or absorber).

Cross-References

- [Doppler Shift](#)
- [Electromagnetic Spectrum](#)
- [Spectrometer](#)
- [Spectroscopy](#)

Spectral Parameters, Solar System Planets

Giulia Alemanno

Institute of Planetary Research, German
Aerospace Center, Berlin, Germany

Keywords

Planets · Surface composition · Minerals ·
Spectroscopy · Spectral features

Synonyms

[Parameterization of spectral data](#)

Acronyms

- OMEGA **O**bservatoire pour la **M**inéralogie,
l'**E**au, les **G**laces et l'**A**ctivité –
Visible and Infrared Mineralogical
Mapping Spectrometer onboard of
Mars Express mission
- CRISM **C**ompact **R**econnaissance **I**maging
Spectrometer for **M**ars onboard of
Mars Reconnaissance Orbiter
mission

Definition

Parameters directly linked to spectral signatures of minerals of interest are known as spectral parameters. The idea is that a given spectral feature can be described by a single parameter value, calculated by applying an algorithm to the spectral data.

Overview

Spectral parameters are a useful tool for the scientific interpretation of spectral orbital and in situ data and a key for future mission landing site selection and operations. A spectral parameter has the intent to capture spectral features diagnostic of a specific mineralogy. For example, mineral

spectra contain absorption features diagnostic of the mineralogical composition. Spectral parameters can be derived from the absorption features present in the spectra, isolating each absorption band. Absorption features can, then, be parametrized by calculating, for example, the band depth. This parameter is defined as $\Delta = 1 - R_{\lambda}/R_{\lambda,*}$, where R_{λ} is the reflectance at the center wavelength of the band and $R_{\lambda,*}$ is the interpolated continuum reflectance at the same wavelength (Clark and Roush 1984). The continuum level is created from a linear fit between two wavelengths from either absorption sides that are part of the local continuum levels. A spectral parameter value can be mapped across a region of a planetary body surface to study spatial variations of the associated spectral feature. These variations are in turn interpreted as spatial variations of the associated mineralogy.

The use of spectral parameters to analyze spectral data has been adopted with success in past and more recent analyses of planetary spectral data (see, for example, Bell et al. 2000; Murchie et al. 2009; Viviano-Beck et al. 2014; Mancarella et al. 2017; Alemanno et al. 2021). In the case of Mars, a set of 60 revised spectral parameters have been published by Viviano-Beck et al. (2014). The dataset published from these authors includes parameters related to OMEGA spectral parameter calculations and new parameters that highlight locations of newly discovered spectral signatures thanks to CRISM data. The analysis performed by Viviano-Beck et al. (2014) shows how the revised set of summary products presented unable to capture the spectral diversity of the Martian surface. Indeed, several works identified minerals on the Martian surface using CRISM data thanks to the application of these spectral parameters.

Cross-References

- [Absorption Spectroscopy](#)
- [Continuum](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Planetary Surface Ages](#)

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Spectral Survey

► [Molecular Line Survey](#)

Spectral Type

Sylvia Ekström
Observatoire Astronomique de l’Université de Genève, Faculté des Sciences, Université de Genève, CHVersoix, Switzerland

Definition

Stars are classified based on the ionization state of their atmosphere and thus on their surface temperature. From hottest to coolest, the classification goes as O, B, A, F, G, K, and M (with the mnemonic “Oh Be A Fine Girl/Guy, Kiss Me”):

Type	Temperature	Main lines
O	≥30,000 K	He II, C III, N III, O III, Si IV
B	10,000–30,000 K	He I, Mg II, Si II
A	7,500–10,000 K	H, Mg II, Fe II, Si II
F	6,000–7,500 K	H, Fe I, Cr I, Ca II
G	5,200–6,000 K	Fe I, Ca II, CH
K	3,700–5,200 K	Fe I, Si I, Mn I, TiO
M	≤3,700 K	TiO, VO, molecular

Each category has ten subdivisions numbered from 0 (hottest) to 9. The spectral type is usually complemented by the *luminosity class*, labeled in roman numbers from I (supergiants) to V (main sequence dwarfs); that is, stars of the same effective temperature may have differing luminosities, depending on their mass and evolutionary state.

The Sun has a spectral class G2V.

History

Historically, spectral types were assigned alphabetically primarily in an order reflecting the decreasing strength of hydrogen absorption lines in their spectra. Only later was it realized that the different spectral types resulted from differing surface temperatures.

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Stellar Evolution](#)

Spectral Veiling of Young Stars

Steven W. Stahler
Department of Astronomy, University of California, Berkeley, CA, USA

Definition

Stellar spectra exhibit sharp absorption lines superposed on a smooth, background flux. The

pattern of lines reveals both the chemical elements present in the stars' surface layers and the temperature of this material. In classical ► [T Tauri stars](#), pre-main-sequence objects of solar mass and below, the absorption lines are partially filled in. This is referred to as veiling and is thought to represent emission from shocks created as material crashes onto the stellar surface. The degree of spectral veiling correlates with the amount of ► [infrared excess](#), which arises from heated dust grains in circumstellar disks. Indeed, the infall creating spectral veiling is thought to arise largely from such disks. Both features are absent in weak-lined T Tauri stars.

Cross-References

- [Gravitational Collapse, Stellar](#)
- [Infrared Excess](#)
- [Pre-Main-Sequence Star](#)
- [Spectral Line](#)
- [T Tauri Star](#)

Spectrofluorometry

- [Fluorometry](#)

Spectrometer

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A spectrometer is an instrument used by scientists to decompose the radiation either emitted by a source or transmitted by a region or substance of interest, so as to measure the intensity as a function of the wavelength in a way that can be recorded. In the visible, it may be based on a prism or a grating; in the infrared, it can be a

Fourier transform technique which is used, and in the radio domain, it is generally an auto-correlator. It produces a spectrum (plural spectra) which is an accurate record of the intensity versus the wavelength.

Cross-References

- [Mass Spectrometry](#)
- [Spectral Line](#)
- [Spectroscopy](#)

Spectroscopic Orbit

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Definition

When two stars orbit each other and the orbital motion is detected spectroscopically from the changes in the Doppler shifts (also known as Doppler velocimetry), the system is traditionally called a spectroscopic binary. Accordingly, the orbital solution based on the observed changes in radial velocities of the two stars is called a spectroscopic orbit. When the companion is a planet, only the spectrum of the host star is detected. In this case, the planet and star revolve around their center of mass. Although the orbit of the primary star around the center of mass is smaller than that of the planet, it is still called a spectroscopic orbit. The five parameters that define a single-lined spectroscopic orbit are the orbital ► [period](#) P , the ► [eccentricity](#) of the elliptical orbit e , the velocity of the center of mass γ , the amplitude of the orbital velocity projected along the line of sight K , the orientation on the sky of the long axis of the ellipse ω , and the time of ► [periastron](#) passage T . When the orbit is circular, $e = 0$ and ω is not defined, so the time of maximum velocity away from the observer is used instead of T .

Radial velocities do not provide enough information to determine the orbital inclination, but do provide some information about the masses:

$$M_B \sin(i) = (M_A + M_B)^{2/3} f^{2/3}$$

Where f is the mass function and is given by

$$f = 1.036 \times 10^7 K_A P (1 - e)^{3/2}$$

M_A and M_B are the masses of the primary and secondary in solar masses, i is the orbital inclination (90° for an edge-on orbit), K_A is the observed semi-amplitude of the orbital velocity of the primary in km/s, P is the orbital period in days, and e is the orbital eccentricity. If the orbital inclination can be determined through other observations, then the $\sin(i)$ ambiguity can be removed. In a binary star, when the spectrum of the secondary star is also detected, the orbital amplitude of both stars can be determined, and thus the mass ratio $q = M_B/M_A = K_A/K_B$ can be obtained.

Cross-References

- [Doppler Shift](#)
- [Eccentricity](#)
- [Inclination \(Astronomy\)](#)
- [Periastron](#)
- [Period](#)
- [Radial Velocity](#)
- [Radial-Velocity Planets](#)

Spectroscopy

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Spectra · Spectral lines · Spectrograph ·
Spectrometer · Spectrum

Synonyms

[Spectral analysis](#)

Definition

Spectroscopy is the technique used to measure the intensity of electromagnetic radiation as a function of either wavelength or frequency. Spectroscopy is an important tool to derive the physical and chemical properties of astronomical objects as well as their velocity. The study of spectral features from atoms, ions, and molecules is of particular importance to give access to abundances, temperature, pressure, magnetic field, radial velocity, etc. The term spectroscopy is also applied in other fields, for example, to the measurement of the abundances by mass of chemical species in a sample (see Mass Spectroscopy).

Overview

Light brings a wealth of information, which a blind person misses badly every day. Generally, we think of this information primarily in the form of images of the world around us that light carries to our retina or to the electronic retinas of our cameras. In astronomy, imaging is often the first phase of discovery to derive morphology, shape, size, and displacement. From the planets to the discovery of giant structures or filaments in the Universe, images have played a major role in astronomy. Light carries yet another crucial piece of information, perhaps richer than the image, its energy. A celestial object indeed registers in the light it emits a footprint, often very accurate, of its composition, its energy state, and its dynamics. On one hand, physical processes will produce photons following a well-defined energy distribution, depending on the physical conditions like temperature or elementary composition of the source (gas of electrons, atoms of different chemical species), and, on the other hand, internal or global movements of this source often subtly alter this distribution.

Whatever is the description of light, photons, or electromagnetic waves, its energy content is perfectly defined. A photon, the particle of light, is described by two parameters only: its energy E and its state of polarization. Energy is the most important parameter because it will drive all the basic properties of the photon-matter interactions. This energy is unchanged as long as the photon is *alive*, that is to say, is not absorbed. If we now consider an electromagnetic wave, the other complementary way to describe light, it carries power in the form of waves progressing very rapidly: at the speed of light of course! Two wave crests are separated at a given moment by a characteristic length, called wavelength, and always denoted by the symbol λ . E and λ are related to the simple law $E = hc/\lambda$, where c is the speed of light and h is a physical constant introduced by Max Planck. The wavelength is a quantity which results in a clearly discernible property that our brain can perceive in visible light, which is the color. For instance, dark red corresponds to a wavelength of 750 nm, typically two times larger than the wavelength of blue light.

Most generally the resulting emission of a given phenomenon is the superposition of several waves at different wavelengths, in fact a continuum. If in music the superposition of wavelengths makes the richness of the sound, in contrast, for the astrophysicist, the wealth comes from the separation into the basic components of the light. This separation or decomposition is essential to analyze the predominance of one portion of the wavelength domain or another or for seeking for *spectral lines* which are reinforcements (known as emission lines) or gaps at a particular wavelength (absorption lines). This information bears the mark of processes that gave birth to the light or have influenced it later and which allow the astrophysicist to go much further in the physical understanding of phenomena than is allowed by the image alone. Spectroscopy is the science of analyzing the light into its components, and it is customary to say that astrophysics, to distinguish it from conventional astronomy, was born in the middle of the nineteenth century with the advent of spectroscopy. It is always amazing to realize the extraordinary richness of the spectroscopic

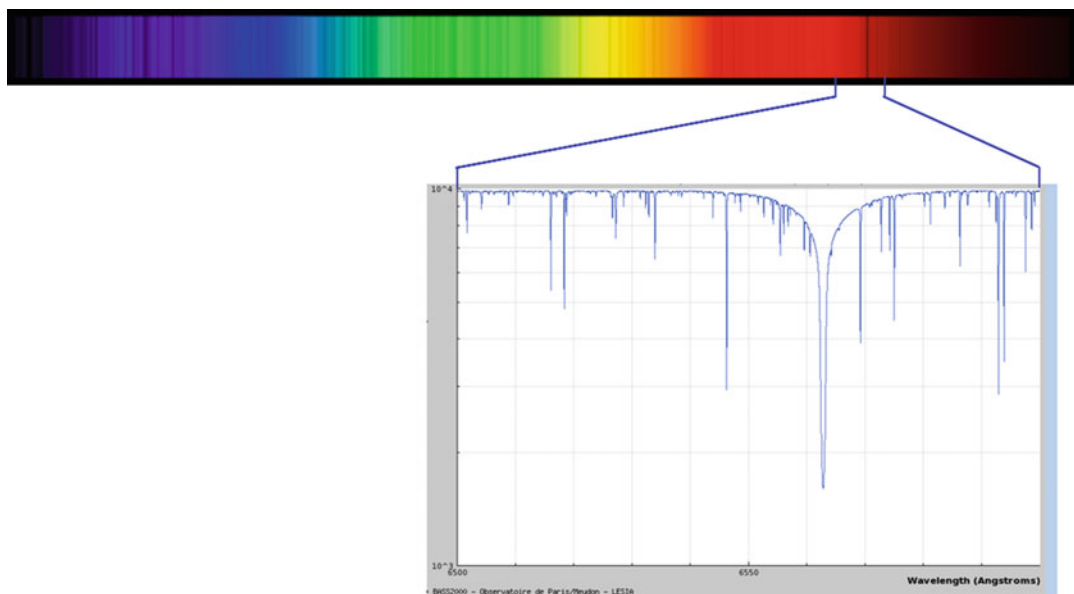
information. It actually gives access to a wide variety of physical quantities: the velocity of an object or even the velocity distribution of its components (for instance, in a galaxy); the composition of the matter it is made of, atoms or molecules; the state of this matter (ionized, atomic, molecular, solid, gaseous); the temperature, density, or pressure of the gas; the intensity and direction of the magnetic field, etc. These quantities are then used by the astrophysicist to constrain physical models describing the objects and their interactions. Predictions are then proposed that new spectroscopic measurements will confirm or deny in a continuously repeated cycle.

Basic Methodology

Spectrographs. Spectroscopy uses dedicated instruments to decompose the light in order to produce a spectrum, i.e., a measure of the light intensity as a function of wavelength. Figure 1 illustrates a spectrum of sunlight in two forms: the colorful one that the eye sees in the spectroscope and the more quantitative one as a plot of light intensity as a function of wavelength. The instrument that makes this decomposition is a spectrograph or a ► [spectrometer](#); however, for the purist, the later term refers rather to an instrument that provides a direct and accurate calibration of the wavelength.

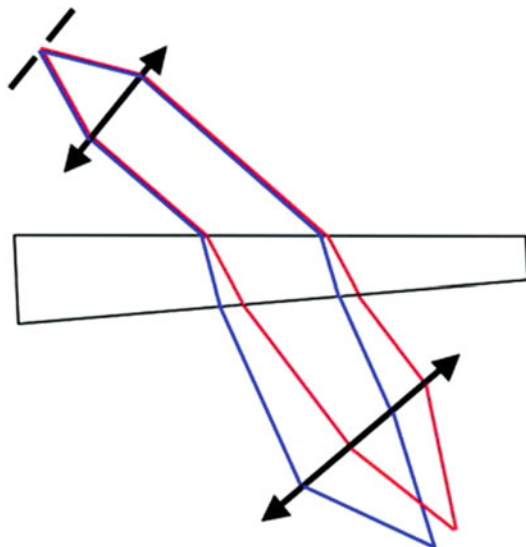
The prism spectrograph. The first spectrographs exploited the variation with wavelength of the optical index of materials to produce differential deviation of the light according to its color (its wavelength) when refracted by a prism. Figure 2 shows the basic elements of a prism spectrograph. Issued from a point source, whose extension is limited by a slit, a parallel beam is formed thanks to the first lens – the collimator; the beam falls then on the prism at a specific angle of incidence – and the second lens after the prism, the camera, reforms a series of distinct images of the source, each one at a given wavelength.

Among the disadvantages of the prism is the size it must have when one wishes to achieve a high resolution. Producing glass blocks of large volume, while guaranteeing a very good



Spectroscopy, Fig. 1 The visible spectrum of the Sun presented in two forms. *Top*: as it appears in a spectroscope, that is to say, as a bright band showing the colors of the rainbow and streaked with many lines more or less dark; *bottom*: a plot giving the accurate information of

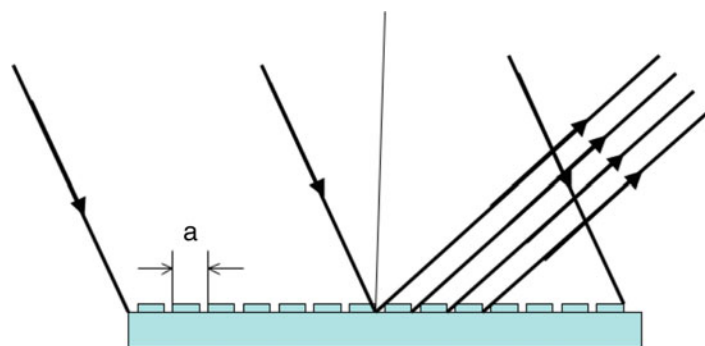
the intensity versus wavelength in a narrow region. Note the significant depression in the spectrum at 656.6 nm: it corresponds to an absorption due to hydrogen (Doc: BASS 2000)



Spectroscopy, Fig. 2 The principle of a prism spectrograph: it includes a slit, a collimator (*double-headed arrow*), the prism, a camera lens (a *second double arrow*), and a detector on which the spectrum is formed

homogeneity of their optical properties, becomes a challenge. The absorption in the glass is another limitation. The prism spectrograph has been supplanted gradually by the grating spectrograph.

The grating spectrograph. The grating spectrograph uses the principle of light interference that stems directly from the wave nature of light. A grating is a reflective surface which has been engraved with a series of fine parallel grooves separated by very small distances, a few micrometers to a few tens of micrometers. If a beam of light falls on the surface, then each slot, because it is very small, will spread the light in all directions (the ► [diffraction](#) phenomenon). In a given direction, there is a unique wavelength for which the wavelets emitted by all the grooves are in phase and will therefore add, as shown in Fig. 3. In a direction somewhat different, waves at that wavelength are somehow out of synchronization, and, as there is a very large number of them, they cancel each other. A given direction is thus associated with a single wavelength whose intensity is preserved, while at all other wavelengths, the destructive phenomenon is extremely effective.

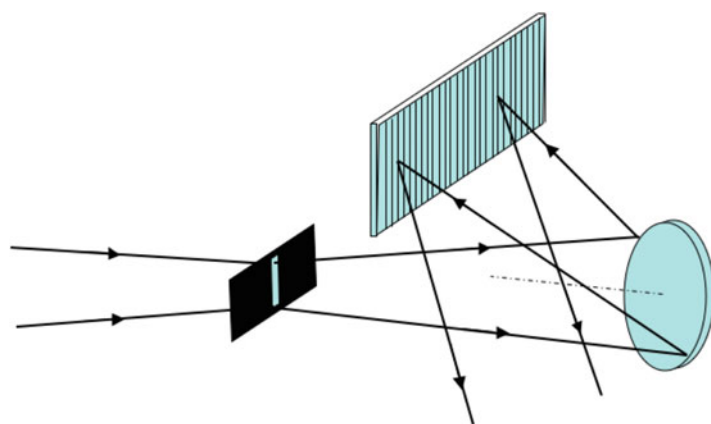


Spectroscopy, Fig. 3 The principle of the diffraction grating. Each groove engraved on the surface of the grating diffracts light in all directions. In a given direction, there is a single wavelength for which all the waves from the

different grooves are constructive. In the same direction but at a different wavelength, the waves are incoherent and destroy each other

Spectroscopy,

Fig. 4 Arrangement of the entrance slit, of collimator (here a spherical mirror), and of the grating in a grating spectrograph



Eventually, we obtain the desired effect: each wavelength is isolated in a given direction.

In practice, for a good separation of wavelengths, one looks for a large number of lines per unit length (about 40–200), a result obtained thanks to a very precise machine equipped with diamond tools. In addition, the grating is used at large angles of incidence of the beam on the grating. Significant progress has been made with the introduction of the *échelette* grating, so named because of the particular stair shape of the grooves: the facets that behave like small mirrors can better focus the light in the direction where the spectral analysis has to be done.

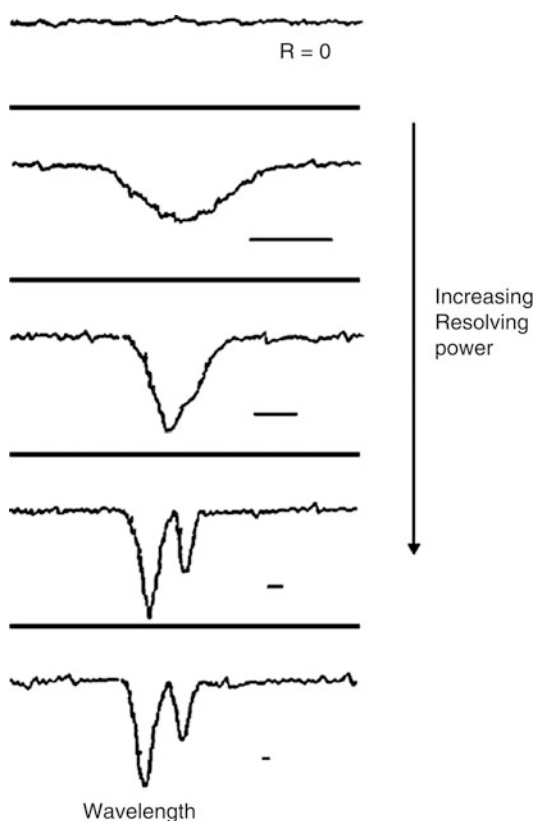
From the viewpoint of its implementation in a spectrograph, the grating is used in a manner quite similar to that of the prism: it is placed in the parallel beam issued from a collimator and a camera objective reforms the image of the entrance slit

on the detector, the slit being oriented parallel to the lines of the grating. Figure 4 illustrates this configuration.

Fourier transform spectrograph. Fourier transform spectroscopy is a clever use of the interference of light to derive the spectrum. The intensity of a beam containing all the different wavelengths of the studied light, but each with a different weighting, is measured by a unique detector. The weighting is due to interferences in a Michelson interferometer, an optical instrument that allows some wavelengths to pass through but blocks partially or totally others. By moving one of the mirrors of the interferometer, the interference structure and thus the weighting is changed, so that repeating the process many times produces as many data points as there are distinct wavelengths. However, this is not yet a spectrum, each measurement being a linear combination of

different intensities of the various wavelengths. Inverting the set of data to produce the spectrum is done with a computer, thanks to a rather simple algorithm called the Fourier transform. One advantage of the Fourier transform spectrograph is the capability to reach very high resolving power. It is becoming a widespread laboratory instrument to measure molecular or atomic spectra.

Performances of a spectrograph. Since the goal of a spectrograph is to separate the wavelengths, its main characteristic is its resolution or resolving power $R = \lambda/\Delta\lambda$, defined as the ratio of the central wavelength to the smallest difference in wavelength $\Delta\lambda$ between two *colors* that can be distinguished unambiguously. $\Delta\lambda$ is called the spectral resolution element. Figure 5 illustrates how the



Spectroscopy, Fig. 5 Observation of a spectral feature in a spectrum (a *double line* in absorption) when the resolving power increases: from a mere depression, one passes to the separation into two distinct components. The spectral resolution element is indicated by the *horizontal line* segment to the right of each curve

information becomes more accurate when the resolving power increases and thus the spectral resolution element becomes smaller. For a grating, one may show that the maximum resolving power is directly given by the ratio of the length of the grating to the wavelength. A large grating is thus required to reach a large resolving power.

The resolution of a spectrograph varies according to the goal to be achieved: for the spectroscopy of faint distant galaxies, a resolution of $R = 2000$ is well suited. In contrast, in spectroscopy of a bright source like the Sun, where extremely fine physical effects can be looked for, resolving powers of several hundreds of thousands are common. In ► [radio astronomy](#), heterodyne techniques can provide even much higher resolution.

A second element of performance is the wavelength range that a spectrograph is able to analyze at once. The size of the detectors often limits the spectral range. Note that the prism has the advantage over the grating in having a spectral range that is bounded solely by the transmission of the glass, while the grating is limited in principle to an octave or less if very high spectral resolution is the goal. However, a clever combination of optics can overcome this limitation and provides simultaneously broad spectral range and high resolution. The trick is to use a second grating or a prism of modest resolving power to disperse the light in a direction perpendicular to the primary dispersion, so that the spectrum is divided into bands that can cover the surface of a CCD detector with no overlap. This setup, called a cross-dispersed spectrograph, is more and more popular in astronomy, and, in particular, it is the choice instrument for the detection of exoplanets through ► [radial velocity](#) measurements.

Among other factors to judge the quality of a spectrograph is its transmission: for instance, it should not lose 95% of the photons reaching the telescope because of too many optical elements.

Key Research Findings

Recent developments in spectroscopic techniques have aimed at responding to new needs of the astronomer. Among them two have particularly emerged: linking imaging and spectroscopy and

simultaneous spectroscopy of a large number of objects (we do not discuss here developments in ► [radio astronomy](#) or very short wavelength astronomy).

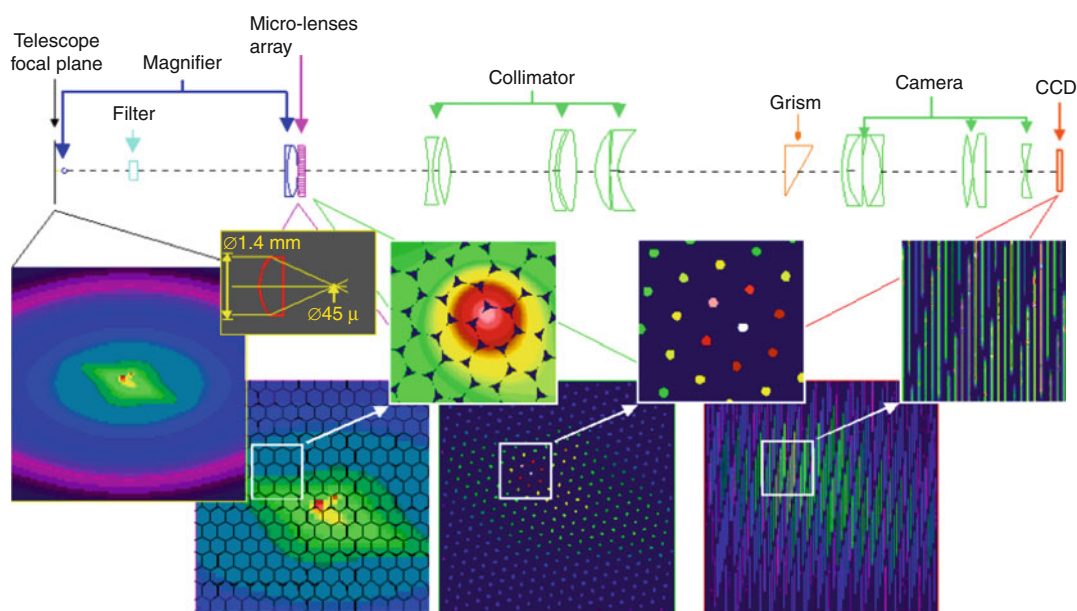
Spectroscopy of extended objects: integral field spectroscopy. Conventional spectrographs are well adapted to stellar physics, which studies essentially spatially unresolved objects. However, when one deals with extended objects such as planets, galaxies, or some nebulae (HII regions, planetary nebulae), the access to spectral information anywhere on the object is required to understand the physics that governs the different parts (e.g., the temperature) or to measure the relative velocities, etc. A conventional spectrograph does not allow it, its entrance slit limiting the field of view.

Different ideas have been proposed to obtain what is called an integral field spectrograph that can simultaneously obtain spectra from all points of the field or at least from a significant number of cells covering the object.

One idea is to divide the field of view into small cells with an array of microlenses, each of which

will form a small bright spot at its focus. Each point feeds one optical fiber among a few tens of fibers arranged in a compact bundle. The light is then carried by each fiber to the entrance slit of a spectrograph where the output fibers are aligned along the slit. This configuration is well suited to simple objects that do not require many pixels. When this is not the case, then other solutions have been proposed. A variant of the previous configuration that uses an array of microlenses is to collimate the light at the focus of each microlens on a diffraction grating (actually a grism, a particular type of grating deposited on a prism and whose advantage is that the central wavelength is not deviated) that will give a spectrum of each micro-point source. All spectra are formed on a CCD array with a trick: the dispersive grating is rotated by a small angle with respect to the pattern of microlenses, so that no overlap occurs, as illustrated below (Fig. 6).

Multi-object spectroscopy. The need to conduct simultaneous spectroscopy of many objects in the same field has emerged with the advent of large surveys in the late 1990s.



Spectroscopy, Fig. 6 The concept of an integral field spectrograph designed by George Courtès. It forms simultaneously the spectra of different regions of an object whose image has been divided into smaller areas by an

array of microlenses. Note that the dispersion is provided by a grism whose direction of dispersion is slightly rotated relative to the pattern of microlenses so as to avoid overlapping spectra of nearby regions

Two concepts have been successfully developed: One is based on the use of a bundle of several tens of optical fibers and the other one on the use of a slit mask. In the first case, the head of each fiber is positioned very precisely in the field of the telescope, at the location, previously measured, of the object. This positioning is performed by robotic arms or by fixing each fiber head on a large metal plate thanks to a magnet. The plate is then placed at the focus of the telescope by a robotic system. The other end of each fiber is placed on the entrance slit of a standard spectrograph that can accommodate a large number of them and produces all spectra simultaneously.

In the second configuration, a mask punched with small slits at the locations of objects whose spectrum is wished is put in place at the focus of the telescope. An optical system, a grism, can then decompose the light from each of the mini-slits to form as many spectra as there are selected objects. One has to choose carefully the slit positions so that the spectra do not overlap and cover almost entirely the surface of a CCD array of large size. The punching of the masks is done by machining a thin metal plate with a power laser, after a picture was first taken from the field and then analyzed, and the objects selected by the astronomer to finally produce a code that controls the movements of the laser. The plates of planned observations are then inserted into a set of “drawers” to be set up rapidly with a great accuracy.

Cross-References

- [Continuum](#)
- [Line Profile](#)
- [Linewidth](#)
- [Spectral Line](#)
- [Spectrometer](#)

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Spectroscopy, Electronic (UV-Vis Astronomy)

Marcelino Agúndez

Instituto de Física Fundamental, CSIC, Madrid, Spain

Definition

Electronic spectroscopy studies the electronic states of a molecule or atom and the radiative transitions between them. Each electronic state is associated with a given configuration of the electrons of the system and it is characterized by a discrete energy. The electronic spectrum is composed of lines that correspond to radiative transitions, that is, those that occur with emission or absorption of a photon, between two electronic states and usually fall in the ultraviolet and visible ranges of the electromagnetic spectrum. For more information, see, for example, the classic books of G. Herzberg (1944, 1950, 1991). Historically, UV-visible spectroscopy was the first spectroscopy used in astronomy, and it is still widely used as it permits to identify atoms in different ionization states and simple molecules like H₂ and HD, and to detect absorption from the so-called diffuse interstellar bands, presumably arising from large molecules.

Cross-References

- [Absorption Spectroscopy](#)
- [Diffuse Interstellar Bands](#)
- [Molecular Spectroscopy](#)
- [Spectroscopy](#)
- [Spectroscopy, Rotational](#)
- [Spectroscopy, Vibrational](#)

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Spectroscopy, History of

Stéphane Le Gars
Centre François Viète, Université de Nantes,
Nantes, France

Keywords

Astronomy · Chemistry · Physics · Gustav Kirchhoff · Robert Bunsen

Definition

Establishing, at the end of the seventeenth century, that sunlight consisted of colors which were refracted differently by prisms, Isaac Newton (1643–1727) laid the foundation of physical optics. It was only at the beginning of the nineteenth century that major experimental innovations allowed the discovery of dark lines in the solar spectrum. Kirchhoff and Bunsen's works published in 1859 gave an explanation of these lines and made the spectral analysis (soon called ► [Spectroscopy](#)) a powerful tool in the fields of astronomy, physics, and chemistry.

Overview

Spectroscopy is the study of luminous spectra, i.e., the analysis of the intensity of radiation as a function of wavelength (color, for visible wavelengths). For the Greek philosophers, such as Xenophanes (c.570–460 BCE), Aristotle (384–322 BCE), or Epicurus (341–270 BCE), the colors observed in the rainbow were only a dimming of the solar light after going through an aqueous medium denser than the air. At the beginning of the seventeenth century, Kepler took an interest in prisms, but only described the colored rays he observed at the exit of the prism, putting forward a “sensual axiom” to justify the coloration of refracted rays. In 1672, in his *Traité d'Optique* published in 1704, Newton proposed a real color theory. Newton quantified refraction for the first time, characterizing each color by a number. Indeed, Newton showed that the colors obtained with the help of the prism are homogeneous and really form the solar light.

In the eighteenth century, the Swiss mathematician Leonhard Euler (1707–1783) adhered to a wave conception of light and gave another meaning to the number connected to each color: He identified it with the wavelength in a given medium. But later on, it was on an experimental level that the study of spectra progressed. Using a slit in front of a prism, British William Hyde Wollaston (1766–1828) discovered in 1802 five dark lines in the solar spectrum; in 1815, the German optician Joseph von Fraunhofer (1787–1826) detected 576 of them by joining an astronomical reflector to the slit-prism system. The nature of these dark lines was identified by the German scientists Gustav Robert Kirchhoff (1824–1887) and Robert Wilhelm Eberhard von Bunsen (1811–1899): They arise from the absorption of light by a medium set in front of the light source. Moreover, under defined conditions of excitation, an object can only emit the radiations it is capable of absorbing. This law, called “Kirchhoff's,” allowed chemical analysis by the study of emission and absorption spectra. The Kirchhoff and Bunsen discoveries sharply affected the scientific world: e.g., spectroscopy ruined with the ideas of Auguste Comte

(1798–1857) about the impossibility of a chemical and physical study of the astronomical objects and permitted the development of astrophysics.

Cross-References

- [Spectral Line](#)
- [Spectrometer](#)
- [Spectroscopy](#)

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Spectroscopy, Rotational

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Definition

Rotational spectroscopy studies the radiative transitions between discrete energy levels associated

with the rotation of a molecule. Rotational level energies are related to the moments of inertia of the molecule, which in turn depend on the masses of the nuclei and the distances and angles between them. Radiative transitions between rotational states, which are only allowed for polar molecules, lead to absorption or emission of photons that usually fall in the microwave and (sub-) millimeter ranges of the electromagnetic spectrum, generally called radio in astronomy. For more information, see, for example, Herzberg (1950) and Townes and Schawlow (1975).

Cross-References

- [Infrared Spectroscopy](#)
- [Molecular Spectroscopy](#)
- [Radio Astronomy](#)
- [Spectroscopy, Electronic \(UV-Vis Astronomy\)](#)
- [Spectroscopy, Vibrational](#)

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Spectroscopy, Vibrational

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Definition

Vibrational spectroscopy is concerned with the study of the vibrational states of a molecule and the radiative transitions between them. The vibrational states of a molecule are characterized by discrete energies that are related to the molecular structure via the masses of the nuclei and the strengths of the chemical bonds. Radiative

transitions between vibrational states lead to the absorption or emission of photons that usually fall in the infrared range of the electromagnetic spectrum. For more information, see, for example, the classic textbooks of Herzberg (1950, 1968).

Cross-References

- [Infrared Astronomy](#)
- [Infrared Spectroscopy](#)
- [Molecular Spectroscopy](#)
- [Spectroscopy, Electronic \(UV-Vis Astronomy\)](#)
- [Spectroscopy, Rotational](#)

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SPECULOOS

Michaël Gillon

Astrobiology Research Unit, University of Liège, Liège, Belgium

Acronyms

SPECULOOS: Search for habitable Planets EClipping ULtra-cOOl Stars

Definition

SPECULOOS (Search for habitable Planets EClipping ULtra-cOOl Stars) is a photometric survey aiming to explore all the ultracool (M7-type and later) dwarf stars within 40 parsecs for transiting rocky planets (Burdanov et al. 2018; Delrez et al. 2018; Gillon 2018; Triaud et al. 2020). Its concept is motivated by the expected

capacity of next-generation giant telescopes to perform the detailed atmospheric characterization of potentially habitable planets at the condition that they transit a very nearby star at the bottom of the main sequence (Kaltenegger and Traub 2009; Gillon et al. 2020). SPECULOOS is based on a network of six 1 m robotic telescopes: the four telescopes of the SPECULOOS-South facility at the Cerro Paranal European Southern Observatory in Chile; the SPECULOOS-North telescope at Teide Observatory in Tenerife; and the SAINT-EX telescope at San Pedro Mártir Observatory in Mexico. SPECULOOS is a project led by the University of Liège (PI: Michaël Gillon) and carried out in partnership with the Universities of Cambridge (Co-PI: Didier Queloz), Birmingham (Co-PI: Amaury Triaud), Bern (Co-PI: Brice-Olivier Demory), and MIT (Co-PI: Julien de Wit). The scientific operations of SPECULOOS-South started in January 2019, and those of SPECULOOS-North and SAINT-EX in summer 2019. The project's prototype (Gillon et al. 2013) discovered the TRAPPIST-1 system composed of seven temperate Earth-sized planets (Gillon et al. 2016, 2017).

Cross-References

- [TRAPPIST-1 System](#)

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Spheroplast

► Protoplast

Spherules

Nadja Drabon

Stanford University, Stanford, CA, USA

Keywords

Meteorite impact · Microtektite · Microkrystite

Synonyms

Distal impact ejecta; Microkrystite; Microtektite

Definition

Spherules are distal deposits of meteorite impacts. They are spherical droplets that can form in two ways: as silicate splash particles of ejected impact melt and as condensates from the rock-vapor plume. Glassy spherules that do not contain any crystallites are called microtektites (Glass 1990). These often contain vesicles and are commonly originated as melt spherules. Crystal-bearing

spherules, in contrast, are typical to have originated from vapor condensates and are termed microkrystites (Glass and Burns 1988). Spherules can be less than a hundred micrometers to a few millimeters in diameter. Spherules may be deposited globally or in *strewn fields* which radiate from the crater.

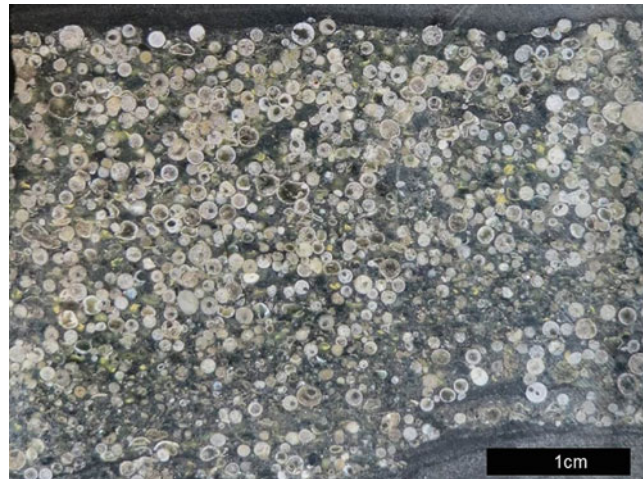
Overview

Spherule beds are sedimentary layers that are composed entirely of spherules or, if reworked, may contain detrital material. Pure spherule beds can be up to a few decimeters thick. The impact-related origin can be recognized by geochemical anomalies that indicate extraterrestrial components, such as abnormally high concentrations of platinum group elements, especially iridium, and extraterrestrial chromium isotope signatures (Shukolyukov and Lugmair 1998, 2000), and by the presence of shocked minerals.

Spherules were first discovered by Bill Glass in 1967 in the Australasian microtektite layer which is the largest Cenozoic strewn field. Since then, spherules have been widely used to identify meteorite impacts in the Earth's and the moon's history (Chao et al. 1970). In contrast to regionally to potentially globally distributed spherule beds, craters are local features and thus more vulnerable to be entirely obliterated by erosion or tectonic processes. To date, 31 spherule layers have been identified. The Archean spherule layers in South Africa and Australia are the oldest evidence of impacts (Fig. 1) (Lowe and Byerly 1986; Lowe et al. 2003) and were formed by the largest impactors identified to date on Earth. Their bolides are thought to have been 20 km to over 100 km in diameter (Lowe et al. 1989; Melosh and Vickery 1991; Kyte et al. 1992; Shukolyukov et al. 2000). Impacts of this size had a profound effect on the environment and early life (e.g., Sleep et al. 1989; Toon et al. 1997; Naumov 2005; Pierazzo and Artemieva 2012; Kring 2003; Abramov and Mojzsis 2009). They include local effects, such as fireballs and shock waves. Large impacts may have had global effects, such as global darkening by dust loading of the atmosphere and global

Spherules,

Fig. 1 Paleoarchean spherules of the Barberton greenstone belt, South Africa



climate change. Because physical changes are relatively short lived and local, the most important biologic effects result from impact-induced environmental changes. These may cause the collapse of the food chain or the destruction of geochemical gradients. Yet, impacts may also be beneficial for life on a molecular to evolutionary scale (Cockell and Bland 2005). They are thought to potentially have carried life to Earth ($\rightarrow$ *Panspermia*) or shock-synthesized the organic building blocks necessary for life during the impact. Impacts also create new habitats such as crater lakes, hydrothermal systems, and shock-weakened rocks and can empty ecological niches to subsequently allow other species to radiate.

Cross-References

► [Panspermia](#)

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SPICAV

► [Venus Express](#)

Spin-Polarized Electron Beam

► [Polarized Electron](#)

Spitzer Space Telescope

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Dust clouds · Exoplanet · Planetary disks · Star formation

Synonyms

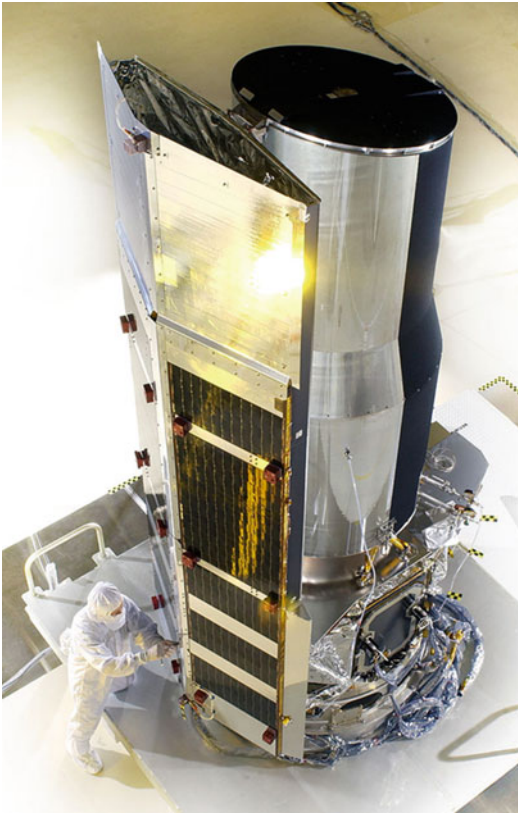
[SIRTF](#); [Space infrared telescope facility](#); [SST](#)

Definition

The Spitzer Space Telescope is the fourth of the Great Observatories that ► [NASA](#) has sent in orbit for astronomy. This three-axis stabilized pointing and scanning telescope with a spectral range from 3 to 180 μm has an 85-cm mirror made of beryllium and cooled by liquid helium (360 l at launch). The 950-kg satellite was placed on a heliocentric orbit on August 25, 2003, by a Delta II rocket launched from Cape Canaveral. Thanks to its unusual heliocentric orbit, it has continued observations with the Infrared Array Camera using only the 3.6 and 4.5 μm channels even after the cryogen was exhausted. This warm mission mode began on May 15, 2009 (Fig. 1).

History

As early as 1979, the US National Academy of Sciences was recommending a Shuttle Infrared Telescope Facility (SIRTF). The proposed 1-m telescope was supposed to operate from the Shuttle cargo bay during orbiting missions. With Shuttle weekly flights able to last up to several weeks, the telescope would be refurbished and refilled with cryogen on the ground, and focal plane instruments could be changed frequently. It appeared in 1985, after the STS-51F flight and tests of the first Shuttle-based Infrared Telescope (IRT), that the Shuttle environment would not be suitable for the IR observations. The planned observatory then changed the first word of its denomination from Shuttle to Space, still keeping the acronym SIRTF. The experience and data gained from the Infrared Astronomical Satellite (IRAS; 1983) as well the later success of the European Infrared Space Observatory (ISO, 1995–1998) led to several remodeling of the SIRTF project. During the following years, the budgetary pressure imposed a dramatic downsizing from an ambitious 5700-kg space platform



Spitzer Space Telescope, Fig. 1 NASA Spitzer Telescope (<http://www.cosmosportal.org/view/article/140793/> last accessed 31 July 2014)

to the actual 950 kg. Technical improvements saved most of the scientific objectives and performances.

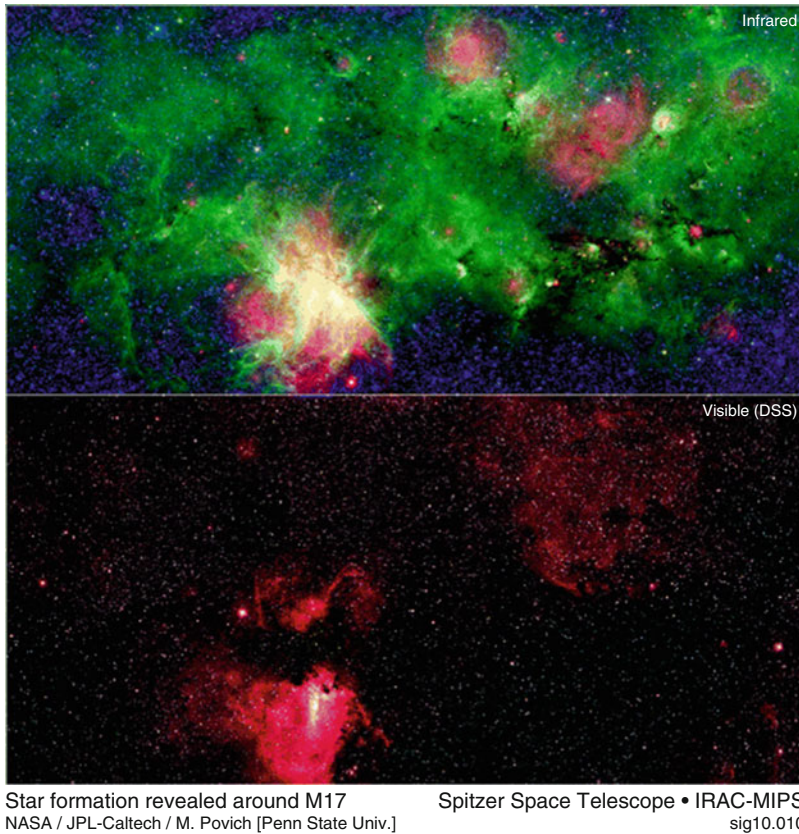
Overview

The Spitzer Space Telescope is a three-axis stabilized pointing and scanning telescope with a spectral range from 3 to 180 μm . The primary 85-cm mirror is made of beryllium, and the instruments are cooled by liquid helium (360 K at launch). The 950-kg telescope was placed on a heliocentric orbit on August 25, 2003, by a Delta II rocket launched from Cape Canaveral. In this orbit, the spacecraft is trailing the Earth around the Sun, drifting away, and “losing” around 15 million kilometers per year. This orbit permits excellent,

uninterrupted viewing of a large portion of the sky without the need for Earth-avoidance maneuvers. In addition, the absence of heat input from the Earth provides a stable thermal environment. This allows innovative passive cooling of the exterior of the telescope to reach a low temperature via radiative cooling. The telescope was launched “warm” and then cooled in space for 45 days. Overall, these innovations drastically reduced the total mass of helium needed. This orbit also simplifies telescope pointing but does require the Deep Space Network for communications. The 1-m-diameter-transmitting antenna is used twice each day to transmit 12 h of stored science data.

Spitzer’s science payload consists of three cryogenically cooled instruments, which together offer observational capabilities stretching from the near to the far infrared. The Infrared Array Camera (IRAC) provides images at 3.6, 4.5, 5.8, and 8.0 μm , with two adjacent fields of view. One field of view images simultaneously at 3.6 and 5.8 μm and the other at 4.5 and 8.0 μm via dichroic beam splitters. The Infrared Spectrograph (IRS) performs both low- and high-resolution spectroscopy. Low-resolution, long-slit spectra can be obtained from 5.2 to 38.0 μm . High-resolution spectra in Echelle mode can be obtained from 9.9 to 37.2 μm . The spectrograph consists of four modules. One of the modules incorporates a peak-up function that can be used in locating and positioning sources on any of the four spectrometer slits. The Multiband Imaging Photometer for Spitzer (MIPS) is designed to provide photometry and super-resolution imaging, as well as efficient mapping capabilities, in three wavelength bands centered near 24, 70, and 160 μm .

The cryogenic mission was planned for 2.5 years and lasted actually around 5.5 years. Since May 15, 2009, after the exhausting of the liquid helium, Spitzer is on a warm mission. In this mode, only the IRAC channels at 3.6 and 4.5 μm are usable. During the cryogenic phase, the focal temperature was stabilized around 15 K, and it has been raised to 30 K during the warm phase. The mission was terminated by NASA January 30, 2020.



Spitzer Space Telescope, Fig. 2 A dragon-shaped cloud of dust seems to fly out from a bright explosion in this infrared light image taken by the Spitzer Space Telescope (*top*), a feature that is entirely cloaked in shadow when viewed in visible part of the spectrum (*bottom*). The infrared image has revealed that this dark cloud, called M17 SWex, is forming stars at a very high rate. The remnants of an older burst of star formation blew a type of bubble to the left, in the region called M17 EB. The visible-light view of the area clearly shows the bright M17 nebula, as well as the glowing hot gas filling the “bubble”

to its left. However, the M17 SWex “dragon” is hidden within dust clouds that are opaque to visible light. It takes an infrared view to catch the light from these shrouded regions and reveal the earliest stages of star formation. The *top* image is a three-color composite that shows infrared observations from two Spitzer instruments. The *bottom* visible-light image is a composite of visible-light data from the Digitized Sky Survey (DSS) from the UK Schmidt Telescope. The image combines two observations that represent the *blue* and *red* light from the region. (Image Credit NASA/JPL-Caltech/M. Povich (Penn State Univ.))

The “warm” Spitzer surveys about 700 near-Earth objects, cataloguing their individual characteristics. Such a survey is helping to gather more accurate estimates of asteroids’ compositions and sizes.

The Spitzer Space Telescope is a NASA mission managed by the Jet Propulsion Laboratory. The science and data archiving as well as the selection of observation times is managed by Spitzer Science Center, located on the campus of the California Institute of Technology and part of NASA’s Infrared Processing and Analysis Center.

Key Research Findings

Spitzer gathered a tremendous amount of data, ranging from the early universe up to extrasolar planets, including the discovery of ► [fullerenes](#) (in 2010).

With the capability of detecting stars behind dusty interstellar clouds, Spitzer snapped the first portraits of stars as they form (Fig. 2). At the same time, it was used to study dying stars, giving some insight into the possible origin of the dust filling up our Universe.

Spitzer telescope was also used to study the ultraluminous infrared galaxies (ULIRGs) emitting more than 90% of their light in the infrared. These galaxies are primarily found in the distant Universe. This large amount of infrared light could come from extreme star formation, an active central supermassive black hole, or both: three hypotheses that Spitzer could help to sort out.

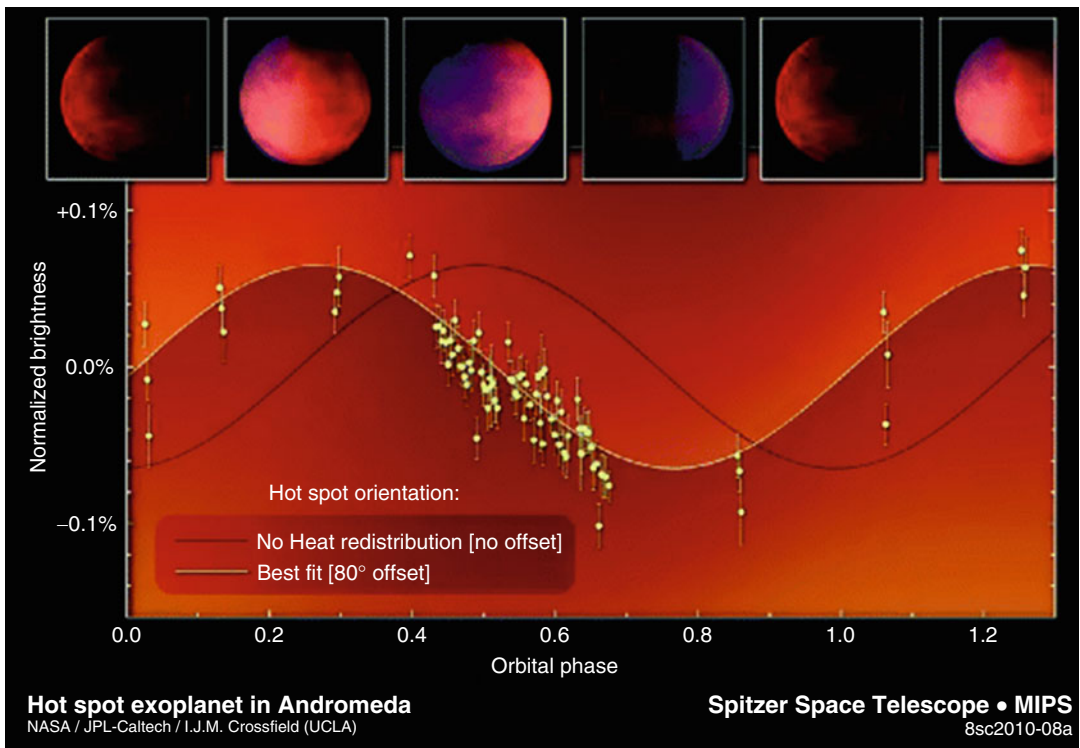
Several “active galactic nuclei” (AGN) have been unveiled which were hidden from X-ray telescopes by large, massive, and dense dust clouds.

Spitzer has discovered thousands of brown dwarves and found some evidence that some of these failed stars may perhaps have planets. The large amount of such brown dwarves could also explain why galaxies are heavier than they look. Part of the “dark matter,” but not part of the exotic

undefined matter, could be represented by these dwarves that do not produce optical light and are too faint to be detected from Earth.

Some discoveries are opening wide possibilities for astrobiology, such as that terrestrial planets form around many, if not most, of the nearby sunlike stars in our galaxy, as well as around dead stars or stars as young as 1 My old.

Spitzer was the first telescope to directly detect light from planets outside of our solar system, allowing “extrasolar” planets to be directly studied and compared. The planet’s glow is extracted from the measurement of the total infrared light collected from both the star and the planet and then measuring the infrared light coming from just the star while the planet dips behind it as part of its regular orbit (see ► [Transiting Planets](#)). In this way, Spitzer identified a planetary hot spot on a hot Jupiter (Fig. 3).



Spitzer Space Telescope, Fig. 3 This plot shows the hot spot on Upsilon Andromedae B. The *black line* shows what the light curve would look like if the hot spot were in the middle of the sun-facing side of the planet. The *yellow line*

is the best fit with actual observations, demonstrating an offset of the hot spot by 80°. (Image credit: NASA/JPL-Caltech/UCLA)

Cross-References

- ▶ [Herschel Mission](#)
- ▶ [IRAS](#)
- ▶ [ISO](#)
- ▶ [JWST](#)
- ▶ [Transiting Planets](#)

- ▶ [Gene Expression](#)
- ▶ [Genetics](#)
- ▶ [Intron](#)
- ▶ [Ribozyme](#)
- ▶ [RNA](#)
- ▶ [Transcription](#)
- ▶ [Translation](#)

Splicing

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Synonyms

[RNA splicing](#)

Definition

In genetics and molecular biology, splicing is the process by which the transcribed RNA – also known as pre-messenger RNA – is modified to produce messenger RNA ready to be translated into proteins by the ribosomes. In eukaryotes, splicing takes place within the nucleus, after or concurrently with transcription. During splicing, introns – intervening, noncoding sequences present in split genes – are removed and degraded, and exons, protein-coding sequences, are covalently joined. This stepwise process is usually catalyzed by ribonucleoprotein complexes called spliceosomes. In turn, autocatalytic splicing is produced when certain introns are able to splice themselves out of the messenger RNA. Thus, the first ribozyme discovered was a self-splicing intron present in the precursor of the large subunit ribosomal RNA of the ciliate protozoan *Tetrahymena thermophila*.

Cross-References

- ▶ [Exon](#)
- ▶ [Gene](#)

Split

- ▶ [Dichotomy, Planetary](#)

Spontaneous Generation, History of

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Keywords

Animalcules · Origins of life

Definition

Spontaneous generations have a very long history from antiquity to the nineteenth century. From the seventeenth century, there have been three successive and important experimental approaches to this problem. From the debate between Louis Pasteur (1822–1895) and Félix Archimède Pouchet (1800–1872), the scientific community has been broadly rejecting the spontaneous generations.

Overview

The idea of spontaneous generations consists in the possibility of the formation of the living being from inert matter. This idea is extremely ancient

and comes from antiquity. For example, the Greek philosopher Aristotle (384–322 BCE) claimed that spontaneous generations existed in nature. From the seventeenth century, there have been three successive and important experimental approaches of this problem.

In 1668, the Italian naturalist Francesco Redi (1626–1697) published the results of his experiments on the possible spontaneous generation of flies. He accurately showed that the larvae of flies never developed in bottles containing meat if the former were closed by gauze. Indeed, in this case, female flies were not able to lay on meat. Therefore, Redi's results argued against the spontaneous generation of insects and visible animals.

However, the discussion carried on during the eighteenth century. For example, the French naturalist Buffon (1707–1788) claimed that spontaneous generations formed each species at the beginning of life on Earth and that spontaneous generations of animalcules occurred in nature. Consequently, according to him, after the cooling of the primitive Earth, the origin of life was the fact of spontaneous generations.

During the eighteenth century, an important scientific debate about the spontaneous generations took place. It notably opposed Joseph Needham (1713–1781) and Lazzaro Spallanzani (1729–1799). The former claimed that in his experiments he had proven the spontaneous generations of animalcules. Indeed, he had placed hot sheep juice in closed bottles and maintained them on warm ash during several minutes to purify them. A few days later, microscopic animalcules had appeared. But Spallanzani did not accept these results. He repeated the experiments, heating and closing the bottles differently, and animalcules never developed. Arguing about their results, Needham, who was an excellent microscopist, very close to Buffon, claimed that Spallanzani had destroyed the vital force because of too much heating.

The debate was not limited to a circle of naturalists and strongly interested philosophers: Denis Diderot (1713–1784) supported the spontaneous generation theory, whereas Voltaire did not.

At the beginning of the nineteenth century, the discussion about the possible existence of spontaneous generations was far from being closed. For example, the French naturalist Lamarck took a significant interest in spontaneous generations in his theory on the transformation of species.

The debate between Pouchet and Pasteur is the main and final episode of the history of this biological problem. As a supporter of spontaneous generations, Pouchet published several papers and a book on heterogenesis at the end of the 1850s. Then, in 1860, the Academy of Sciences of Paris created a contest about the experimental proofs of spontaneous generation. At the time, the debate between Pouchet and Pasteur was very active and they discussed their own protocols and experimental results. In his experiments, Pasteur showed that microorganisms appeared in sterilized solutions containing organic mixture, only if there was a contamination from the environment. In his conclusions, Pasteur firmly asserted that he had proved the inexistence of spontaneous generations. Pasteur's position on the spontaneous generations was linked to his conception of life. Indeed, according to him, the molecular dissymmetry in living beings could be the proof of an impassable frontier between inert and living bodies.

In 1862, the Academy of Sciences of Paris favored Pasteur, and from this date, the scientific community has been broadly rejecting the spontaneous generations.

Cross-References

- [Buffon's Conception of Origins of Life](#)
- [Lamarck's Conception of Origins of Life](#)
- [Life](#)

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Spore

Wayne L. Nicholson^{1,2} and Ralf Moeller³

¹Space Life Sciences Laboratory, University of Florida, Merritt Island, FL, USA

²Space Life Sciences Laboratory, Kennedy Space Center, University of Florida, Gainesville, FL, USA

³German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Keywords

Bacillus · *Clostridium* · Endospore

Definition

A small, usually single-celled asexual reproductive body produced by many nonflowering plants, ► [fungi](#), protozoans, and ► [bacteria](#) that is capable of developing into a new individual without sexual fusion.

History

For information on the early history of microbiology, including the discovery of the bacterial spore, the reader is directed to Brock (1999) and de Kruif (1926). A short history of early milestones in *Bacillus* spore research can be found in Nicholson (2004).

Overview

This entry will concentrate on bacterial spores, upon which the most information has been gathered. When faced with nutrient starvation, bacteria of several genera, most notably *Bacillus* and *Clostridium*, possess the ability to differentiate from actively growing cells into dormant resting structures called ► [endospores](#), or spores. In the context of astrobiology, bacterial spores are

important organisms to study for a number of reasons.

First, bacterial spores can persist in the environment for at least millennia and are arguably the longest-lived organisms known (reviewed in Nicholson 2004). Spores are globally distributed and are found in ► [extreme environments](#) around the world. The underlying mechanisms of why spores exhibit such incredible hardiness have been the subject of intense study for the past half-century. Spores are highly resistant to being killed by a large range of physical parameters such as extremes of temperature, radiation, or pressure, as well as by various chemical disinfectants. Some of the various mechanisms of spore resistance are quite well understood at the molecular level, such as resistance to ultraviolet radiation (reviewed in Nicholson et al. 2000, 2005; Setlow 2006). However, the molecular details of spore resistance to other lethal treatments, such as heat, pressure, or certain chemicals, are not as well understood and are the subjects of current research.

Second, because of their notorious resistance and longevity, spores have been studied as possible candidates for natural transfer of life between the planets. This theory, variously dubbed “► [panspermia](#),” “► [lithopanspermia](#),” or “transpermia,” postulates that viable microorganisms, residing within meteors ejected from a planet’s surface by large impacts, could survive a trip through space to another planet (reviewed in Nicholson et al. 2000; Nicholson 2009). Spores have been shown to inhabit the interiors of near-surface igneous rocks such as ► [granite](#) and ► [basalt](#) (the most likely candidates for launch by impact) and have been experimentally demonstrated to survive the rigors of impact-mediated launch, transfer through space, high-speed atmospheric entry, and landing (reviewed in Fajardo-Cavazos et al. 2007; Nicholson 2009).

Third, spores are important in the field of ► [planetary protection](#). By international convention, spacecraft sent on life-detection missions to other planets must meet rigorous criteria for disinfection, to avoid the risk of contaminating the target planet with Earth microbes (Rummel 2001;

reviewed in Nicholson et al. 2009). To comply with planetary protection requirements, robotic landers and rovers are assembled in ultraclean rooms inside Spacecraft Assembly Facilities (SAFs). Interestingly, precisely because of their environmental ubiquity and resistance to killing by chemical and physical disinfection procedures, bacterial spores are common isolates from the ultraclean rooms in which spacecraft are assembled and indeed from the spacecraft themselves (Venkateswaran et al. 2001, reviewed in Nicholson et al. 2009). In fact, the most resistant spore discovered to date, *Bacillus pumilus* strain SAFR-032, was isolated from a SAF (Link et al. 2004). Therefore, it appears that ultraclean SAFs act as extreme environments which select for ► survival of only the hardiest microbes, such as spores – and these are exactly the types of organisms best able to survive the journey through space (Link et al. 2004; Crawford 2005). For these reasons, spores pose a particular risk of contaminating spacecraft sent on life-detection missions to destinations such as ► Mars, Jupiter’s moon ► Europa, or Enceladus (Nicholson et al. 2009).

Future Directions

Unlike rocks transferred between planets by chance impacts, spacecrafts are (i) designed to be launched and landed gently, (ii) highly protected from space exposure during transit, and (iii) launched on trajectories with short transit times. Therefore, spores contaminating spacecraft would have a relatively high probability to survive a voyage between Earth and, say, Mars. However, in order for such “forward contamination” to be ecologically relevant, an organism transferred into a new extraterrestrial environment must be able not only to survive, but to grow and proliferate in that environment. Recent research has been conducted to understand the ability of bacterial spores to survive, germinate, and grow in extraterrestrial environments such as the surface or near-subsurface of Mars. To date, it has been found that the surface environment of Mars – characterized by intense UV and ionizing radiation, extreme cold, a CO₂-dominated low-pressure atmosphere, and a lack of liquid water and organic nutrients –

poses a formidable barrier to survival and proliferation of spore-forming bacteria and of microbes in general (Fajardo-Cavazos et al. 2008; Nicholson and Schuerger 2005; Schuerger and Nicholson 2006; Tauscher et al. 2006).

Cross-References

- Bioburden
- BIOPAN
- Colonization, Biological
- Endospore
- EXPOSE
- Exposure Facilities
- Extremophiles
- Fungi
- Granite
- Lithopanspermia
- Long Duration Exposure Facility
- Planetary Protection
- Radiation Biology
- Sterilization
- STONE
- UV Radiation, Biological Effects

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Sporicide

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

A sporicide is a compound that kills microbial spores.

Cross-References

► [Spore](#)

Sporogenesis

► [Sporulation](#)

Sporulation

Gerda Horneck
German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Synonyms

[Sporogenesis](#)

Definition

Sporulation is a differentiation process of bacteria and fungi by which a vegetative cell becomes converted into a dormant structure. Bacteria of the genus *Bacillus* and *Clostridium* form ► [endospores](#), i.e., spores inside the cell at the end of their growth period when nutrients become limited. During the different stages of the sporulation cycle, different proteins are synthesized. Sporulation includes the following subsequent steps: structural changes of DNA, septum formation, separation of ► [spore](#) DNA, synthesis of a prespore, engulfment, forespore formation, cortex formation, deposition of spore coats, spore maturation, lyses of the sporangium, and release of the spore. The released spore is more resistant to environmental stressing conditions than the vegetative mother cell.

Cross-References

► [Endospore](#)
► [Spore](#)

SPR

► [Surface Plasmon Resonance](#)

Sputtering

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Definition

Sputtering is the process in which a solid surface, as of an ► [interstellar dust](#) grain, is eroded by the impact of atoms or ions from the gas phase. Chemical sputtering occurs when the impacting particle has relatively low kinetic energy, chemical bonds are formed between it and the surface, and desorption of a newly formed molecule incorporating surface atoms occurs. Physical sputtering occurs when the impacting particle simply knocks surface atoms into the gas; this process can involve either thermal motion for high temperature gas or non-thermal impact if a solid particle and the gas have high relative velocities. Sputtering of interstellar grains commonly occurs in shocks.

Cross-References

- [Interstellar Dust](#)
- [Shock, Interstellar](#)

Square Kilometre Array

Jeff Wagg¹, Izaskun Jimenez-Serra²,
Tyler Bourke¹, Robert Braun¹, Phil Diamond¹,
William Garnier¹, Jimi Green³ and
Mathieu Isidro¹

¹Square Kilometre Array Observatory,
Macclesfield, UK

²Centro de Astrobiologia (CSIC/INTA), Torrejon
de Ardoz, Spain

³CSIRO Astronomy and Space Sciences, Parkes
Observatory, Parkes, NSW, Australia

Keywords

Radio · Astronomy · Instrumentation

Definition

The Square Kilometre Array (SKA) will be the largest radio telescope in the world for observations at centimeter and meter wavelengths. It is an international project involving more than fifteen countries, coordinated by the SKA Observatory (SKAO). The SKA is planned to be built in two phases, with the first consisting of two radio interferometers located at two sites, SKA LOW in Western Australia and SKA MID in South Africa. Construction activities began in 2021 and are expected to be completed toward the end of the decade. The SKA will deliver transformational science in a number of astronomy and physics fields, including astrobiology as described below.

History

The original concept that would later evolve into the SKA began formulating in the late 1980s and was led by a group from the Netherlands. This idea was discussed with members of the UK astronomy community in 1990 at the 10th anniversary meeting of the Very Large Array, and in 1993 the International Union of Radio Science (URSI) established the Large Telescope Working Group to develop the scientific goals and technical specifications for a next generation radio observatory. In 1997, eight institutions from six countries (Australia, Canada, China, India, the Netherlands, and the USA) signed a Memorandum of Agreement to cooperate in a technology study. The number of countries increased to 11 during 1999 for the creation of the International Square Kilometre Array Steering Committee (ISSC). In 2007, an international SKA Project Office was established in the UK. The Square Kilometre Array Organisation (SKAO) was then established in 2011 as a nonprofit company in the UK to formalize relationships between the international partners and to centralize the leadership of the project. In 2012, it was agreed that phase 1 of the SKA should be built on two sites in Western Australia and South Africa, both chosen for their remarkable radio quietness. In 2015, a cost

reduction exercise scaled back the number of telescopes from three to two, and the design work would continue focusing on SKA LOW in Australia and SKA MID in South Africa. The design phase formally concluded in 2020, and in 2021 the SKA organization transitioned into an intergovernmental organization with the birth of the SKA Observatory. The main SKAO office is located at the Jodrell Bank Observatory south of Manchester, UK. As of July 2021, there are seven member countries who have ratified the SKAO treaty to become formal members, with an additional six partner countries.

Overview

SKA1 construction activities formally began in July 2021 and are expected to last for 7 or 8 years. The design baseline for SKA LOW consists of 512 stations, each containing 256 log periodic dipole antennas operating within the frequency range of 50 to 350 MHz. The maximum separation between these stations will be approximately 65 km. In the case of SKA MID, the existing 64 antenna MeerKAT array will be combined with 133 15 m diameter dishes equipped with single-pixel feed receivers operating between 350 MHz and 15 GHz. The maximum separation between SKA MID dishes will extend out to 150 km. Signals between stations or antennas will be correlated by the central signal processors, located at the Murchison Radio Observatory (MRO) in the case of SKA LOW, and in Cape Town for SKA MID. The engineering teams will be located at centers in Geraldton, Western Australia, and in Carnarvon, Northern Cape.

SKA science operations centers are being established in both Perth and Cape Town, which will also be the sites of the high-performance computing facilities hosting the science data processors (SDPs). A SDP will produce nearly science-ready data products that will be distributed to the SKA regional centers (SRCs) for advanced processing. These SRCs will serve as the interface between the observatory and the broader scientific community.

Applications

The topic of Cradle of Life/Astrobiology represents one of the main SKA science drivers. The SKA will contribute to the field of astrobiology by performing sensitive and broadband spectroscopic surveys to discover unknown complex organic molecules of prebiotic interest in space. Prebiotic molecules are defined as molecular species believed to be involved in the origin of life. Precursors of proteins, lipids, nucleotides, and sugars are considered as prebiotic molecules. Among them, one may find glycine and alanine (the simplest amino acids), butanol and butanoic acid (amphiphilic molecules precursors of fatty alcohols and fatty acids, proposed to be prebiotic lipids; Ruiz-Mirazo et al. 2014), hydroxylamine or urea (precursors of ribonucleotides; Becker et al. 2019), and glyceraldehyde, erythrose, or ribose (the simplest sugars; Patel et al. 2015). Some prebiotic scenarios for the origin of life contemplate the possibility that these precursors formed in space and were brought to a primitive Earth through the impact of meteorites and comets during the period of the Late Heavy Bombardment (life emerged soon after, at about 3.8 billion years ago). Prebiotic molecules such as urea, glycine, and ribose have indeed been detected in meteorites and comets (Pizzarello 2006; Altwegg et al. 2017; Furukawa et al. 2019), which supports this hypothesis. The SKA will investigate whether the chemistry found in space (especially in the medium between stars or interstellar medium) efficiently forms prebiotic molecules, to be later on incorporated into planetesimals during the formation of solar-type systems.

Prebiotic species are discovered in interstellar space thanks to observations of their rotational spectra with radio telescopes. These species are large in size, and therefore their rotational line spectra appear shifted toward centimeter wavelengths as opposed to lighter, smaller molecules, whose rotational spectra are shifted to millimeter and submillimeter wavelengths. The SKA capabilities are therefore perfectly suited for the search for interstellar prebiotic molecules. Observations at the highest frequencies of SKA MID (with the Band 5 receivers, between 4.8 and 15 GHz) have

the potential to discover unknown prebiotic species, especially under the coldest excitation conditions of interstellar space. This potential has recently been demonstrated by deep spectroscopic surveys carried out at 3 cm and 7 mm with SKA precursors such as the Green Bank Telescope and the Yebes 40 m telescope, which have discovered a plethora of large molecules such as ethanolamine (a prebiotic species that represents the simplest head group of phospholipids; see Rivilla et al. 2021) and small polycyclic aromatic hydrocarbons (Cernicharo et al. 2021; McGuire et al. 2021).

Future Directions

The second phase of the SKA is not yet defined but may consist of an order of magnitude increase in survey speed and angular resolution. This is likely to incorporate new technologies such as a wide field of view-phased array feeds, or wide-band receivers. The possible extension of SKA MID to higher frequencies (e.g., Conway et al. 2020) would increase the detection capabilities of the SKA for the search of prebiotic species in interstellar space.

Cross-References

- [Long Wavelength Astronomy](#)
- [Molecular Spectroscopy](#)
- [Prebiotic Chemistry](#)
- [Protoplanetary Disk](#)
- [Pulsar](#)
- [Radio Astronomy](#)
- [SETI](#)

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SRB

- [Sulfate Reducers](#)

SSB, USA

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Space Studies Board](#)

Definition

The Space Studies Board (SSB) is a unit of the US National Research Council. The original charter of the Space Science Board was established in June 1958. The Space Science Board became in 1989 the Space Studies Board (SSB) and provided expert external and independent scientific and programmatic advice on a continuous basis from NASA's inception until the present. Today, the SSB is providing an independent, authoritative forum for information and advice on all aspects of space science and applications. The SSB also serves as the US National Committee for the Committee on Space Research (COSPAR) of the International Council for Science.

The Board is composed of prominent scientists, engineers, industrialists, scholars, and policy experts in space research appointed for 2-year staggered terms. The Board itself does not

conduct studies, but it oversees advisory studies and program assessments conducted by ad hoc study committees formed in response to a request from a sponsor. It publishes the reports of such studies. Decadal surveys are a major outcome from the SSB, providing strategic direction to NASA and other agencies on the top priorities over the next 10 years in astronomy and astrophysics, solar system exploration, solar and space physics, and Earth science.

Concerning astrobiology, the SSB has issued numerous reports in addition to the decadal surveys – about ► [Mars exploration](#), ► [planetary protection](#), and mission categorization. Special focus was given to the ► [Mars sample return mission](#).

Cross-References

► [COSPAR](#)

References and Further Reading

<http://sites.nationalacademies.org/SSB/index.html>

SS-Bond

► [Disulfide Bond](#)

SST

► [Spitzer Space Telescope](#)

Stable Isotopes

Vincent Busigny
Institut de Physique du Globe de Paris, Paris,
France

Keywords

Isotopes · Isotope fractionation · Fractionation factor · Stable isotopes · Nontraditional

Definition

The term isotope defines the various forms of a chemical element, characterized by the same number of protons but different numbers of neutrons in their nucleus. Isotopes share the same atomic number and location in the periodic table, but have distinct atomic weights. Two types of isotopes can be distinguished: radioactive or stable. Stable isotopes of a single element have roughly identical properties due to similar electronic configuration and atomic size, but their mass differences induce variations in terms of bound energy and chemical reactivity. In a specific process, stable isotopes are thus fractionated according to either equilibrium or kinetic reactions.

History

Stable isotope geochemistry was born around 1945, and its first application was dedicated to geothermometry (Urey 1947). Experimental applications were initiated by McCrea (1950) and illustrated by the early work of Urey et al. (1951) on ambient paleotemperatures of the Upper Cretaceous in the northern hemisphere, measuring oxygen isotopes in carbonates. Since then the development of stable isotope geochemistry has been rapid and exponential, with applications to all kinds of geological and extraterrestrial environments.

Overview

Stable isotopes in natural environments have been identified for 81 elements, from hydrogen to lead. Contrasting with radioactive isotopes, which are mostly used for dating or deciphering mixing processes, stable isotopes can be applied to trace any type of physicochemical reaction such as diffusion, dissolution/precipitation, oxidation/reduction, acid/base exchange, evaporation/condensation, or adsorption. Stable isotopes can be useful to distinguish biotic from abiotic signatures recorded in ancient terrestrial rocks or meteorites.

For extensive reviews on stable isotopes and their use in geochemistry, the reader should refer to textbooks such as Criss (1999) and Hoefs (2004).

Stable isotopes are presently classified as either “traditional” or “nontraditional.” Traditional stable isotopes refer to isotopic tracers developed since the earliest works in the 1950s and include systems such as C, O, H, N, or S. A common feature of these traditional stable isotopes is the analytical method based largely on gaseous Isotope Ratio Mass Spectrometry (IRMS). For instance, C and N isotope compositions are measured on the molecules CO₂ and N₂, respectively. Nontraditional stable isotopes refer to isotopic systems developed more recently (since the 1990s) and include heavy metals such as Fe, Cu, Zn, Cr, Se, and Mo and alkali or alkaline earth metals such as Li, Mg, and Ca. These elements are usually separated from sample matrix using aqueous chemistry and chromatographic methods. Isotope analyses are performed either on solid using thermo-ionization mass spectrometry (TIMS) or aqueous solution using multicollector inductively coupled plasma mass spectrometry (MC-ICPMS). It is likely that nontraditional stable isotopes may become traditional in the next few decades, and this term may need to be revised. Recent reviews on traditional and nontraditional stable isotopes have been published in volumes of Reviews in Mineralogy and Geochemistry (Valley and Cole 2001; Johnson et al. 2004).

Basic Methodology

Stable isotope compositions are generally reported in δ notation, which is a deviation of an isotopic ratio relative to the same ratio in a standard, and can be written as

$$\delta^i E = \left(\frac{R_{spl}^{i/j} - R_{std}^{i/j}}{R_{std}^{i/j}} \right) \times 10^3$$

where R is the ratio of the two stable isotopes i and j of element E , spl is the sample of interest, and std is the standard reference material. The δ unit is expressed in parts per thousand or “per mil,” noted ‰. The ratio i/j usually corresponds to

heavy over light isotopes so that positive δ value indicates that the sample is enriched in heavy isotope relative to the standard (and vice versa). A careful examination of the standard material is thus crucial when considering δ values. For traditional stable isotopes, the standards are well established. For instance, carbon stable isotope composition (ratio $^{13}\text{C}/^{12}\text{C}$) is always expressed as $\delta^{13}\text{C}$ relative to the fossil marine carbonate standard (PDB), while the standard for hydrogen isotope composition (D/H ratio) is Standard Mean Ocean Water (SMOW). In contrast, for recent “nontraditional” stable isotopes, data from the literature are sometimes reported relative to various standards (e.g., igneous rock or IRMM-014 synthetic metal for Fe isotope composition, see Craddock and Dauphas (2010)).

Isotope fractionations between species or phases can be determined experimentally or predicted from theoretical calculation (e.g., Richet et al. 1977). The isotopic fractionation factor associated to an isotope exchange reaction between two species A and B is defined as:

$$\alpha_{A-B} = \frac{R_A^{i/j}}{R_B^{i/j}}$$

and can be expressed in terms of δ values as

$$\alpha_{A-B} = \frac{1,000 + \delta^i E_A}{1,000 + \delta^i E_B}$$

The isotope fractionation between two species A and B represents the difference between their isotope compositions and can be related to the fractionation factor using the following formulae (e.g., Criss 1999):

$$\Delta_{A-B} = \delta^i E_A - \delta^i E_B \approx 1,000 \cdot \ln \alpha_{A-B}$$

Applications

Stable Isotopes in Astrobiology

The main questions in astrobiology concern the origin and evolution of life on Earth and whether life may have risen elsewhere in the Solar System and on extrasolar planets. Stable isotopes are powerful tools for tracing microbial processes and the

origin of biomolecules in various geological and extraterrestrial systems. Applications range from direct analyses of organic components to identification of biominerals, formed through biological-induced (extracellular) or biological-controlled (intracellular) pathways. One of the key observations is that traditional stable isotope systems such as C, H, N, O, and S all represent the basic components of life. This was recognized very early in studies of stable isotope geochemistry, so that these systems were rapidly used for searching for life signatures in the geological record. The most famous system is probably C isotopes, and one of its well-known applications can be summarized as follows. Inorganic carbon assimilation by autotrophic organisms is based on various carboxylation pathways with specific kinetic isotope fractionations, favoring light isotope assimilation. Organic carbon is thus ^{12}C enriched relative to the source of inorganic carbon (DIC: dissolved inorganic carbon), with an isotopic fractionation $\Delta^{13}\text{C}_{\text{DIC-Corg}}$ generally between -20‰ and -30‰ (see review in Thomazo et al. 2009). In contrast, carbonate precipitation from dissolved inorganic carbon roughly records the composition of the source (i.e., the equilibrium isotope fractionation is $\sim 1\text{‰}$). The difference of isotope compositions between carbonate and organic carbon coexisting within a single rock sample can thus be used to determine if organic carbon is related to biological activity or not and eventually define the C assimilation pathway. This feature was recognized in the 1970s and has been used to infer the existence of life on Earth as early as 3.8 Ga ago (Schidlowski 1988). The virtue of stable isotopes for life identification is that even though a rock experienced strong modifications of structure and mineralogy due to metamorphism, the primary isotope signature may be preserved.

A Reliable Biosignature?

An important limit on the application of stable isotopes as tracers of life is that abiotic processes may mimic isotope fractionations usually ascribed to biogenic origin. For instance, several experimental studies demonstrated that the production of organic carbon through abiotic pathways such as ► [Fischer-Tropsch-Type Reaction](#) generates C isotope compositions similar to those expected

for biological pathways. Thus the question of the origin of ► [methane](#) on Mars and Titan (which has been suggested to derive from bacterial methanogenesis or abiotic ► [serpentinization](#) process) will probably not be solved from C isotopes alone. One possibility to explore further may be the simultaneous measurement of C and H isotopes in methane and other types of hydrocarbons (Sherwood Lollar et al. 2002).

Sulfur isotope composition recorded in ancient sedimentary sulfides may represent one of the most reliable isotopic biomarkers, with no abiotic counterpart. Indeed, bacterial sulfate reduction (BSR) produces a strong kinetic isotope fractionation, favoring the light S isotopes in the hydrogen sulfide product by $\sim 45\text{‰}$ in terms of $^{34}\text{S}/^{32}\text{S}$ ratio (see the pioneer work by Harrison and Thode 1958). When aqueous Fe^{2+} is present, hydrogen sulfide immediately precipitates as FeS and is then transformed into pyrite (FeS_2). Watanabe et al. (2009) showed experimentally that abiotic thermochemical sulfate reduction produces hydrogen sulfide either enriched or depleted in light S isotopes, with a range of $\Delta^{34}\text{S}_{\text{SO}_4\text{-H}_2\text{S}}$ from -20‰ to $+5\text{‰}$. The record of very negative $\delta^{34}\text{S}$ values in pyrite thus remains an unchallenged tracer of bacterial sulfate-reduction activity. The main drawback of this method is that the expression of the isotope fractionation depends strongly on the size of the sulfate reservoir. At low sulfate concentrations, the uptake and reduction of sulfate by microorganisms does not result in significant discrimination between sulfur isotopes and, therefore, does not produce significant fractionations. In contrast, at high sulfate concentration, large isotope fractionation can be efficiently transferred to sedimentary sulfides. Based on this interpretation, the long-term evolution of the sulfur isotope record on terrestrial sediments has been interpreted to reflect the response of sulfate-reducing bacteria to changes in oceanic sulfate concentrations (Canfield et al. 2000).

Future Directions

The identification of biological activity from a single isotope system is limited by the possibility of producing similar isotope fractionation from abiotic reactions. Unequivocal evidence for life

will require the combination of several isotope tracers (C and H in methane, S and Fe in iron sulfides, Fe and O in iron oxides, Ca, Mg, Fe, C, and O in carbonates. . .). Additionally, a coupling with other methods such as mineralogy (shape, size, crystallinity) or chemistry (e.g., purity) will put further constraints on potential biological origin as exemplified by multidisciplinary study of the Martian meteorite ► [ALH 84001](#) (McKay et al. 1996). A promising field, which grows with improvement of the analytical precision on stable isotope measurements, is the analysis of multiple-isotope systems for elements that possess three or more isotopes (e.g., O, S). Once calibrated, application of these systems may provide useful tools for distinguishing biological from abiotic pathways (Farquhar et al. 2003).

Cross-References

- [Fischer-Tropsch-Type Reaction: Effects on Isotopic Fractionation](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Iron Isotopes](#)
- [Isotopic Exchange Reaction](#)
- [Isotopic Fractionation \(Interstellar Medium\)](#)
- [Isotopic Ratio](#)
- [Nitrogen Isotopes](#)
- [Oxygen Isotopes](#)
- [Silicon Isotopes](#)
- [Sulfur Isotopes](#)

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Stagnant Lid Convection

Doris Breuer

German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany

Definition

Stagnant lid convection is a form of convection that occurs in a material with strongly temperature dependent viscosity for a viscosity contrast larger than about 10^4 . It is characterized by an upper stagnant layer – the stagnant lid – that

forms on top of the convecting layer. Heat in the stagnant lid is transported mainly by heat conduction. Stagnant lid convection is typical of ► [mantles](#) of the ► [terrestrial planets](#), ► [Mercury](#), ► [Mars](#) and ► [Venus](#) and large rocky satellites such as the Moon. Stagnant lid convection may also occur in the ice layers of the icy satellites of the outer ► [Solar System](#). Stagnant lid planets are usually also one-plate planets. Their tectonic style differs substantially from planets with mobile lid convection or ► [plate tectonics](#) like Earth. Here, the near-surface layers take part in the convective flow and are recycled with the interior.

Cross-References

- [Interior Structure, Planetary](#)
- [Mantle](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Planet](#)
- [Plate Tectonics](#)
- [Satellite or Moon](#)
- [Solar System, Inner](#)
- [Terrestrial Planet](#)
- [Venus](#)

Star Counts

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

Counting the number of stars per unit area on the sky, when compared to the equivalent “star count” in an adjacent region of the sky, can illustrate the presence of extinction by ► [interstellar dust](#).

Cross-References

- [Extinction, Interstellar or Atmospheric](#)
- [Interstellar Dust](#)

Star Dust

Sun Kwok
Faculty of Science, The University of Hong Kong, Hong Kong, China

Keywords

Infrared spectroscopy · Evolved stars · Stellar winds

Synonyms

[Circumstellar grains](#)

History

The fact that stars can manufacture solid-state particles in large quantities (stardust) was first recognized through the discovery of infrared excess in the spectra of evolved stars. Infrared spectrophotometric observations in the late 1960s have revealed that stars in the ► [asymptotic giant branch](#) (AGB) of evolution show excess emission above the stellar photospheric continuum emission (Woolf and Ney 1969). This excess is interpreted as the result of thermal emission by micron-size solid particles (grains) heated by the stellar radiation. These solid particles absorb visible light from the star and reemit the energy in the infrared.

Overview

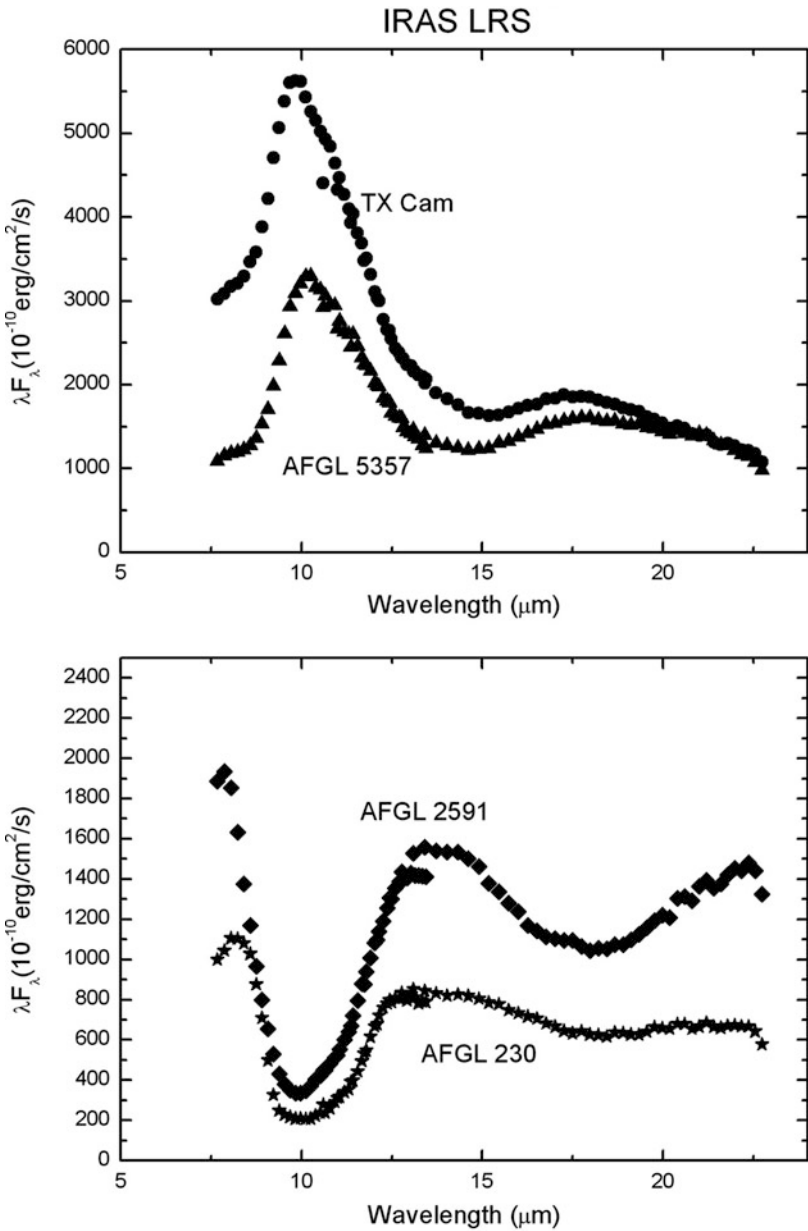
Stardust also manifests itself through the absorption of starlight. Circumstellar dust can cause very large extinction in the visible. In extreme cases, the entire photospheric output of a star is converted to dust emission, making the star itself extremely faint or even invisible in optical light (Volk et al. 1992). The most well-known examples of such stars are IRC + 10216 and AFGL 3068, which are very bright in the infrared but very faint in the visible.

In terms of chemical composition, stardust can be either oxygen rich or carbon rich. The most common kinds of oxygen-rich solid particles are

amorphous silicates, which manifest themselves through their Si–O stretching mode at 9.7 μm and the Si–O–Si bending mode at 18 μm . In the *Infrared Astronomical Satellite* ($\blacktriangleright$ [IRAS](#)) low-resolution spectrometer (LRS) all-sky survey, over 4000 oxygen-rich AGB stars were found (Fig. 1). The most common kind of carbon-rich stardust is silicon carbide, which is detected in over 700 carbon-rich AGB stars (Kwok et al. [1997](#)).

In addition to amorphous silicates and silicon carbide, silicate minerals (olivines and pyroxenes) as well as several refractory oxides are also made in the circumstellar envelopes of AGB stars. A broad feature centered around 13 μm , first discovered by the IRAS LRS, could be due to corundum ($\alpha\text{-Al}_2\text{O}_3$, which has a feature at 12.7 μm), glass (amorphous SiO_2 , 12.3 μm), spinel ($\text{Mg}_2\text{Al}_2\text{O}_4$, 12.95 μm), or rutile (TiO_2 ,

Star Dust, Fig. 1 Infrared spectra of amorphous silicates. The 9.7 and 18 μm features of silicates can be seen both in emission (*top panel*) and in self-absorption (*bottom panel*). (Data obtained from the low-resolution spectrometer observations from the $\blacktriangleright$ [Infrared Astronomical Satellite](#))



13.4 μm). An emission feature at 19.5 μm observed by ► [ISO](#) has been attributed to a mixture of Mg-Fe-oxides (e.g., $\text{Mg}_{0.1}\text{Fe}_{0.9}\text{O}$) (Posch et al. 1999, 2002). The detection of minerals in stellar environments has led to the establishment of the field of astromineralogy (Henning 2003).

Stardust of organic composition has also been found in carbon-rich ► [planetary nebulae](#). Organic stardust has not been detected in AGB stars, suggesting that these particles are synthesized in the post-AGB phase of evolution, after the synthesis of gas phase molecules such as acetylene and benzene (Kwok 2004).

Stardust can also be found in the vicinity of young stars, Wolf-Rayet stars, planetary nebulae, novae, and supernovae. The disc shape of the dust-emitting region around young stars is suggested to be the precursor of the nebula out of which planets form.

The exact mechanism of stardust formation is not known. It is usually assumed that these solid particles are the result of ► [nucleation](#) through collision of gas-phase molecules. When the particles are far enough from the stellar surface such that the radiation temperature of the particles has fallen below the condensation temperature of the solid, it will condense spontaneously, similar to soot formation in a flame. Spectral monitoring of novae has shown that novae change from a gaseous free-free spectrum to a dust thermal emission spectrum over periods as short as a few days, suggesting that dust can condense in novae ejecta very quickly (Ney and Hatfield 1978).

Stardust is generally believed to be the source of solid-state particles found in the interstellar medium (► [interstellar grains](#)). Through radiative and physical processes, the morphology and/or chemical composition of stardust may be modified in the interstellar medium. Most interestingly, various presolar grains (SiC, diamonds, corundum, silicates) of stellar origin have been found in meteorites, suggesting that we actually can hold stardust in our hands (Zinner 1998). The presence of stardust in the solar system provides evidence that stardust is sturdy enough to survive its journey through the ► [interstellar medium](#).

Cross-References

- [Asymptotic Giant Branch Star](#)
- [Interstellar Dust](#)
- [Meteorites](#)
- [Nova](#)
- [Nucleation of Dust Grains](#)
- [Organic Dust, Synthesis by Stars](#)
- [Stellar Winds](#)
- [Supernova](#)

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Star Formation Rate

Daniele Galli
INAF Osservatorio Astrofisico di Arcetri,
Florence, Italy

Acronyms

SFR

Definition

The star formation rate (SFR) is the mass of stars formed per unit time in galaxies or in star-forming regions within galaxies. It is usually measured in solar masses per year ($M_{\odot} \text{ yr}^{-1}$), or in solar masses per year per square parsec ($M_{\odot} \text{ yr}^{-1} \text{ pc}^{-2}$). Currently, the SFR in our Galaxy is about $4 M_{\odot} \text{ yr}^{-1}$. Methods for estimating the present-day SFR in galaxies are generally based on measuring the emission of tracers of the young stellar population, for example, *high-mass stars* and *supernovae*. The SFR is one of the key ingredients in models of galactic chemical evolution. A related concept is the star formation history (SFH), the time evolution of the star formation rate. Suggested readings: Kennicutt and Evans (2012), Krumholz (2014).

Cross-References

- [Galaxy](#)
- [Interstellar Cloud](#)
- [Initial Mass Function](#)

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Star Formation, Feedback

Mark Krumholz
Research School of Astronomy and Astrophysics,
Australian National University, Canberra, ACT,
Australia

Definition

Star formation feedback refers to the collection of processes by which newly formed stars alter the

interstellar gas from which they form, or alter their interstellar environment more broadly. These processes include radiative heating, photodissociation, and photoionization, and acceleration and shocking by stellar outflows, winds, and supernova explosions. In most cases, feedback inhibits further star formation or disperses the star-forming interstellar clouds, reducing the overall star formation rate in the region. In some special circumstances, however, feedback processes can also accelerate star formation locally; this is known as positive feedback or star formation triggering.

History

While many of the individual processes involved in feedback have been known since the early- to mid-twentieth century, the study of star formation feedback as a collective phenomenon has two main roots, one Galactic and one extragalactic. Zuckerman and Evans (1974) and Scoville and Solomon (1975) pointed out that if the molecular clouds in the Galaxy were all collapsing freely into stars, the resulting rate of star formation would greatly exceed the observed rate. They suggested that the large velocities detected in molecular clouds via Doppler measurements must therefore represent turbulent motions rather than collapse and suggested that feedback might be responsible from driving the turbulence and inhibiting collapse. On the extragalactic side, Larson (1974) and Dekel and Silk (1986) suggested that the observed lack of star formation in elliptical galaxies and the low surface brightness and metal content of dwarf galaxies, respectively, could only be explained if these galaxies were to lose a substantial fraction of their interstellar gas and metals to the intergalactic medium. They argued that ejection of gas from the galaxy by supernova feedback was likely responsible for this loss.

Cross-References

- [Star Formation Rate](#)
- [Star Formation, Theory](#)
- [Star Formation, Triggering](#)

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Star Formation, Observations

Maria Teresa Beltrán¹ and Gopal Narayanan²

¹INAF-Osservatorio Astrofisico di Arcetri,
Florence, Italy

²Five College Radio Astronomy Observatory,
University of Massachusetts, Amherst, MA, USA

Keywords

Gravitational collapse · Molecular clouds ·
Interstellar medium · Spectral energy
distribution

Definition

Star formation is the process by which denser regions of interstellar ► [molecular clouds](#) fragment and collapse into smaller cores that become hot enough at the center to initiate the process of nuclear fusion, thereby creating a star. Observations of star formation require all wavelengths from radio to X-ray and help elucidate the

processes underlying the birth of both low-mass and high-mass stars.

History

It is worth reviewing a little bit of the history behind the realization that star formation is an ongoing process in our Galaxy. By the middle of the twentieth century, the theory of stellar structure and evolution had already demonstrated that the hottest stars (OB stars) consume their nuclear fuel at such a prodigious rate that they can live for only a short fraction of the lifetime of our Galaxy. So the very fact of their continued existence was proof that star formation has occurred in the present epoch of galactic history. In addition, in the 1940s, the Armenian astronomer Viktor Ambartsumian showed that OB stars are in associations (see “► [OB Association](#)”) whose internal motions would cause them to be disrupted on timescales in agreement with the nuclear ages of the individual stars in the association (that is, on times much less than the age of the Galaxy), again providing direct observational evidence that star formation is still ongoing in our Galaxy. The last piece of the puzzle was provided by the discovery of the ► [interstellar medium](#) (ISM) of gas and dust in the early part of the twentieth century. Observations of the ISM established that the clouds of interstellar material (giant molecular clouds) had roughly stellar chemical composition, but were much more massive than individual stars or stellar associations. The presence of the ISM showed that the raw material needed to make stars was relatively abundant in the Galaxy.

For many years, direct observations of the star formation process, and subsequent development of a good theory, have been hampered severely by the fact that the earliest phases of star formation occur in dark clouds which have an extremely large amount of extinction toward them, rendering them optically opaque. Fortunately, over the past 40 years, significant advances in infrared to millimeter wavelength technologies have spurred progress in a new generation of ground and space telescopes and associated instrumentation that has allowed to trace the cold ISM material and to

study in detail even the most deeply embedded stages of star formation. Important milestones in the star formation field from an observational point of view include: the first all-sky infrared images provided by the ► [Infrared Astronomical Satellite](#) (IRAS) space telescope, launched in 1983, which identified the coldest regions in the ISM; the spectral classification of embedded young infrared sources in different evolutionary classes depending on the shape of their spectral energy distribution, which is related to the amount and distribution of the surrounding dust and its temperature (Lada and Wilking 1984; Lada 1987); the discovery of collimated optical and infrared jets and of bipolar molecular outflows traced by high-velocity CO emission; the spectacular optical and infrared view of star-forming regions provided by Hubble since its launch in 1990; the first images of the dust continuum emission from the youngest protostars in the 1990s; the Infrared Space Observatory (ISO) discovery of water and other important molecules in the ISM; Spitzer space telescope systematic imaging in the near- and mid-infrared for a complete census of protostellar populations in the 2000s; the ubiquitous presence of filaments in the ISM revealed by the Herschel Space Observatory in 2010s, where most of the star formation in the Milky Way is taking place; and since 2011, the multiple results obtained with ALMA, including the stunning images of protoplanetary disks with rings, gaps, and spirals.

Overview

The theory of ► [stellar evolution](#), which has been very successful in explaining the life history and the death of stars, has nevertheless been unable to explain how stars form. It is likely that the inherent complexity of the physical processes behind star formation is the main reason for this inability of the theory. Knowledge of the physical mechanisms that govern the formation of stars within molecular clouds is crucial, as it has a wide-ranging impact on a variety of other fields of astronomy. Thus, understanding star formation is necessary to form a clear picture of galactic

evolution from the Big Bang to the current time in cosmic history. The development of a theory of star formation (see “► [Star Formation, Theory](#)”) is also important for the study of the origin of planetary systems, which in turn has implications for biology outside the solar system (see “► [Protostars](#)”).

The fact that star formation is an ongoing and continuous process that extends from the early universe into the present epoch is an important property of the universe. This facilitates the study of star formation because it allows us to investigate the physical processes of various stages of star formation with observational methods.

Basic Methodology

We know from observations that the dark patches that can be seen crossing the Milky Way in the night sky are not devoid of material. They are made up of many interstellar dark clouds which contain gas and tiny opaque dust grains that effectively absorb and scatter starlight (see “► [Interstellar Dust](#)”). These dark clouds are the sites of star and planet formation in the Galaxy. The first millimeter-wavelength observations in the 1970s showed that these dark clouds are predominantly molecular in composition (see “► [Molecular Cloud](#)”) and with a temperature of 10–15 K are some of the coldest objects in the universe. The observations that were performed were molecular line surveys of carbon monoxide, CO. While cold molecular hydrogen has no detectable emission spectrum, CO is the next most abundant molecular species after H₂ in these regions and is easily detected at millimeter wavelengths. CO observations show that the molecular mass of the Galaxy is about two billion solar masses and that this mass is concentrated tightly in the flattened galactic disk and is dominated by giant molecular clouds (GMCs). The physical properties of GMCs are reviewed exhaustively in many papers (see, e.g., Evans 1999). With sizes ranging from 20 to 100 pc, and masses ranging from 10⁴ to 10⁶ M_☉ (solar masses), these objects are the largest structures in the Milky Way and rival ► [globular clusters](#) for sheer mass. The mean densities of

GMCs are $50\text{--}100\text{ molecules cm}^{-3}$ which, given their cold temperatures, implies that they are gravitationally bound, if not stable entities (see “► [Jeans Criterion](#)”). Measurements of molecular line widths indicate cloud velocity dispersions of $2\text{--}3\text{ km s}^{-1}$. Given the cloud sound speed $c_s \sim 0.2\text{ km s}^{-1}$, the velocity fields of these objects are highly supersonic. These supersonic motions are not for the most part due to systematic motions such as collapse or expansion, but appear to be turbulent in nature. For example, the relation between molecular line width and cloud size is similar to that expected for incompressible turbulent flows (Larson 1981). The lifetime of typical GMCs is an area of considerable controversy, with estimates ranging from an order of the free-fall time of the GMC (a few million years) to as much as 100 million years. Clearly it is important to have a better constraint on the ages of these complexes to understand the evolution of such clouds into stars.

Within GMCs, there are identifiable discrete entities with higher densities. These are referred to as dense cores, have typical sizes ranging from 0.1 to 1 pc, and typical mean densities of $10^4\text{ molecules cm}^{-3}$, with central densities reaching up to 10^6 cm^{-3} . The fraction of GMC mass in these dense cores is typically 1–10%, with the most evolved GMCs having higher percentages. The masses of these dense cores vary from 1 to $1000\text{ M}_\odot$. The frequency distribution of the masses tends to follow a power law, such that most of the mass in dense molecular gas is located in $M \geq 100\text{ M}_\odot$ cores. The velocity dispersions of dense cores tend to be supersonic, with the low-mass cores tending to have smaller dispersions, which in some cases become subsonic. Higher-mass cores tend to be warmer and more turbulent.

The mass distribution of dense cores in star-forming regions, the so-called core mass function (CMF), would be the precursor of the stellar initial mass function (IMF), which describes the distribution of masses for a population of stars (see “► [Initial Mass Function, Origin of](#)”). The IMF can be well described by a power law of the type $dN/dM \propto M^{-\alpha}$ for masses above about a solar mass, with $\alpha = 2.35$, the well-known Salpeter IMF (Salpeter 1955). Knowledge of the CMF

and of the content and distribution of ► [protostars](#) and young stellar objects (YSOs) within the GMCs or any molecular cloud is important for understanding how the process of star formation proceeds within it. Since protostars are often buried deep within the clouds, they tend to be invisible optically. However, the opacity of dust is an order of magnitude smaller in these sites at longer wavelengths compared to optical wavelengths. The younger or less evolved the star is, the more heavily obscured it typically is, and for such objects, far-infrared and submillimeter observations are required to study them.

The initial conditions and the earliest stages of star formation in dense cores are still areas of active study for observers and theorists. In active star-forming clouds such as those in Orion and Taurus, a large fraction of dense molecular cores harbor stars, while in clouds with a low level of star formation, 75% of the dense cores are starless (Lee and Myers 1999). Starless and prestellar cores offer a unique opportunity to constrain the initial conditions of star formation. Submillimeter observations of the dust emission from prestellar cores show that these cores have densities that are not strong functions of cloud radius, unlike cores with stars. It is also interesting to note that the measured emission line widths of starless cores are consistent with purely thermal internal motions and do not show any evidence of turbulent broadening. This may indicate that dense cores form initially from turbulent cores, but evolve by dissipating the internal turbulence before forming stars. Interestingly, observations of gravitationally bound prestellar cores indicate that the CMF of these cores is similar to the ► [initial mass function](#) (IMF) of Galactic field stars. This suggests that the origin of the initial distribution of stellar masses could be the CMF.

At least in isolated, low-mass dense cores, the formation of stars from dense cores is now well understood and backed with a wealth of observations and a good theoretical underpinning (see e.g., Shu et al. 1987; Larson 2003). The theoretical process can be described as follows: Before being incorporated into a forming star, the molecular material within the collapsing dense core must increase in density by 20 orders of

magnitude and decrease in size by 7 orders of magnitude relative to its initial state. Because the dust in the material is optically thin, internal energy and heat generated by collapse is radiated away, thereby maintaining the same temperature in the core. The collapse thus proceeds in an isothermal, dynamical manner, with the inner layers becoming denser and collapsing faster than the outer layers which are left behind. Eventually the inner layers become dense enough to become optically thick to their own radiation, resulting in the formation of a quasi-static stellar core surrounded by an infalling envelope. Magnetic fields, together with turbulence, may play a role in the whole process of star formation. Indeed, according to Shu et al. (1987), magnetic fields could be strong enough to be responsible for the low rate of star formation in the Milky Way (see “► [Magnetic fields and Star Formation](#)”). The morphology and strength of the magnetic field in star-forming regions can be estimated from dust polarized observations, assuming that the polarization pattern is due to dust grains with their shortest axis parallel to the magnetic field, and Zeeman splitting of suitable molecular lines.

Key Research Findings

Giant Molecular Clouds and Dense Cores

The IRAS space telescope in the early 1980s produced the first sensitive surveys in the mid- to far-infrared emission of GMCs. By the end of that same decade, near-infrared imaging detectors mounted on ground-based telescopes added complementary data. In the late 1980s and 1990s, the IRAS observations were followed up with targeted millimeter and submillimeter observations of star-forming regions. Large-scale CO surveys of molecular clouds revealed the vast extent of CO in the Galaxy and allowed us to study not only the physical properties but also the kinematics of GMCs (e.g., see Dame et al. 1987; Jackson et al. 2006; Schuller et al. 2017). All these competing but complementary surveys revealed that (1) stars form in dense molecular gas ($\geq 10^4$ H₂ molecules cm⁻³), (2) most stars form in embedded clusters, and (3) the overall efficiency of star

formation in GMCs is quite low (1–3% or less). The low global star formation efficiency is rather significant. This indicates that the bulk of the molecular mass in GMCs does not participate in the star formation process and exists in a semi-stable configuration. In this sense, the problem of star formation shifts from finding what makes the bulk of the material collapse to finding what holds up the bulk of the material against global collapse (see Shu et al. 1987). Molecular emission line and extinction surveys do find that a small fraction of molecular gas is at high density, and, not surprisingly, the efficiency of star formation in dense cores is much higher (10–20%) compared to the efficiency in the entire GMC. The highest efficiencies are found in the most massive cores that form embedded clusters (e.g., Lada 1992). At the turn of the millennium, a large number of ground-based near-infrared surveys combined with space telescope observations such as Hubble Space Telescope, Spitzer Space Telescope, and Herschel Telescope were used to study dense cores. Herschel Telescope observations of the ISM revealed the ubiquitous presence of complex networks of filamentary structures within interstellar clouds (see “► [Interstellar filaments](#)”) that play a crucial role in the star-forming process (see, e.g., André et al. 2010; Molinari et al. 2010). Indeed, dust continuum observations of filaments in nearby clouds have shown that prestellar cores preferentially form in the densest filaments, which suggests that the formation of dense cores would be the result of the fragmentation and gravitational collapse of such filaments.

From Dense Cores to Stars

In the last two decades of the twentieth century, evidence of this so-called pure infall stage was sought by many astronomers. The search for unique collapse signatures in dense cores with and without stars has been carried out by way of spectroscopic observations of molecular species that trace high density (like HCO⁺, CS, and N₂H⁺). But surprisingly, the first YSOs studied with molecular spectroscopy showed evidence for expansion signatures rather than collapse signatures. In fact, it was discovered that most if not all protostellar objects have vigorous bipolar

outflows (see “► [Bipolar Flow](#)”) that are predominantly molecular and extend sometime to parsec scales from the driving source (see Snell et al. 1980 for the discovery of molecular outflows). It is now understood that outflows originate from YSOs due to angular momentum conservation issues. Observations indicate that the specific angular momentum of cloud cores is 6 orders of magnitude larger than the material on the surface of typical stars. The tendency of collapsing material to preserve specific angular momentum causes the infalling material to form a flattened structure or disk around the protostellar core (the accretion disk; see also “► [Protoplanetary Disk](#)”). At the end of the twentieth century, the Hubble Space Telescope obtained spectacular images of circumstellar disks at optical and infrared wavelengths by imaging the dusty optically thick disks in dark-silhouette against the bright reflection nebula (e.g., O’Dell and Wen 1994; Padgett et al. 1999). At millimeter wavelengths, the dust emission of the disks is usually optically thin and can be easily imaged at high-spatial resolution with interferometers, such as ALMA. Molecular line emission of CO and isotopologues at millimeter wavelengths also allows us to study the kinematics of the disks. Observations suggest that circumstellar disks can range from a few hundred to a few thousand AU in diameter. The initial mass of the protostar is only $0.01 M_{\odot}$, not enough to increase the internal temperature to the stage of nuclear ignition. The embryonic star will have to accrete more material from the disk in order to build up mass. Material in the disk can fall into the star only if it loses angular momentum. Viscous accretion can result in the net outward transport of angular momentum, thereby allowing material to fall in (Lyndon-Bell and Pringle 1974). However, we still have the problem that material at the inner edge of the accretion disk has higher angular momentum compared to the star. Nature invented bipolar outflows to get rid of this angular momentum problem.

Bipolar outflows are a manifestation of primary winds generated by the protostar itself, and are typically traced at millimeter and centimeter wavelengths by transitions of CO. Close to the surface of the star, the wind appears as highly collimated circumstellar jets. These jets are hot

and ionized and emit radiation from optical to centimeter wavelengths. Typical jet tracers at near- and mid-infrared wavelengths are ro-vibrational and rotational transitions of H_2 and forbidden lines such as [Fe II], [S I], [S II], [O I], and [Ne II], while at millimeter and centimeter wavelengths, the most typical tracer is silicon monoxide, SiO. Such jets are often seen to terminate in bow-shock structures called Herbig-Haro (HH) objects. Further away from the star, these winds sweep up massive amounts of molecular material which shows up as bipolar molecular outflows.

Bipolar outflows are highly energetic and pack mechanical luminosities that are appreciable fractions of the total radiant luminosities of these objects. Observations indicate that the mechanical luminosities of these outflows are proportional to the rate at which they are accreting matter. It is becoming increasingly clear that the sizes of these outflows can completely dwarf the putative accretion disk, reaching parsec scales in many cases. One consequence of an accretion driven outflow is that this expanding material tends to disperse the surrounding material, thereby ultimately limiting the mass accreted onto the star.

During the earliest phases of protostellar evolution, the young star is completely surrounded by the disk and envelope structure and emits like a blackbody with its peak in the far infrared. This stage is called the Class 0 phase. As the putative outflow disperses the surrounding material and the accretion disk and the embedded star are revealed, at least from the polar directions, the spectral energy distribution (SED) shifts its peak into the near infrared and subsequently into the optical part of the spectrum, with a large infrared excess compared to regular main sequence stars. These phases are called Class I, II, and III (see “► [Spectral Classification of Embedded Stars](#)”). Observationally, the early stages are best studied at submillimeter wavelengths. Gradually, as the circumstellar material is dispersed, the protostar becomes revealed in the mid- to near-infrared, which can be studied with sensitive observations with space telescopes like Hubble, Spitzer, and Herschel, and especially with James Webb in the near future.

Planet formation probably commences quite early in the evolution, with the infalling dust settling down into the midplane of a circumstellar disk due to drag forces resulting from interaction with the gas in the disk (e.g., Lissauer 1993). Micron-sized dust particles collide and merge together to form increasingly more massive and larger particles. Once they reach kilometer size, they are called planetesimals. Planets are theorized to form from the mutual accretion of planetesimals. Such planets can grow massive enough to create gaps in the circumstellar disk. Such gaps were observed for the first time at millimeter wavelengths using ► [ALMA](#) (e.g., HL Tau: ALMA Partnership 2015), and later on, in scattered light at optical and near-infrared wavelengths (e.g., TW Hydrae: van Boekel et al. 2017). High-angular resolution observations at millimeter and infrared observations have revealed that protoplanetary disks exhibit a variety of morphologies, with not only gaps, but also rings and spirals (see e.g., Andrews et al. 2018).

Future Directions

The study of star formation is going through a golden period thanks to the current and planned new instrumentation. The increasing sensitivity and angular resolution achieved at submillimeter/millimeter wavelengths with ALMA and infrared wavelengths with, for example, the VLT will allow us to study the star formation process down to the smallest scales, close to the forming stars and planets. Only then will a complete picture of the entire process from large-scale GMCs to small protoplanetary disks and forming planets will be available. In the near future, the JWST space telescope will provide the sharpest and most accurate picture of the warm dust and molecular gas in young stars and protoplanetary disks, in particular at mid-infrared wavelengths, difficult to observe from the ground.

Cross-References

- [Bipolar Flow](#)
- [Initial Mass Function, Origin of](#)

- [Interstellar Dust](#)
- [Interstellar Filaments](#)
- [Interstellar Medium](#)
- [Jeans Criterion](#)
- [Magnetic Fields and Star Formation](#)
- [Molecular Cloud](#)
- [OB Association](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Spectral Classification of Embedded Stars](#)
- [Star Formation, Theory](#)
- [Stellar Evolution](#)

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Star Formation, Theory

Patrick Hennebelle

Service d'Astrophysique, Gif-sur Yvette, France

Keywords

Collapse · Giant molecular clouds · Stars · Interstellar medium · Magnetic field · Turbulence · Instabilities · Numerical simulations

Definition

The theory of star formation aims at understanding the physical processes, which drive the evolution of the interstellar medium from a very dilute gas into a dense medium in which nuclear reactions take place. It covers a very broad range of spatial and temporal scales that go from the giant molecular clouds, whose sizes are several tens of light years, to the stars themselves. It is believed that this evolution is largely triggered by gravity, magnetic field, turbulence, thermodynamics, as well as stellar feedback.

Overview

The interstellar medium within galaxies is filled by a gas, out of which stars eventually form. This gas presents a complex multiscale structure with temperatures ranging from 10 to 10^6 K and densities from 0.01 to at least 10^6 cm⁻³ and beyond. However, it remains much less structured than the stars themselves which occupy a tiny fraction of the galaxy volume but contain most of their (baryonic) mass. The star formation theory (Stahler and Palla 2005; Ward-Thompson and Whitworth 2011) aims to understand exactly how this transition, from a continuous to a discrete media, arises. This question bears important consequences for our universe. Not only stars are its building blocks but they strongly influence the evolution of galaxies through the feedback that the most massive stars exert during their life time, in particular at the end of their life when they explode in supernovae. Low-mass stars are also fundamental for it is well established now that they are hosting planetary systems like ours. Last but not least, stars synthesize heavy elements such as carbon and oxygen that drastically modify the thermal properties and the structure of the galactic gas and eventually permit the existence of complex molecules and life.

Historically a few outstanding questions have dominated the field of star formation although eventually many more should be addressed. The first challenge is to understand the efficiency at which stars formed in our Galaxy, a quantity also called the star formation rate (Kennicutt and Evans 2012). The second major issue is to understand the mass distribution of stars. Indeed, the properties of stars are largely determined by their masses. The mass distribution of stars is usually called the initial mass function (Offner et al. 2014; Lee et al. 2020). Finally, many stars are not isolated but are binary that is to say possess at least a companion whose distance may vary from less than an astronomical unit to a fraction of parsec. Understanding exactly how this happens as well as the characteristics of binary systems is another challenge for star formation theory. More recently with the discovery of extrasolar planets, which form within circumstellar disks, the

question of the disk formation, closely connected to the formation of binary systems, also became a major topic.

Various physical processes are triggering the evolution of the interstellar medium and eventually determine the star formation process (MacLow and Klessen 2004; McKee and Ostriker 2007). First of all, the gravitational force induces the formation of self-gravitating entities such as molecular clouds and dense cores that eventually collapse to form stars. An important concept has been inferred by Jeans (1902), the so-called Jeans length (Ward-Thompson and Whitworth 2011), which determines the spatial scale above which a cloud of a given density and temperature is prone to gravitational instability. To determine whether a cloud collapses or not, one must compare the time needed for this cloud to contract gravitationally (the freefall time) with the time needed for the sound waves to cross it. If this time is shorter than the freefall time, then the sound waves are unable to erase the density perturbations, which develop under the influence of self-gravity. Second, supersonic turbulence (Elmegreen and Scalo 2004; Scalo and Elmegreen 2004; Hennebelle and Falgarone 2012) is playing a major role in the interstellar medium, particularly in molecular clouds. On one hand, turbulent eddies tend to disperse their gas, thus contributing to reduce the efficiency of star formation. Indeed, if there was no support to resist the gravitational force, the number of stars formed each year in the Galaxy would be around 300, hundred times more than what is currently observed. However, turbulence is playing a dual role because it also compresses the gas locally through shocks. The spectrum of density fluctuations, which is then generated, may have fundamental consequences by setting the mass of the stars and being at the origin of their mass spectrum. Magnetic field is another physical process that likely has important consequences. Indeed, it has even been believed that magnetic field could be strong enough to be entirely responsible for the low star formation rate measured in the Milky Way (Shu et al. 1987). The idea was that because the ionization of the molecular clouds is rather low, most of the gas is not subject to the magnetic Lorentz force; thus, ionized species

could drift away carrying with them the magnetic field lines and reducing the magnetic intensity to the point where magnetic field would not be dominant anymore. Although this remains a controversial issue, the recent observational measurements seem to indicate that magnetic fields, while not negligible, are not dominant. Magnetic field however is having nevertheless a significant impact on the star formation process because it may contribute to reduce somehow the star formation efficiency. It also modifies the statistical properties of the supersonic turbulence, and finally during the collapse, it contributes to reduce the rotational support by transporting the angular momentum of the gas from the inner to the outer part of the collapsing cloud. As the collapse proceeds, the centrifugal force becomes more and more important and stops the gravitational infall, thereby leading to the formation of centrifugally supported disks. This process known as the centrifugal barrier requires the existence of various mechanisms to transport the angular momentum (Bodenheimer 1995; Hennebelle et al. 2013) and to permit the accretion onto the protostars. Angular momentum is at the origin of binary stars and planets. Indeed, the formation of a few objects orbiting around their center of mass constitutes an efficient way to store the angular momentum of the cloud. In the solar system, for example, the angular momentum of Jupiter is by far the dominant contribution. It is comparable to the angular momentum, which is believed to be typical for the prestellar core that led to the formation of the sun.

Finally, it is now well established that the feedback induced by the massive stars during their life, such as powerful winds, ionizing radiation, or protostellar jets, and particularly as they die and explode in a powerful supernovae, plays a major role in star formation (MacLow and Klessen 2004). First of all, this feedback is most probably an important source for the galactic turbulence. Second, the stellar feedback likely disperses the cloud in which the massive stars have formed and therefore significantly limits the star formation efficiency which otherwise would be far larger than the value deduced from observations.

Basic Methodology

Star formation appears to be a complex multi-scales and multiphysics problem. As such, it is necessary to combine various approaches to make progress in this field. First of all, high-resolution observations must be carried out using the most accurate telescopes at various wavelengths. Second, due to the complexity of the equations, which govern the fluid evolution, star formation theory makes extensive use of the numerical simulations. These calculations are performed on massively parallel supercomputers. They require millions of computer hours and generate terabytes of data. To solve the fluid equations accurately, complex algorithms have been developed such as Riemann and Poisson solvers (Teyssier 2002; Springel 2005). In parallel, one also needs to develop simpler analytical calculations for some of the key processes and to confront the results and the predictions with the numerical simulations. Such approach is necessary to assess the simulation results but also to identify and understand the nonlinear phenomena at play.

The numerical models take into account the microphysical properties of the chemical elements contained in the interstellar medium and determine, for example, the rate at which it cools or forms complex molecules (Le Petit et al. 2006). The knowledge of these microphysical processes is also a challenge, which requires dedicated observations, laboratory experiments, and heavy calculations. Third, the comparison between observations and theory is another necessary and complex step. To achieve this goal, it is sometimes necessary to produce synthetic observations using the models. That is to say, one needs to simulate the luminous signal, which would be observed if an object like the model was observed with a telescope (Commerçon et al. 2012).

Cross-References

- [Accretion](#)
- [Ambipolar Diffusion](#)
- [Dense Core](#)
- [Fragmentation of Interstellar Clouds](#)

- [Freefall](#)
- [Initial Mass Function](#)
- [Interstellar Cloud](#)
- [Magnetic Fields and Star Formation](#)
- [Magnetohydrodynamics](#)
- [Molecular Cloud](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Shock, Interstellar](#)
- [Star Formation, Triggering](#)
- [Turbulence, Interstellar](#)

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Star Formation, Triggering

Annie Zavagno

CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, Aix Marseille Université, Marseille, France

Institut Universitaire de France, Paris, France

Keywords

Star formation · Young stellar object (YSO) · HII region

Definition

► **Star formation** takes place in ► **molecular clouds** and occurs via two ways that can be either spontaneous or triggered. In the triggering case, an external agent (compression) acts as a precursor. This extra pressure has different origins and favors the collapse of molecular condensations to form stars. One mechanism of triggered star formation is based on the expansion of HII region around massive stars, but massive stars also impact on their surrounding via winds and supernova explosion at the end of their life. Recent multi-wavelength and multiscale data sets in our galaxy have shed light on star formation processes and revealed how important feedback processes may be.

Overview

Massive stars ($M > 8 M_{\odot}$) are rare and evolved rapidly, but they play a crucial role in the chemical

and dynamical evolution of galaxies. They produce a high amount of ultraviolet photons that can ionize the surrounding medium, especially neutral hydrogen (HI). This leads to the creation of an ionized (HII) region that expands in the surrounding medium, due to the temperature difference between the hot inside region and the cold surrounding gas (Dyson and Williams 1997). Massive stars also impact on their surrounding via winds and supernova explosion at the end of their life. They create heavy elements that are expelled and enrich the surrounding interstellar medium. Blaauw and Morgan (1953) first observed a sort of “in chain reaction” in the formation of massive stars, suggesting that the massive star HD34078 was formed in a compression region of a nebula that might have been itself pushed away from the Orion region. In a subsequent review, Blaauw (1964) observed spatial separation of OB subgroups with different ages. This observation leads Elmegreen and Lada (1977) to propose a mechanism of triggered star formation based on the expansion of HII regions. This mechanism has been called the collect and collapse model as a layer of material is collected during the expansion of the ionized region and then collapses to form fragments where new stars may form. With the progress made in infrared detectors and all-sky infrared surveys, it becomes clear that an over-density of young stellar objects is observed at the edges of HII regions in our galaxy and in external galaxies. In 2005, Deharveng et al. published a paper where, using the results from the Spitzer telescope, they studied in the infrared a series of Galactic HII regions where triggered star formation was likely to occur. Starting from this study, many international groups have worked on this subject with the aims to characterize the physical mechanisms responsible for this way of forming stars and to quantify its importance.

Multi-wavelength large-scale surveys together with pointed observations reveal active ongoing star formation at the edges of galactic and extragalactic HII regions (Deharveng et al. 2005; Zavagno et al. 2007; Galametz et al. 2013; Bernard et al. 2016). In the study of triggered star formation by expanding HII regions, the key question is to

establish the causal link, if any, between a given HII region's expansion and the star formation observed at its edges. One also wants to understand the physical mechanisms that control this way of forming stars (Schneider et al. 2020) and to quantify the importance of this phenomenon on a galactic scale (Palmeirim et al. 2017).

Massive stars form ionized regions. These regions expand in the surrounding medium at a supersonic speed ($v \sim 10$ km/s) creating a shock front preceding the ionized front. During the expansion of the HII region, neutral material accumulates between the ionization front and the shock front. A layer of dense neutral material builds up around the ionized region. With time, this layer becomes massive and a new generation of stars may form in it. This phenomenon is called triggered star formation by the expansion of ionized regions (Fig. 1).

Basic Methodology

In the study of star formation triggered by the expansion of HII regions, the first step is to detect

and to characterize the properties of YSOs that are observed at the edges of HII regions. Images give two-dimensional information, and the observed young stellar objects (which are stars in the process of forming) may not be associated with the observed HII region we are looking at but may be a by-chance projection observed on the line of sight. Complementary spectroscopic data give information on the velocity of the YSOs and the ionized region and allow to demonstrate the real association of the YSO with the ionized region. The physical properties of the YSOs (luminosity, mass, age, evolution stage) can be obtained by measuring their flux at different wavelengths covering a large spectral range (ideally from the optical to the millimeter) and by fitting the complete set of fluxes with theoretical models that predict their evolution. The early stages of star formation are also characterized by a strong dynamical and chemical evolution. Such information is obtained with spectroscopic data and is also crucial in our determination of young stellar objects' age. Indeed, the triggered star formation mechanism supposes that the first generation of massive star (s) that creates the ionized region has to be older than the YSOs observed at its edges, if a causal link exists between the expansion of the ionized zone and the further formation of YSOs observed on its edges.

Key Research Findings

Many recent infrared and submillimeter surveys have shown that we are living in a "bubbling galactic disk" where thousands of ionized regions are observed with bright YSOs sitting at their edges (Deharveng et al. 2010; Kendrew et al. 2012). These authors have shown that triggered star formation seems to be an efficient way of forming massive stars as at least 30% of the massive YSOs are observed at the edges of HII regions in the galaxy (Palmeirim et al. 2017, Kumar et al. 2020). Deharveng et al. (2010) have shown that many physical mechanisms can be responsible for triggered star formation at the edges of HII regions. Among these are small-scale gravitational instabilities, large-scale gravitational instabilities that lead



Star Formation, Triggering, Fig. 1 RCW 120: a galactic HII region with active star formation observed with the infrared Herschel satellite and the PACS and SPIRE instruments (Credits: ESA/PACS & SPIRE Consortium, Dr. Annie Zavagno, LAM, HOBYS Key Programme Consortia)

to the formation of high-mass fragments, ionizing radiation acting on a turbulent medium, and radiation-driven compression of preexisting dense clumps. All these mechanisms can act at the edges of a given ionized region.

Herschel observations of Galactic HII regions compared with results of numerical simulations show that the expansion of the ionized region has a real impact in increasing the density at the edges of the ionized gas and that compression from the ionized gas really impacts on star formation (Minier et al. 2013; Tremblin et al. 2015). Radiative compression occurs at the edges of HII regions and enhances the local density (Zavagno et al. 2020). However, numerical studies (Dale et al. 2013) show that it is very difficult to separate the preexisting and triggered star formation at the edge of ionized regions. Herschel data provide a lot of key information especially on the structure of the dense regions that surround HII regions that allow us to really characterize the role of these regions in the star formation observed at their edges. Billot et al. (2011) used a minimum spanning tree algorithm to characterize the spatial distribution of galactic far-IR sources and derive their clustering properties using the results of the Herschel infrared GALactic (Hi-GAL) plane survey (Molinari et al. 2010). They show that protostars surrounded by warm molecular material and detected at short infrared wavelengths tend to be clustered in dense and compact groups around HII regions. Detailed studies of galactic ionized regions such as Gum 31 (Ohlendorf et al. 2013) show that the location of associated YSOs in the photodissociation region is suggestive of their being triggered by a collect and collapse scenario. However, the study of an infrared dark filament in interaction with an HII region (Tackenberg et al. 2013) shows that the evidence for triggered star formation there is not obvious, even if a massive (preexisting) clump is observed. The difficult point remains to prove that the collapse that will lead to star formation is really favored by the expansion of the ionized region.

Recent statistical studies and multiscale analysis (from >10 pc to the core scale <0.01 pc) of a sample of high-mass starless clumps (HMSCs) that are expected to represent the earliest (and

still unperturbed) stages of high-mass star formation bring very interesting results: Zhang et al. (2020, 2021) show that the HMSCs associated with HII regions have different physical properties (luminosity and temperature) than the ones observed away from HII regions. The HMSCs associated with HII regions (i.e., observed at their edges) are also more turbulent. This demonstrates for the first time the physical impact from HII regions on massive clumps at the very early stages of their formation.

Future Directions

The wealth of data provided by the Herschel satellite, combined with high-resolution ALMA data and forthcoming data such as the ones provided by the JWST, allow an in-depth study of the star formation in our galaxy and in external galaxies.

The global view we have with large imaging and spectral surveys allows to study the triggered star formation phenomenon and to quantify its importance on galactic scales. This global view will be complemented with detailed, high-resolution pointed observations in the infrared with ground- and space-based facilities and in the millimeter with the ALMA interferometer. The idea with high-resolution pointed observations is to go in depth in our understanding of the physical mechanisms that control star formation on small spatial scales, including fragmentation of clumps into cores on spatial scale <0.01 pc, whatever the way (either spontaneous or triggered) of forming star is. Future observing facilities either ground and space based go in this direction of high resolution. The James Webb Space Telescope (JWST) and the Extremely Large Telescope (ELT) will play a crucial role in this context. All the knowledge that will be gained with these observations will help to further constrain the theoretical models that describe with more and more details the mechanisms that control star formation. The possibility to address this issue in external galaxies will also become possible with these high-resolution and high-sensitivity facilities.

Recently, the role of magnetic field in the star formation process has gained much interest in

research, mainly driven by the progress in magnetic field measurements (Bracco et al. 2020). The study of the magnetic field observed toward HII regions and its role in star formation will be a major research topic in the coming years.

Some of the key questions that still have to be addressed are:

- How important and how efficient is this way of forming stars? Herschel images revealed highly embedded sources that were not detected before at the edges of HII regions. This means that these sources were not “counted” and that their presence, if firmly related to the impact of the ionized region, will increase the efficiency of this way of forming stars. Spectroscopic studies show that most of the young sources observed at the edges of HII regions are physically associated with them (Martins et al. 2010). However, in some cases, the sources are not associated with the ionized region, contrary to what is suggested by two-dimensional images. This result also changes the statistics, as soon as a non-associated young source may be counted (as being under the influence of the ionized region) if no spectroscopic information exist for it. The existence of spectroscopic data will improve this situation, allowing a clear association between YSOs and HII regions.

The high-resolution ALMA data offer a unique opportunity to address this question by looking at the central part of the clumps located at the edges of HII regions. The fragmentation of these clumps form the cores that will form the future stars. Looking at the population of cores in clumps allows to study this process at the heart of star formation, especially for clumps observed at the edges of HII regions compared to clumps observed away from HII regions (Zhang et al. 2021).

- What are the mechanisms that control star formation at the edges of HII regions? Observations and comparison with numerical simulations are needed now to understand the different physical processes that take place to possibly favor star formation, including a careful treatment of the radiative transfer of the

incoming radiation from the ionized region onto the dense clump that will host the future star formation. The role of turbulence and magnetic field at small and large scale in the star formation process in general and in this specific way of forming stars in particular is still not clear. Zhang et al. (2020) show that the physical properties of massive clumps are changed at the edges of HII regions when compared to similar clumps observed away from HII regions. The physics of this change has to be modeled and understood, including all the physical ingredients.

- What is the impact of HII region in the mass distribution of young stars that form at their edges? The study of the initial mass function (IMF) is a key question in astrophysics. A systematic study of young clusters at high resolution has to be done to address this question. The combination of high-resolution and high-sensitivity data in the infrared with the JWST and with ALMA in the submillimeter range is very promising for this topic.
- What is the importance of this phenomenon in external galaxies? High resolution allows to study this phenomenon in external galaxies and to see how it proceeds under specific environment, including low-metallicity galaxies. If massive stars can trigger the formation of a new generation of massive stars, this phenomenon may be important for cosmology and the formation of the first massive stars in the universe. On this topic also, the combination of ALMA and JWST data offers a very bright future.

Cross-References

- [ALMA](#)
- [Herschel Mission](#)
- [JWST](#)
- [Protostars](#)

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Stardust Mission

Hugues Leroux

Unité Matériaux et Transformations (UMET),
University Lille 1, Lille, France

Keywords

Accretion · Comet · Meteorites · Primitive material · Solar system · Spacecraft mission

Definition

Stardust is a spacecraft mission which returned to Earth samples from the ► [comet Wild 2](#). The main objective of the mission was to contribute to the understanding of the evolution of the solid matter which marked the passage of the interstellar matter in the solar nebula and constrain models of formation and evolution of dust particles in the protoplanetary disk.

Overview

Stardust is a ► [NASA](#) mission whose main objective was to collect samples in the coma of the

comet Wild 2. The spacecraft was launched on February 1999 and returned to Earth on January 2006. It is the first sample return mission to collect cometary dust. These cometary particles are believed to be relicts of the primitive material of the early solar system. Their sojourn in a comet nucleus probably allowed the preservation of primordial signatures. The main scientific objective of the mission was to understand the evolution of solid matter which marked the passage of the interstellar matter in the solar nebula and constrain models of formation and evolution of dust particles in the protoplanetary disk.

The cometary dust in the coma was trapped at a relative velocity of 6.1 km/s using a dust collector which contains ultralow-density aerogel trays. The role of the aerogel was to reduce the particle speed gradually in order by the temperature rise to minimize the physical and chemical alteration due to the high-velocity capture. A large number of particles were returned to Earth and were studied using various investigation techniques by several international laboratory consortia.

The impact of particles in aerogel generated deceleration tracks in which the cometary material is unevenly distributed in various proportions. The largest particles were found well preserved from the hypervelocity impact. Their study showed that most of them display clear evidence for high-temperature processes that likely occurred at the inner edge of the ► [protoplanetary disk](#) before the accretion on the comet. On the opposite, the fine-grained material shows clear evidences of thermal modification in addition to strong intermixing with the aerogel due to the capture process at very high velocity. This thermally modified material originates from fine-grained, loosely bound, dust aggregates for which the composition is close to the solar photosphere or the most primitive ► [meteorites](#).

Particles returned by the Stardust spacecraft show that the comet Wild 2 accreted “cold” dust from the icy parts of the outer solar system and also thermally processed particles coming from the inner region close to the Sun. The protoplanetary disk at the accretion stage of the ► [solar nebula](#) period was thus animated by large radial mixing.

Cross-References

► [Comet](#)

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- <http://stardust.jpl.nasa.gov/overview>

Stars

Patrick Eggenberger¹ and Sylvia Ekström²

¹Geneva Observatory, University of Geneva, Geneva, Switzerland

²Observatoire de Genève, Université de Genève, Geneva, Versoix, Switzerland

Keywords

Stars · Hydrostatic equilibrium · Radiative equilibrium · Molecular cloud · Nuclear reactions · Nucleosynthesis · Chemical enrichment

Definition

Stars are spheres of plasma in hydrostatic equilibrium, where the inward force of gravity is balanced by the outward gas pressure. The energy source for the gas is gravitation, sustained and prolonged by nuclear energy resulting from

thermonuclear fusion reactions in the hot stellar interior. Stars form by contraction of a portion of a molecular cloud.

Overview

Stars are spheres of gas that can most of the time be considered as in hydrostatic and radiative equilibrium. They form during the contraction of cold molecular clouds. In the process of star formation, a part of the original matter of the cloud may form a disk around the star, and in such a disk, planets could be built.

At the center of the collapsing cloud, the temperature rises until it is sufficient for nuclear reactions to take place; thus, a new star is born. Through these reactions, new chemical elements are synthesized (→ nucleosynthesis) accompanied by a production of energy. The energy release sustains the star against its own gravity. Successive fusion phases can be identified in the course of the evolution of stars: deuterium and lithium at the very beginning of the evolution and then hydrogen (→ main sequence). Stars more massive than 0.5 Msol go on with a phase of helium fusion (“burning”), and the ones more massive than 8–9 Msol enter the advanced phases: carbon burning, neon photodisintegration, oxygen, and eventually silicon burning.

The way stars end their evolution depends on their initial mass: below 8 Msol, they experience a strong wind evaporating their external layers, and they end as white dwarfs surrounded sometimes by a planetary nebula. Between 8 and 10 Msol, they ignite carbon in degenerate conditions, building an O-Ne core. If the core at the end of C burning is large enough, the star can explode in what is called an electron-capture supernova (→ supernova); otherwise, it ends its life as an O-Ne white dwarf. Above 10 Msol, stars end their evolution in the explosion of a supernova. The remnant may be a neutron star or a black hole, depending on the mass of the iron core at the time of the collapse.

Stars are the source of most heavy elements in the Universe (there is also the phenomenon of spallation by cosmic rays). The products of nucleosynthesis that occurs in their core are spread in

the interstellar medium by the winds or the supernova explosion, contributing to the general chemical enrichment of the Universe.

Cross-References

- ▶ [Asteroseismology](#)
- ▶ [High-Mass Star](#)
- ▶ [Low Mass Star](#)
- ▶ [Magnetic Fields and Star Formation](#)
- ▶ [Stellar Evolution](#)
- ▶ [Supernova](#)

Šteins

Ekkehard Kührt
Institute of Optical Sensor Systems, German
Aerospace Center, Berlin, Germany

Definition

Asteroid 2867 Šteins is a main-belt asteroid of the rare spectral E-type with an effective spherical diameter of 5.4 km and a rotation period of about 6.05 h. The interior structure is thought to be a rubble pile. On September 5, 2008, the Rosetta Spacecraft flew by Šteins at a distance of 800 km with a speed of 8.6 km/s and collected a great amount of scientific data.

History

Asteroid 2867 Šteins was discovered in 1969 by the Soviet and Russian astronomer, Nikolai S. Chernykh. It is named after Kārlis Šteins, a Soviet and Latvian astronomer.

Cross-References

- ▶ [Asteroid](#)
- ▶ [Rosetta Spacecraft](#)
- ▶ [Taxonomy](#)

Stellar Cluster

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

Stars located in the same region that move together through space must be physically related and indeed must share a common origin – such stars form a stellar cluster. Within our own galactic neighborhood, all stellar clusters are relatively young and eventually disperse. In some groups, called open clusters, the coherence is maintained by the mutual gravitational attraction of the member stars. In others, called T associations, the stars are gravitationally bound to a parent ▶ [molecular cloud](#). OB associations, a third type, are unbound and actively dispersing. The very youngest stars are in groups so deeply embedded in cloud gas that they can be detected only in the infrared or submillimeter wavelength ranges.

Cross-References

- ▶ [Globular Cluster](#)
- ▶ [Molecular Cloud](#)
- ▶ [OB Association](#)
- ▶ [T Association](#)

Stellar Evolution

Patrick Eggenberger
Geneva Observatory, University of Geneva,
Geneva, Switzerland

Keywords

Stars · Stellar physics · Internal stellar structure

Definition

Stellar evolution refers to the changes in the internal and global properties of stars during their lifetime.

Overview

Stars are fundamental entities providing light and energy in the Universe, as well as producing most of the chemical elements. The study of their internal structure and evolution is thus at the basis of astrophysics. In addition, since many stars host planetary systems, their study is a basic aspect of astrobiology. In this entry, the basic concepts of stellar evolution are first introduced by deriving the equations describing the evolution of the internal structure of a star. These equations are then used to obtain simple analytical estimates of stellar properties and to qualitatively understand the different phases of stellar evolution in terms of basic physical considerations. The evolutionary scenarios obtained by numerically solving the equations of stellar evolution are then discussed for stars with different initial masses. In addition to this global view of standard stellar evolution, the inclusion of nonstandard-stellar physics is finally briefly discussed together with the future developments expected in the field. Since this entry only provides a brief overview of stellar evolution, readers interested in a more in-depth description of the subject are referred to the books already available in the literature (e.g., Kippenhahn and Weigert 1990; Prialnik 2000; Hansen et al. 2004; de Boer and Seggewiss 2008; Maeder 2009).

Basic Methodology

Hydrostatic Equilibrium

To understand stellar evolution, we first note that most stars are in such long-lasting evolutionary phases that no significant changes in their global properties can be directly observed. Indeed, during the main part of their life, stars are in mechanical equilibrium or hydrostatic equilibrium. This

implies that all forces acting on a given element of the star compensate each other. To prevent the gravitational force from accelerating a mass element toward the center, a force of the same absolute magnitude must be acting outward. This force is due to pressure and, more precisely, to the pressure gradient present in stellar interiors. The equation expressing the hydrostatic equilibrium of a star can be very simple derived by considering a thin shell in a spherically symmetric star with a radius r and $r + dr$ with pressures of P and $P + dP$, respectively. The radius r is defined here as the distance to the stellar center. The difference of pressure dP between r and $r + dr$ is then balanced by gravitation such that

$$dP = -\rho g dr, \quad (1)$$

with ρ is the density and g the magnitude of the vector gravity directed toward the stellar center. By defining M_r as the total mass interior to the radius r , Newton's Law of Gravitation gives $g = GM_r/r^2$ where G is the constant of gravitation, and then,

$$\frac{dP}{dr} = -\frac{GM_r}{r^2} \rho. \quad (2)$$

This equation of hydrostatic equilibrium constitutes the first basic equation describing the structure of a star. It simply means that at any point in the interior of a star at equilibrium, the pressure gradient sustains the stellar matter against the gravity force.

The second basic equation governing the structure of a star concerns the variation in mass within a star and is directly related to the conservation of mass. In spherical symmetry, the change of the mass M_r contained in a sphere of radius r is given by

$$dM_r(r, t) = 4\pi r^2 \rho dr - 4\pi r^2 \rho v dt. \quad (3)$$

The first term on the right-hand side of this equation corresponds to the change of mass resulting from a variation in the radius r at a given time t , while the second term represents the flux of mass out of the sphere of radius r due

to a motion with velocity v . At equilibrium, this velocity v equals 0, and we are left with the following equation:

$$\frac{dM_r}{dr} = 4\pi r^2 \rho. \quad (4)$$

This is the second basic equation describing the internal structure of a star. It is interesting to note that if the pressure P is a function of the density ρ alone, Eq. 4 together with Eq. 2 form a complete set of equations describing the structure of the star. However, under normal stellar conditions, pressure also depends on temperature. This means that the presence of a pressure gradient required to achieve hydrostatic equilibrium also results in a gradient in temperature inside the star. The central layers of a star are then found to be hotter than the superficial layers. Recalling that a higher temperature leads to a larger amount of energy contained per unit volume in the radiation field, an energy flow will take place from the central parts to the stellar surface, so that a star continuously loses energy. The luminosity (total energy radiated per unit time) of the star is then a direct consequence of hydrostatic equilibrium: stars evolve because they lose energy in order to counteract the gravitational force and to achieve hydrostatic equilibrium. The sources of this stellar energy will directly influence the evolution of the star and the duration of the various evolutionary phases.

Energy Production

Gravitational contraction is a major source of stellar energy. By a global contraction, a star can indeed directly extract energy from the gravitational potential. Conversely, an expansion of the star leads to an absorption of energy and a decrease of its luminosity. This production of energy takes place on a characteristic timescale called the Kelvin-Helmholtz timescale τ_{KH} . This timescale can be simply calculated from elementary physics, such that the global gravitational energy Ω of a star of mass M and radius R is given by $\Omega = -qGM^2/R$ (with $q = 3/5$ for a constant density). The star will then be able to produce an average luminosity L at the expense

of its gravitational energy on a timescale given by this energy divided by the energy production per second:

$$\tau_{KH} = \frac{\Omega}{L} \approx \frac{GM^2}{RL}. \quad (5)$$

For the Sun, this gives a typical value of about 3×10^7 years. This lifetime of a few tens of million years is, of course, too short to be in agreement with our knowledge of the past history of the Earth. This indicates that another main source of stellar energy exists.

In addition to gravitational contraction, a star can produce energy by thermonuclear reactions in its central layers where the physical conditions in terms of temperature and density needed for such processes to occur are met. The timescale of energy production through nuclear reactions can be simply estimated from the hydrogen-burning phase, the longest phase of stellar evolution, during which the fusion of hydrogen into helium occurs (astronomers refer to nuclear fusion as “burning”). The hydrogen burning transforms four protons into one helium nucleus with a release of energy due to a relative mass defect of about 0.007. Simply speaking, this means that 1000 g of hydrogen is converted into 993 g of helium, while 7 g is transformed into energy, where $E = mc^2$. The characteristic timescale associated with this reaction can then be expressed as the ratio of the total energy that can be created by this process to the stellar luminosity, the analogue of Eq. 5. If nuclear reactions would take place in the whole star of total mass M , this energy would be equal to $\Delta Mc^2 = 0.007 M$ (with c the speed of light). However, nuclear reactions only take place in the central parts of the star, so that this energy estimate has to be corrected by a factor q equal to the fraction of the stellar mass where nuclear reactions occur. This leads to the following timescale of energy production by nuclear reactions:

$$\tau_H \approx 0.007 \frac{q_c Mc^2}{L}. \quad (6)$$

For the Sun, this estimate gives a typical lifetime of 10 billion years (with $q_c = 0.1$), which is in

agreement with our knowledge concerning the past history of the Earth. These very simple estimates of characteristic timescales for the stellar energy production show that nuclear reactions are of major importance to understanding how a star can shine during long durations. Nuclear energy is, however, not absolutely necessary to explain the observed stellar luminosities, since a star can be shining even without nuclear reactions in its core (but only on limited timescales) thanks to the energy production by gravitational contraction. The role of nuclear reactions is of course not limited to the energy equilibrium of the star, since nuclear reactions transform chemical elements in stellar interiors and are therefore at the basis of stellar nucleosynthesis.

The energy conservation in a star leads to the third basic equation for stellar structure. It simply implies that the gain of energy in a mass element is equal to the difference between the energy produced and the energy escaping. With the hypothesis of spherical symmetry of the star, it can be shown that the equation of energy conservation can be written as

$$\frac{\partial L_r}{\partial r} = 4\pi r^2 \rho (\varepsilon + \varepsilon_{\text{grav}}), \quad (7)$$

where L_r is the luminosity at radius r , ε is the energy produced by nuclear processes per unit of time and mass, and $\varepsilon_{\text{grav}}$ is the energy provided to the system due to a change of structure.

Energy Transfer

Like the mechanical equilibrium of the star, its energetic equilibrium plays a key role in determining its structure and evolution. This equilibrium describes the balance between the energy production discussed in the preceding section and its transport to the stellar surface. The energy production rate of a star regulates itself to reproduce the radiative losses at the surface. In this sense, a star can be considered as a self-controlled nuclear reactor. Assuming that more energy is produced in the stellar center than what can be transported to the surface would lead to an accumulation of energy in the central layers resulting in an expansion of the star. The internal pressure

and temperature would then decrease as a result of this expansion, thereby reducing the energy production rate by nuclear reactions. The transport of energy in the interior of a star is thus of prime importance to determine its structure. The transport by photons, or radiative transfer, plays the main role. Convection is another important process for the transport of energy, but it generally occurs only over limited zones of the stellar interior, while radiative transfer is present in the whole interior. Conduction by electrons is the third process for the transport of energy; it only plays an important role in degenerate conditions (e.g., in white dwarfs).

To discuss radiative transfer in stellar interiors, we first consider a photon emitted in the central layers of a star. This photon will be rapidly absorbed by an atom, then re-emitted in a random direction, reabsorbed by another atom, re-emitted, and so on until it reaches the stellar surface. The length of the mean path of this photon between two interactions, which is called the mean free path, is much smaller than the stellar radius. In the case of the Sun, this mean free path is indeed approximately equal to 0.01 cm in the center and 1 cm in the envelope (near the surface, this value may of course be much larger given the very low density of the external layers). Thus, sometime will be spent before a photon emitted in the stellar core reaches the surface; in the case of the Sun, this value is typically of the order of ten million years.

In addition to the photon mean free path, another quantity is important in the context of radiative transfer: the mean gradient of temperature inside the star. This value can be roughly estimated by using the solar values of radius and central temperature:

$$\begin{aligned} \left\langle \left| \frac{dT}{dr} \right| \right\rangle &\approx \frac{T_{\text{central}} - T_{\text{surface}}}{R} \approx \frac{T_{\text{central}}^{\text{sun}}}{R_{\text{sun}}} \\ &\approx 10^{-4} \text{ K cm}^{-1}. \end{aligned} \quad (8)$$

Comparing this value with the photon mean free path and recalling that temperatures in the internal layers of the Sun are typically of the order of ten million K, we see that the relative

variation of the temperature is very small over the mean free path of a photon. This implies that the radiation field in a star can be well described by the radiation of a blackbody with the local value of temperature T : this is called local thermodynamic equilibrium (LTE). From this, we can ultimately derive the fundamental equation of radiative transfer:

$$F = \frac{L_r}{4\pi r^2} = -\frac{4acT^3}{3\kappa\rho} \frac{dT}{dr}. \quad (9)$$

where κ is the opacity or absorption coefficient of the stellar matter and the radiation constant a is equal to $4\sigma/c$, with σ = Stefan's constant. The radiative flux F is thus proportional to the thermal gradient.

In addition to radiation, convection can also transport energy in stellar interiors. These convective motions take place in stellar regions where a heat excess is present that cannot be transferred by radiation alone. Since the treatment of convection is a difficult task involving the complexity of turbulent motions, we only give here the basic transfer equation describing adiabatic convection, which applies in the deep stellar layers:

$$\frac{dT}{dr} = \nabla_{\text{ad}} \frac{T}{P} \frac{dP}{dr} \text{ with } \nabla_{\text{ad}} = \frac{P\delta}{C_P\rho T}, \quad (10)$$

where C_P is the specific heat and $\delta = -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_P$.

Key Research Findings

Basic Equations of Stellar Evolution

In the preceding section, the fundamental concepts of stellar evolution have been introduced to obtain the four equations that describe the evolution of the structure of a star (when rotational and magnetic effects are ignored):

- Hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{GM_r}{r^2} \rho \quad (11)$$

- Mass conservation (continuity equation):

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \quad (12)$$

- Energy conservation:

$$\frac{\partial L_r}{\partial r} = 4\pi r^2 \rho (\varepsilon + \bar{v}_{\text{grav}}) \quad (13)$$

- Transport equation:

$$\frac{dT}{dr} = -\frac{3\kappa\rho}{4acT^3} \frac{L_r}{4\pi r^2} \text{ in radiative zones} \quad (14)$$

$$\frac{dT}{dr} = \nabla_{\text{ad}} \frac{T}{P} \frac{dP}{dr} \text{ in convective zones} \quad (15)$$

The properties of the stellar matter appear through the following physical ingredients, which are required to solve these equations:

- The nuclear reaction rates are needed to evaluate the corresponding production of energy.
- The equation of state expresses the relation between the three physical parameters P , T , and ρ . For a given chemical composition, the equation of state is required to determine the third physical parameter from the two others and to obtain the thermodynamic quantities needed for the computation of a stellar model.
- The opacities are required to calculate the energy transport by radiative transfer and to determine the radiative gradient. A prescription for the energy transport by convection is also required to calculate the temperature gradient in a convective zone. In particular, the hypothesis of adiabaticity is correctly justified in deep stellar layers, but becomes inadequate for outer convective zones. In this case, an appropriate approximation has to be used, as, for instance, the standard mixing-length theory (Böhm-Vitense 1958).

Finally, together with this system of equations, the equations of the evolution of chemical element abundances are solved.

Simple Estimates of Stellar Properties and the Mass-Luminosity Relation

The general equations governing stellar evolution are, of course, too complicated to be solved analytically. The structure and evolution of a star is thus computed by numerically solving this system of equations. It is, however, interesting to notice that very simple estimates of some basic stellar properties can be directly deduced from these equations. For instance, using the equation of hydrostatic equilibrium, one can readily obtain an order-of-magnitude estimate of the pressure and temperature inside a star. First, the pressure gradient of Eq. 11 is approximated by

$$\left| \frac{dP}{dr} \right| \approx \frac{P_{\text{center}} - P_{\text{surface}}}{R} \approx \frac{P_{\text{center}}}{R}. \quad (16)$$

By also taking simple average values for the other quantities appearing in Eq. 11, $M_r < M/2$, $r < R/2$, and $\rho < 3 M/(4\pi R^3)$, one obtains an estimation of the pressure in the central parts of a star:

$$P_{\text{center}} \approx \frac{3}{2\pi} \frac{GM^2}{R^4}. \quad (17)$$

The corresponding rough estimate of the central stellar temperature can then be obtained by assuming a chemically homogeneous star with the perfect gas law:

$$P = nkT = \frac{\rho}{\mu m_u} kT, \quad (18)$$

with k the Boltzmann constant, m_u the atomic mass unit, μ the mean molecular weight (i.e., the average number of atomic mass units per particle), n the number of particles per unit volume, and ρ the density. Combining this relation with the above estimate of the central pressure (Eq. 17), we obtain

$$T_{\text{center}} \approx \frac{\mu m_u}{k} \frac{GM}{R}. \quad (19)$$

In the case of the Sun, these crude estimates give values of about $5.5 \times 10^{15} \text{ g}^{-2} \text{ cm}^{-1}$ and

$3 \times 10^7 \text{ K}$ (assuming a mean molecular weight of $\mu = 0.5$ corresponding to ionized hydrogen) for the central pressure and temperature, respectively. This shows that very high values of pressure and temperature are encountered in the deep stellar interior. These simple estimates are also significant in that they illustrate the functional dependence of these internal stellar properties on the global stellar parameters M and R .

While simple estimates of internal stellar properties can be derived from the relation of thermodynamic equilibrium, an estimate of the fundamental relation between stellar luminosities and masses can be obtained from the equation of radiative transfer. Starting from Eq. 14 with a simple approximation of the radiative pressure gradient expressed in terms of temperature

$$\begin{aligned} \frac{dP_{\text{rad}}}{dr} &= \frac{d}{dr} \left(\frac{1}{3} a T^4 \right) = \frac{1}{3} a \frac{dT^4}{dr} \\ &\approx \frac{1}{3} a \frac{T_{\text{surface}}^4 - T_{\text{center}}^4}{R} \\ &\approx -\frac{1}{3} a \frac{T_{\text{center}}^4}{R}, \end{aligned} \quad (20)$$

and with approximations for the quantities $L_r \sim L$ (with L the total luminosity) and $r \sim R/2$, one obtains

$$L \approx \frac{\pi ac}{3} R \frac{T_{\text{center}}^4}{\kappa \rho}. \quad (21)$$

Using the estimate for the central temperature derived above (Eq. 19) and the mean value of the stellar density of $\rho < 3 M/(4\pi R^3)$, this finally leads to

$$L \approx \frac{4\pi^2 ac}{9} \left(\frac{Gm_u}{k} \right)^4 \frac{\mu^4 M^3}{\kappa}. \quad (22)$$

This fundamental relation between L and M is called the mass-luminosity relation. Eq. 22 is, of course, only a crude estimation of the relation. However, it enables us to clearly illustrate some fundamental stellar properties. First, the luminosity is found to rapidly increase with the stellar mass. This increase, which is proportional to the

third power of the mass, correctly reproduces the properties of stars during the long-lasting main sequence phase of core hydrogen burning. Second, the luminosity is found to depend on the opacity κ but not on the nuclear energy production. This nicely illustrates the fact briefly discussed above that nuclear reactions enable the star to shine during long periods of time but that its luminosity depends on the ability of photons to travel through the stellar matter to reach the stellar surface.

Evolution in Degenerate and Nondegenerate Conditions

After briefly studying how basic stellar properties can be simply derived from the general equations of stellar structure, we are now interested in investigating how these properties evolve during a stellar lifetime. As discussed above in the section devoted to stellar energy production, two main sources of energy are available for a star: thermonuclear reactions and gravitational contraction. Consequently, the evolution of a star can be schematically represented as a succession of phases during which the energy is mainly produced by nuclear reactions and phases during which the energy production related to gravitational contraction dominates. Indeed, as soon as all the nuclear fuel present in the core of a star has been burnt by nuclear reactions, energy is mainly produced by gravitational contraction until the physical conditions in the stellar center enable it to ignite a new series of nuclear reactions. Thus, the temperature and density increase in the central parts of a star during its evolution as a result of the succeeding contractions. This can lead to significant changes in the physical properties of stellar matter with a transition from nondegenerate to degenerate conditions.

We recall here that degeneracy pressure is of nonthermal origin and results from quantum-mechanical effects. According to Pauli's exclusion principle, each quantum cell of the six-dimensional phase space $\{x, y, z, p_x, p_y, p_z\}$ cannot contain more than two electrons (x, y, z correspond to the space coordinates of the electrons with volume $dV = dx dy dz$, while p_x, p_y, p_z correspond to the momentum space). The

volume of such a quantum shell is defined by $dx dy dz dV$ and is equal to h^3 , with h the Planck constant. When the density increases, the volume dV is reduced so that some electrons will exhibit large impulses. These electrons with large velocities will then exert a new sort of pressure that solely depends on density and not on temperature. Note that this holds not only for electrons but also for other fermions like the neutrons.

Interestingly, the two main sources of energy production, nuclear reactions and gravitational contraction, lead to completely different effects when the stellar matter is degenerate compared to the nondegenerate case. Indeed, in nondegenerate conditions, a contraction leads to an increase of the central temperature of the star, while in degenerate conditions, a contraction may produce a cooling of the stellar matter. To illustrate these different behaviors, we first consider a uniform contraction of a given mass M . This results in a variation δr of the radius together with variations in pressure δP and density $\delta \rho$. Using the equation of hydrostatic equilibrium, the relation between the variations in pressure and radius is given by

$$\frac{\delta P}{P} = -4 \frac{\delta r}{r}. \quad (23)$$

The equation of mass conservation leads to the following relation between the variation in density and radius:

$$\frac{\delta \rho}{\rho} = -3 \frac{\delta r}{r}. \quad (24)$$

Combining these equations, we obtain the relation between the variations in pressure and density:

$$d \ln P = \frac{4}{3} d \ln \rho. \quad (25)$$

We then use the general form of the equation of state

$$d \ln \rho = \alpha d \ln P - \delta d \ln T, \quad (26)$$

with $\alpha = \left(\frac{\partial \ln \rho}{\partial \ln P}\right)_T$ and $\delta = -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_P$ to obtain the relation between the variations in temperature and density:

$$d \ln T = \frac{4\alpha - 3}{3\delta} d \ln \rho. \quad (27)$$

This relation between the changes in temperature and density during a slow contraction is sensitive to the equation of state of the stellar matter through the coefficients α and δ . For a perfect gas, $\alpha = \delta = 1$, and this relation simply gives

$$d \ln T = \frac{1}{3} d \ln \rho. \quad (28)$$

This means that during a slow contraction in nondegenerate conditions, the star evolves along a straight line with a slope of one-third in the diagram showing the variation of the central values of $\log T$ versus $\log \rho$. This situation approximately applies during the contraction of the star on a Kelvin-Helmholtz timescale before the ignition of hydrogen and also between the main nuclear burning phases when gravitational contraction provides the needed energy.

It is interesting to note that a slope of one-third in the $\log T_c$ versus $\log \rho_c$ diagram implies that the star can enter the domain of degenerate matter during its evolution. Indeed, the frontier between nondegenerate and degenerate conditions is defined by a straight line with a slope of two-thirds. This can be readily understood by recalling that for a completely degenerate non-relativistic gas, degenerate electronic pressure is related to density of $P < \rho^{5/3}$. Since $P < \rho T$ for a perfect gas, we then obtain $\rho T < \rho^{5/3}$ and hence $T < \rho^{2/3}$ when the perfect gas pressure of electrons equals the degenerate pressure. When a star approaches the domain of complete electron degeneracy, the values of the coefficients α and δ tend to 3/5 and 0, respectively. During this transition, α becomes therefore smaller than four-thirds before δ equals 0, so that the coefficient relating the density to the temperature variation in Eq. 27 above becomes negative. For a star entering the degenerate domain, a contraction does not produce an increase in the

temperature as in the nondegenerate case, but can instead result in a cooling of the stellar matter.

The effects of nuclear reactions are also completely different in degenerate conditions. Contrary to the nondegenerate case, an excess of energy production in the stellar center will not result in an expansion of the star when the matter is degenerate. In this case, an increase in temperature occurs in the center, but this increase does not produce a corresponding increase in the central pressure, which is solely determined by density in degenerate conditions. Consequently, nuclear reaction rates increase further and produce more and more energy, leading to a flash or an explosion. While nuclear reactions are stable in nondegenerate conditions, they are thus found to be unstable in degenerate conditions.

Applications

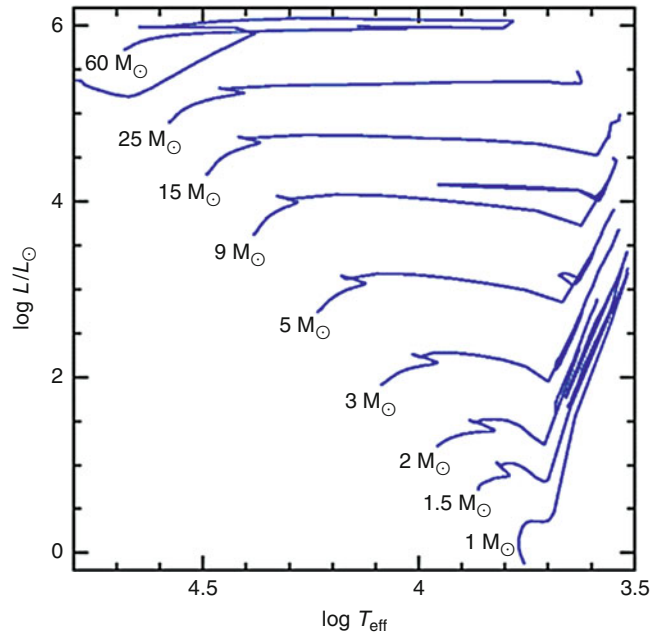
By numerically solving the equations of stellar structure derived above, the evolution of the internal and global properties of stars is obtained. This evolution can be quite different depending on the initial mass and chemical composition of the star. The evolutionary tracks in the theoretical Hertzsprung-Russell (HR) diagram showing the variation of the luminosity of the star as a function of its temperature is given in Fig. 1 for stars with a solar chemical composition. Different evolutionary scenarios can be distinguished according to the initial stellar mass.

Substellar Objects

Objects with initial masses below about $0.08 M_\odot$ never reach the central temperature required for hydrogen-burning ignition. These objects enter the degenerate regime during their contraction phase, leading to further contraction and cooling of the central layers as explained above. They are the progenitors of brown dwarfs. Note that for masses larger than about $0.012 M_\odot$, deuterium burning occurs. This nuclear energy release is, however, not sufficient to compensate for the radiative energy losses, so that these objects continue to cool down.

Stellar Evolution,

Fig. 1 Evolutionary tracks in the HR diagram for stars with a solar chemical composition and mass between 1 solar mass and 60 times the solar mass



Stars in a Mass Range of $0.08\text{--}0.5\ M_{\odot}$

Stars with initial masses between about 0.08 and $0.5\ M_{\odot}$ enter the phase of hydrogen burning. During this main-sequence phase, the energy production is due to the release of nuclear binding energy by transforming four hydrogen nuclei into one helium nucleus. As briefly mentioned when estimating the typical timescale of nuclear energy production, this corresponds to a mass defect of about 0.7% , which is approximately ten times the energy that may be liberated by other fusion processes. This fusion can take place through two main series of reactions: the proton-proton chain (pp chain) and the **CNO cycle**. The pp chain is named after its first reaction, which requires two protons to form a deuterium nucleus ${}^2\text{H}$. The deuterium then reacts with another proton to form ${}^3\text{He}$. The formation of ${}^4\text{He}$ can be achieved through three different branches: pp1, pp2, and pp3. For the pp1 chain, two ${}^3\text{He}$ nuclei are needed to obtain ${}^4\text{He}$, while the other chains require that ${}^4\text{He}$ already exists. The relative frequency of the pp branches is sensitive to the temperature, density, and chemical composition of the stellar layers. Having larger temperature sensitivity than the pp1 chain, the pp2 and pp3 chains will then dominate when the temperature increases.

The CNO cycle is the second main series of reactions for hydrogen burning. In this case, isotopes of C, N, and O are needed to obtain ${}^4\text{He}$. The temperature sensitivity of the CNO cycle is much higher than for the pp chain. Consequently, the pp chain will dominate over the CNO cycle at low temperatures (for temperatures typically lower than about $15 \times 10^6\ \text{K}$), while it becomes negligible compared to the CNO cycle for higher temperatures. Thus, hydrogen burning will mainly occur through pp. chains for lower-mass stars (typically for stars with masses lower than about $1.5\ M_{\odot}$) and CNO cycle for more massive stars.

After hydrogen exhaustion, the helium core becomes electron degenerate before reaching a temperature sufficient for helium ignition. Consequently, these stars only go through the hydrogen-burning phase and end up as helium white dwarfs. The duration of the hydrogen-burning phase is much larger than the age of the Universe for these stars, which are still burning hydrogen in their core. The observed helium white dwarfs are thus thought to come from more massive progenitors whose evolution has been radically changed by belonging to close binary systems.

Stars with an Initial Mass Between About 0.5 and $2.3 M_{\odot}$

These stars enter both the hydrogen and the helium burning phases. During the main sequence, these stars exhibit small convective cores or no convective core (for masses smaller than about $1.2 M_{\odot}$). After central hydrogen exhaustion, there will be a transition from central hydrogen burning to hydrogen fusion in a shell surrounding the core, resulting in a slow increasing of the mass of the helium core. At this point, the temperature of the core is still far from being high enough for helium ignition: the star is in a phase of hydrogen shell burning. Together with the core contraction, there is an expansion of the hydrogen-rich envelope resulting in a shift in the HR diagram toward lower surface temperatures. The star then begins to ascend the [red giant](#) branch. The densities in the central layers are high enough for the electron gas to become degenerate. At the tip of the red giant branch, helium ignites in degenerate conditions, leading to a strong temperature rise within a very short time interval (of the order of the dynamic timescale) that is called the helium flash. This temperature rise stops when the temperature is high enough to lift the degeneracy of the electron gas. The helium flash removes therefore the degeneracy in the stellar core and enables the helium-burning phase to continue in nondegenerate conditions.

Helium burning requires temperatures higher than about 10^8 K. The fundamental reaction at the basis of the formation of ^{12}C from three ^4He nuclei is the triple alpha reaction. Note that the star is not totally disrupted by the helium flash, since the massive shell surrounding the helium zone is able to damp the explosive shock wave produced in the internal layers. After the helium flash, the star finds a new equilibrium configuration either on the horizontal branch in the HR diagram (at low metallicity) or on the so-called red clump (at solar and higher metallicity) where core helium burning takes place. After the helium-burning phase, the star evolves along the asymptotic giant branch (AGB) until the outer envelope is removed by wind and thermal pulses, and a planetary nebula forms around the white dwarf.

Stars with an Initial Mass Between About 2.3 and $10 M_{\odot}$

The beginning of the evolution of stars with an initial mass in the mass range of $2.3\text{--}10 M_{\odot}$ is similar to the evolution of lower-mass stars undergoing a helium flash. Their evolution differs after the exhaustion of hydrogen in the central stellar core. This difference is mainly due to the fact that hydrogen burning for these more massive stars occurs in well-mixed convective cores leading to a helium core with a nonnegligible mass at the end of the main sequence. Due to the absence of a central energy source, the helium core tends to become isothermal, while hydrogen shell burning occurs at the bottom of the surrounding hydrogen-rich envelope. The star then rapidly crosses the HR diagram to become a red giant. The contraction of the core proceeds approximately on a Kelvin-Helmholtz timescale, and goes with an expansion of the hydrogen-rich envelope. The core contraction occurs in nondegenerate conditions resulting in the heating of the central layers. The central temperature rises until it reaches the temperature required to ignite helium (about 10^8 K). This results in a new source of central energy that stops the rapid contraction of the core: the star is then again in a phase of complete equilibrium, which terminates when ^4He is entirely transformed into ^{12}C , ^{16}O , and ^{20}Ne . Stars with initial masses below about $8 M_{\odot}$ evolve along the asymptotic giant branch and experience a prolonged phase of thermal pulses leading to the ejection of the envelope and the formation of a carbon-oxygen white dwarf, as in the case of the lower mass stars experiencing the helium flash.

For stars with initial masses between approximately 8 and $10 M_{\odot}$, the situation is more complex. Indeed, the evolution depends on the competition between the changes of temperature and densities in the central layers, which can reach values required for carbon ignition, and the efficiency of mass loss at the stellar surface, which can remove the envelope. This evolution will then depend on three key mass limits: the maximum initial mass that leads to the formation of a white dwarf, the maximum initial mass that leads to a collapse by electron capture, and the minimum

initial mass that leads to a non-explosive carbon ignition in the core. From a theoretical point of view, the main difficulty relies on the fact that these mass limits are close to each other and are sensitive to many physical ingredients adopted in the models, as the mass loss rates, or the modeling of convection. A plausible scenario is that the mass limit that leads to a non-explosive carbon ignition in the core is lower than the mass limit that leads to a white dwarf that is itself lower than the mass limit leading to a collapse by electron capture. In this case, an oxygen-neon white dwarf would be obtained for stars with initial masses between about 8 and 9 $M_{\odot}$, electron capture supernovae would occur for stars between about 9 and 10 $M_{\odot}$, and core collapse supernovae will occur for more massive stars.

Massive Stars

Massive stars can be simply defined as stars that go through all nuclear burning phases: hydrogen, helium, carbon, neon, oxygen, and silicon burning. The minimum initial mass for a star to proceed through this whole sequence of nuclear phases is approximately of 10 $M_{\odot}$. This series of nuclear burning phases comes to an end with the formation of an iron core since no further exothermic fusions are then possible. The evolution of the central layers of these stars can be simply viewed as following succeeding cycles of nuclear burning, exhaustion of nuclear fuel, core contraction, and heating enabling the ignition of the next burning phase. As a result of these succeeding evolution cycles, heavier elements gradually accumulate near the center of the star. This leads to the characteristic “onion-skin structure” of the interior of evolved massive stars, where heavier elements are present on separated mass shells as the distance to the stellar center decreases.

Mass loss plays a major role in the evolution of massive stars. Indeed, these stars are characterized by a high temperature-to-density ratio resulting in a high radiation-to-gas pressure ratio, which favors mass loss by ► [stellar winds](#). Wolf-Rayet stars nicely illustrate the effects of mass loss on massive stars. These stars exhibit high mass loss rates and strong emission lines with highly nonsolar chemical abundances. The abundance of anomalies

observed on the surface of Wolf-Rayet stars clearly indicates that a mechanism is able to efficiently remove the surface layers of the star. This can either be done through stellar wind losses in single stars, or through Roche lobe overflow in binary systems.

Massive stars end their lives in supernovae explosions, enriching the interstellar medium with processed material and leaving a neutron star or a black hole as a remnant, depending on the mass of their iron core. When the mass of the core exceeds the so-called Oppenheimer-Volkoff mass (around 2 $M_{\odot}$), a black hole is formed. Otherwise, the pressure of degenerate neutrons is able to stop the collapse and lead to the formation of a neutron star.

Future Directions

The classical view of stellar evolution described above is based on many simplifying hypotheses: stars are considered as spherical systems in hydrostatic and radiative equilibrium, where mixing only occurs in convective zones. In particular, the effects of rotation and magnetic fields are neglected. This classical theoretical description correctly accounts for many astronomical observations. However, with the increasing amount of observational data, quantitative discrepancies appear between observations and theoretical predictions of standard models. For instance, standard stellar models are unable to reproduce neither the observed abundance anomalies of helium and nitrogen at the surface of massive stars nor the observations of light element abundances at the surface of solar-type stars. This suggests that other transport mechanisms take place in stellar radiative zones. Rotation is one of the key physical processes that have a deep influence on all aspects of stellar structure and evolution. The effects of magnetic fields on the internal stellar structure need also to be taken into account to obtain a coherent picture of stellar evolution. Consequently, various theoretical models of these physical processes have been developed and compared to observational data in order to make progress in our understanding of stellar physics. These comparisons are, however, somewhat limited by the

fact that classical astronomical observations only give us access to properties of the surface of the star, such as the effective temperature, luminosity, and surface chemical composition. Indeed, the opacity of a star is so large that only a tiny layer surrounding the star, the photosphere, can be observed. This is insufficient to compare and constrain a whole theoretical structure of the stellar interior, where complex physical processes are taking place. Obtaining direct observational constraints on the internal properties of stars is thus required. In this context, the rapidly developing field of ► [asteroseismology](#) offers a valuable opportunity to make significant progress in our understanding of stellar structure and evolution.

We finally note that the evolution of binary stars can be quite different from the classical single-star evolutionary scenarios briefly described above. All physical processes discussed here for single stars also apply to binary stars but with a higher degree of complexity due to possible mass transfers, tidal interaction and mixing, tidal generation of gravity waves, etc.

Cross-References

- [Asteroseismology](#)
- [Binary Stars, Young](#)
- [CNO Cycle](#)
- [Chronological History of Life on Earth](#)
- [Hertzsprung-Russell Diagram](#)
- [High-Mass Star](#)
- [Low Mass Star](#)
- [Nucleosynthesis, Stellar](#)
- [P-P Chains](#)
- [Red Giant](#)
- [Star Formation, Observations](#)
- [Stars](#)
- [Stellar Populations](#)
- [Stellar Rotation](#)
- [Stellar Winds](#)

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Stellar Oscillation

- [Stellar Pulsation](#)

Stellar Populations

Leticia Carigi
Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, Mexico

Keywords

Galaxies · Initial mass function · Metallicity · Stars · Stellar evolution

Acronyms

Pop Population

Definition

Astronomers use the terms Populations I, II, and III to refer to groups of stars whose mass fraction

of elements heavier than helium is similar to the Sun (Population I), much less than the Sun (Population II), or negligible (Population III, not yet observed but hypothesized to be the earliest generation of stars). In general, stars with greater abundances of heavier elements are younger than those with lower abundances.

Overview

One of the more common classifications of stellar populations is based on age and metallicity, where metallicity is the proportion of the stellar mass made up of chemical elements other than hydrogen and helium. In that classification, the stars are divided into Populations I, II, or III. The stellar populations show a continuum of properties, and it is difficult to place some stars in a given population.

Population III stars are hypothesized to be the first ones formed in the Universe when the composing gas was only H and He. Since no stars of zero metallicity have been observed yet, the vast majority of these stars would have had high masses, in other words, they followed a different initial mass function compared to the present one.

When the most massive of those stars exploded as supernovae, they ejected heavy chemical elements into the interstellar medium where subsequently the very metal-poor Population II stars formed. By combining data from different ongoing and future surveys, it will shed light on the very metal-poor stars, and consequently about Population III.

Population II stars are mainly located in the halo of the Milky Way, in most globular clusters and dwarf galaxies with no gas. These stars are older than about 10 Gyr and have metallicities between 0.001% and 10% of the solar value.

Population I stars are located on the disk; these stars are the youngest of the galaxy and show metallicities between about one-tenth and three times the solar value. All observed stars with planetary systems, including the Sun, are Population I stars, and the stars with metallicities

higher than the solar one show a trend to harbor giant planets.

There are some stars that do not follow these rules: (1) elliptical galaxies, bulges, and the inner disk of spiral galaxies show metal-rich stars that are older than 10 Gyr; and (2) dwarf irregular galaxies and the outer disk of spiral galaxies show metal-poor stars that are younger than 1 Gyr.

Another common classification of stellar populations is based on the photometric properties: stellar groups dominated by blue stars are called early-type populations, and those dominated by red stars are called late-type populations. Yet another concept of stellar population is commonly used in the evolution of stellar groups, like a galaxy or a galactic component, is the Simple Stellar Population (SSP). In an SSP, all stars have the same age and the same metallicity; in addition, they are born in the same region of space. Since a galaxy is formed by diverse types of stars, a galaxy can be studied as a combination of SSPs of different ages, metallicities, and masses. Therefore, the SSPs allow observational astronomers to infer the age, the metallicity, and the mass of the stars that shine in a galaxy.

Cross-References

- ▶ [Exoplanets, Discovery](#)
- ▶ [Globular Cluster](#)
- ▶ [Initial Mass Function](#)
- ▶ [Metallicity](#)
- ▶ [Milky Way](#)
- ▶ [Stars](#)
- ▶ [Stellar Evolution](#)
- ▶ [Supernova](#)

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Stellar Pulsation

Patrick Eggenberger
Geneva Observatory, University of Geneva,
Geneva, Switzerland

Synonyms

[Stellar oscillation](#)

Definition

Stellar pulsations or oscillations are periodic variations of the size, brightness, and temperature of the star induced by some internal physical processes. These pulsations can be either radial, with symmetric expansions and contractions over the whole stellar surface, or non-radial when the spherical symmetry of the star is not preserved. Stellar pulsations provide us with a valuable opportunity to study the internal properties of stars that are not accessible otherwise and to obtain a cosmic distance scale by calibrating the luminosity of stars with their pulsation periods.

Cross-References

► [Asteroseismology](#)

Stellar Rotation

Sylvia Ekström
Département d'astronomie de l'Université de
Genève, Faculté des Sciences, Versoix,
Switzerland

Keywords

Stellar evolution · Mixing · Nucleosynthesis ·
Supernova · Spectral type · Absorption lines

Definition

The fact that a star rotates induces changes in its evolution. The centrifugal force brings an additional component which adds to pressure in sustaining the star against its own gravity. Rotation induces instabilities which in turn induce mixing. The mixing leads to larger cores and longer life-time and also modifies the nucleosynthesis. For the most massive stars, fast rotation can modify the dynamics of the final supernova, breaking the spherical symmetry during the collapse. From an observational point of view, rotation modifies the spectral type and luminosity class inferred for the star. It also widens the absorption lines, because of the differing Doppler velocity of the approaching versus the receding side of the star.

Overview

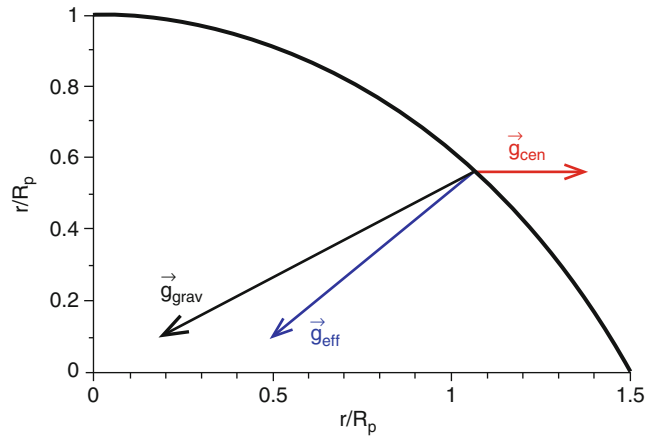
Roughly summarized, a star is a sphere of ionized gas held in hydrostatic equilibrium by the competition between gravitation and pressure. Any additional force will modify the equilibrium and thus the characteristics of the object. Rotation brings such an additional force.

During star formation, a molecular cloud with a typical radius of 0.1 pc contracts to form a newborn star with a reduction of radius through six orders of magnitude. Angular momentum conservation implies that the slightest rotation movement in the cloud will convert into fast stellar spin. It is not yet clear how the excess angular momentum is driven away so that the star can actually form, probably through magnetic interactions between the star and the protoplanetary disk or through the formation of binary stars, where angular momentum is transformed into orbital motion.

If the angular momentum kept by the young star is high enough, the centrifugal force that it experiences becomes nonnegligible and adds a sustaining force against gravity (see Fig. 1). At the very beginning of its evolution, the star behaves as if its mass were smaller: the luminosity and effective temperature are shifted to lower values. As the evolution proceeds, rotation

Stellar Rotation,

Fig. 1 Maximal surface deformation of a rotating star. (Courtesy C. Georgy). The x and y axis are the radius, normalized to the polar one. The gravitational force is in black, the centrifugal force in red, and the resulting effective gravity in blue



triggers various instabilities inside the star, among which:

- The *shear instability*: As the star does not rotate like a rigid body, the differential rotation induces a shear between layers with different angular velocities. The shear drives a turbulent mixing of the chemical species through the different layers.
- The *Eddington-Sweet circulation*: Rotation deforms the star (Fig. 2), so except at the equator, the centrifugal force is not parallel to gravity – the resultant effective gravity is not radial, as shown in Fig. 1. The radiative flux, which depends on the local effective gravity, is not constant on equipotential surfaces. According to von Zeipel (1924), the star cannot be in hydrostatic and radiative equilibrium at the same time. This drives a large-scale current, also known as the *meridional circulation*, which mainly transports the angular momentum inside the star.

The main observable characteristics of the star (effective temperature, gravity, luminous flux) become colatitude-dependent, feature which can now be observed by interferometric techniques (Domiciano de Souza et al. 2003).

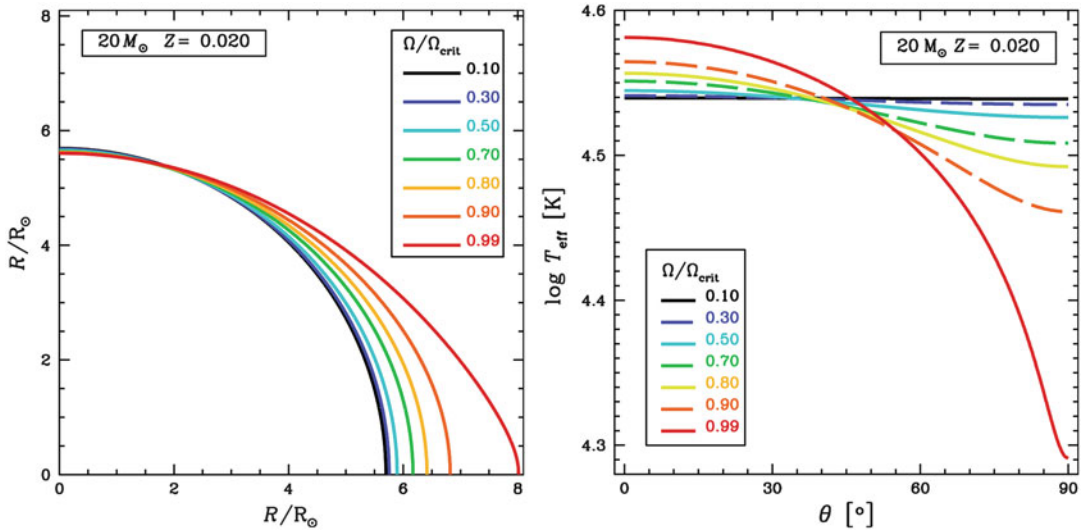
The shear mixing brings fresh hydrogen into the burning core which grows, enhancing the luminosity of the star. Since more fuel is available, the duration of the main sequence is increased.

Rotation enhances the mass loss by radiative winds through three mechanisms:

- The stronger effective gravity at the poles induces a stronger flux in that direction.
- The lower effective temperature at the equator increases the opacity and thus the atomic line-driven winds.
- Later during core He burning, rotational mixing brings freshly synthesized heavy elements to the surface, increasing the effective metallicity of the star.

Generally, rotation favors a redward evolution in the HR diagram. Its inclusion in stellar evolution codes has improved the match between models and observations in many aspects, as the evolution of the surface abundances during the main sequence (Heger and Langer 2000; Maeder and Meynet 2000), the variation with metallicity of the red-to-blue supergiant ratio (Maeder and Meynet 2001), and the Wolf-Rayet to O-type stars ratio (Meynet and Maeder 2003; Vink and de Koter 2005).

Shear mixing induces a transport of elements between the burning core and the burning shells, modifying the nucleosynthesis. For example, the transformation of carbon produced in the He-burning core into nitrogen in the H-burning shell is supposed to be the origin of the primary nitrogen observed at very low metallicity (Meynet and Maeder 2002).



Stellar Rotation, Fig. 2 *Right* – deformation of the surface of $20 M_{\text{sol}}$ rotating stellar models. The curves show increasing (from black to red) ratios of the angular velocity to the critical one, which is the angular velocity at which the outer layers of the star are no more gravitationally bound. At critical velocity, the equatorial radius is 1.5

times the polar one. *Left* – effective temperature as a function of the colatitude (pole, $\theta = 0^{\circ}$; equator, $\theta = 90^{\circ}$) for the same models. Fast rotation leads to hotter poles and cooler equator, the difference amounting to a factor of 2 at critical rotation. (From Ekström et al. (2008))

Asteroseismic observations of the internal rotation of red giants and subgiants (Beck et al. 2012; Deheuvels et al. 2014) have shown that the differential rotation between the core and the envelope is less pronounced than expected by models during this phase of rapid core contraction and envelope expansion. This points to an additional angular momentum transport mechanism being needed in models (Eggenberger et al. 2012). The source of this mechanism is not yet identified.

By modifying the geometry of the explosion, rotation influences strongly the supernova dynamics. It is thought that the collapse of a rapidly rotating massive star is at the origin of the long-duration Gamma-ray bursts (Woosley 1993; Woosley and Bloom 2006).

Cross-References

- Diffusion
- Hertzsprung-Russell diagram
- Stellar Evolution

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Stellar Seismology

► [Asteroseismology](#)

Stellar Winds

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Young star · High mass star

Definition

The tenuous outer layers of stars can be driven off into space, creating the flows known as stellar winds. In main-sequence stars like the Sun, the winds are driven by thermal pressure in the hot stellar corona. The wind, being guided by the star's magnetic field, is anisotropic. More massive stars and red giants propel gas by radiation pressure. Young stars have especially vigorous winds that are responsible for dissipating ambient cloud gas and circumstellar disks, thus ending planet formation. Here, gas is believed

to be flung out centrifugally along magnetic field lines embedded in the star and its surrounding disk.

Overview

Stars of all masses and all evolutionary phases slough off their outermost layers of gas. The resulting, low-density flow is known as a stellar wind. The most familiar example is the solar wind, which has been extensively studied by satellites and other spacecraft for half a century. Ionized gas from the Sun flows past the Earth at an average speed of 500 km/s. Some ions become trapped in the Earth's magnetic field, creating the auroral glow seen near both the north and south poles.

The solar wind is driven by the pressure of very hot gas of several million degrees at the base of the Sun's corona. Other main-sequence stars with the Sun's mass and below are thought to generate similar winds. The most massive winds from main-sequence objects are produced by O stars, which also have the highest luminosity. These winds are driven by the radiation pressure from ultraviolet photons acting on ionized gas in the stellar atmosphere. The gas piles up periodically and creates internal shocks, which are detected by the X-rays they emit.

Aging stars that have left the main sequence also attain large luminosities and emit relatively massive winds. Here, the driving force is radiation pressure from infrared photons. The pressure is exerted not on the gas itself, but on dust grains that condense in the flow. Indeed, dust grains throughout interstellar space ultimately arise from nucleation within the winds of red giants.

Young stars, even those of low mass, produce vigorous stellar winds. The winds from classical ► [T Tauri stars](#) are seen by characteristic P Cygni line profiles in the stellar atmosphere and by spatially extended jets. These stars have strong magnetic fields and also rotate relatively fast. Accordingly, the winds are driven by material being flung out along magnetic field lines. The field is anchored in the stellar surface and the innermost region of its circumstellar disk. Similar

winds of even greater strength must arise from embedded protostars.

Whatever their origin, the winds from young stars play a fundamental role in star and planet evolution. Those emitted by protostars dissipate the surrounding molecular clouds, thus ending the accretion of gas and revealing the star optically. Winds from ► [pre-main-sequence stars](#) are responsible for driving off their circumstellar disks, terminating the process of planet formation.

Cross-References

- [Bipolar Flow](#)
- [High-Mass Star](#)
- [Pre-Main-Sequence Star](#)
- [Skumanich Law](#)
- [T Tauri Star](#)

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Stellar Yield

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The mass of nuclides ejected by a star into the interstellar medium, at the end of or during its life (through the final explosion or its wind, respectively) may be called the stellar yield. For instance, a star of $\sim 20 M_{\odot}$ ejects $\sim 1 M_{\odot}$ of oxygen. In general, lighter elements are produced during the hydrostatic evolution of the star, while heavier elements are produced by the final explosive nucleosynthesis. The *net* stellar yield is the

difference between that quantity and the amount of the nuclide incorporated in the star at its formation (i.e., the amount of newly synthesized nuclei) and contributes to the chemical evolution of the galaxy. Stellar yields depend on the mass of the star but also on its initial ► [metallicity](#), mass loss, rotation, etc. They are theoretically calculated but rarely validated by observations (the only case being supernova SN1987A, a 18–20 $M_{\odot}$ star, which produced 0.07 $M_{\odot}$ of ^{56}Fe , as inferred from the evolution of its luminosity).

Cross-References

- [Metallicity](#)
- [Stars](#)
- [Stellar Winds](#)
- [Supernova](#)

Steranes, Rock Record

Ross H. Williams
CRESST II/UMCP, Center for Research and Exploration in Space Sciences and Technology/
University of Maryland, College Park, MD, USA
Solar System Exploration Division, NASA
Goddard Space Flight Center, Greenbelt, MD, USA

Keywords

Biomarkers · Biosignatures · Eukaryotes ·
Hydrocarbons · Molecular fossils

Synonyms

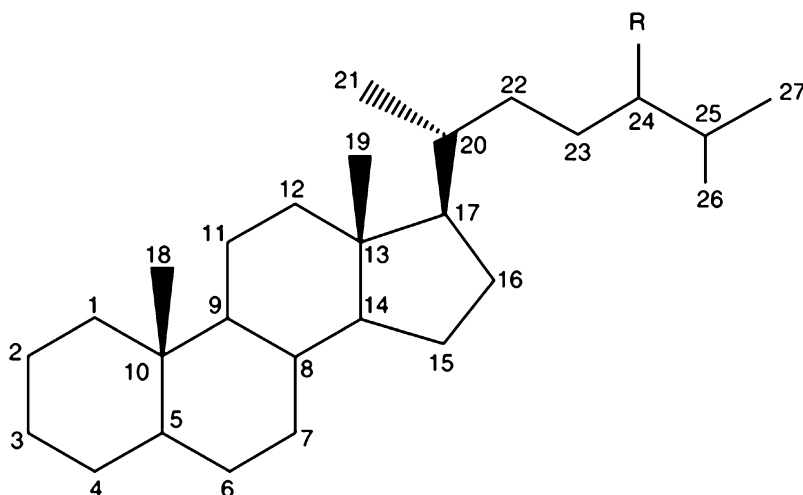
[Steroids](#)

Definition

Steranes is a class of four-ringed cyclic compounds derived from steroids or sterols via diagenetic degradation and thermal maturation. The sterane structure is fully saturated with hydrogen atoms (Fig. 1) and makes up the hydrocarbon core of all steroids

Steranes, Rock Record,

Fig. 1 Core structure of steranes composed of C–C bonds (lines) and saturated with hydrogen atoms (not shown). The key stereochemical variants occur at C-5, C-14, C-17, and C-20 positions. Additional methylation is common at C-2, C-3, C-24, and C-23. R = H, methyl, ethyl, *n*-propyl, and isopropyl groups



and sterols. Steranes are often regarded as molecular fossils of eukaryotic organisms, particularly those having a side chain at the C-24 position.

Overview

The precursor compounds of steranes, steroids and sterols, are essential lipids for maintaining rigidity and permeability of membranes in all eukaryotes. Steroids are isoprenoids and synthesized from squalene in complex biosynthesis in which multiple steps require reactions with molecular oxygen.

Most variations in steroid structures (i.e., position and number of double bonds, hydroxyl groups, and other functional groups) are lost during the diagenesis and thermal maturation. However, structural variants with alkyl side chains are preserved over geological time-scale in bitumen and oils and as constituents in kerogen of Cenozoic to Archean rocks. Although most sterol structures are widespread among eukaryotes, some alkylated structures are specific to particular taxonomic groups (e.g., sponges and algal groups) and may be distinguishable in the molecular fossil record as different steranes. Oftentimes, individual steranes may be produced by members outside of the proposed taxonomic group and so further investigation of compound abundance or ratio to related compounds must be undertaken prior to source inference.

Steranes and their precursors exist as three-dimensional structures. Despite the 100s of possible stereochemical variations in the structures, steroid biomolecules are very specific (especially at C-5, C-14, C-17, and C-20 positions). Steroid and sterol stereochemistry is regarded as a classic example of stereochemical specificity of biomolecules in general – a fundamental biosignature of life. During diagenesis and thermal maturation, the specific biomolecular stereochemistry is lost and other isomers are formed. The relative abundances of some sterane isomers are commonly used to indicate particular geological or thermal conditions.

Most molecular fossils including steranes are thermally released from kerogen in ancient rocks, either naturally to form bitumen and oil or artificially in the laboratory. Sterane precursors are typically bound to the kerogen matrix through weaker C–O and C–S bonds resulting in their early release during thermal alteration. The sterane composition of bitumen and oils is typically determined by extracting hydrocarbons from rock or directly from oil using a nonpolar organic solvent (such as hexanes) and then analyzed via gas chromatography mass spectrometry instrumentation.

Cross-References

- [Bitumen](#)
- [Eukarya](#)

- [Eukaryotes, Appearance and Early Evolution of](#)
- [Hydrocarbons](#)
- [Isoprenoids](#)
- [Kerogen](#)
- [Membrane](#)
- [Molecular Fossils](#)

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Stereochemistry

Gilles Bruylants
Engineering of Molecular NanoSystems,
Université Libre de Bruxelles, Brussels, Belgium

Definition

Stereochemistry refers to the relative spatial arrangement of atoms within molecules. Also

known as 3D chemistry, it spans the entire range of organic, inorganic, biological, physical, and supramolecular chemistries. Stereochemistry focuses on ► [stereoisomers](#), molecules that have the same chemical formula and in which the atoms have the same connectivity but different spatial distributions. If two stereoisomers are mirror images of each other, they are called ► [enantiomers](#). If they are non-mirror images of each other, they are diastereoisomers.

Cross-References

- [Achiral](#)
- [Chirality](#)
- [Enantiomeric Excess](#)
- [Enantiomers](#)
- [Isomer](#)
- [Racemic Mixture](#)
- [Stereoisomers](#)

Stereoisomers

Robert Hazen
Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA

Keywords

Chiral pairs of molecules · Enantiomeric pairs of molecules · Mirror symmetric pairs of molecules

Synonyms

[Stereoisomers](#)

Definition

Stereoisomers are molecular ► [isomers](#), in which two or more molecules have identical molecular formulas and atomic connectivities, but in which the atoms are arranged differently in space. Stereoisomers thus contrast with constitutional

isomers, which have identical molecular formulas but differing atomic connectivities.

Stereoisomers are divided into two important groups. Conformational isomers are interchangeable by a rotation around a single bond. By contrast, configurational isomers are not readily transformable from one to the other; bonds must be broken to achieve such a transformation.

Configurational isomers are further subdivided into enantiomers (mirror image pairs of molecules) and diastereomers (which are not related by mirror symmetry). ► [Enantiomers](#), unlike diastereomers, display many identical properties, including density, vapor pressure, melting and boiling points, and other thermochemical properties.

Cross-References

- [Enantiomeric Excess](#)
- [Enantiomers](#)
- [Isomer](#)

Stereoomers

- [Stereoisomers](#)

Steric Effect

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, a steric effect is an influence on a reaction's course or rate determined by the fact that all of the atoms within a molecule occupy space; thus, certain collision paths are either

disfavored or favored. When atoms are brought close together, there is an associated cost in energy due to overlapping electron clouds, and this may affect the molecule's preferred conformation and reactivity. Steric effects are frequently contrasted with electronic effects in explaining chemical reactivity. Steric effects can play a significant role in ► [molecular recognition](#).

Cross-References

- [Molecular Recognition](#)

Sterile

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

[A sterile spacecraft hardware element or environment is one that has statistically less than one viable microorganism present, as detected by a specific assay or following application of a certified sterilization process.]

Cross-References

- [Assay](#)
- [Microorganism](#)
- [Sterilization](#)

Sterility Assurance Level

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

[The sterility assurance level describes the probability that an object could be nonsterile after it has

been subjected to a sterilization process, thus a sterility assurance level of 1×10^{-6} describes an object with a one-in-a-million chance of not being sterile.]

Cross-References

► [Sterilization](#)

Sterilization

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

For ► [planetary protection](#), sterilization is the application of a process that reduces the ► [bioburden](#) on spaceflight hardware until the hardware is free, or nearly free (consistent with the desired specification), of viable ► [microorganisms](#).

Cross-References

► [Bioburden](#)
► [Bioburden Reduction](#)
► [Disinfection](#)
► [Inactivation](#)
► [Microorganism](#)
► [Pasteurization](#)
► [Planetary Protection](#)

Steroids

► [Steranes, Rock Record](#)

Sticking Coefficient

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Definition

The probability that an incident atom or molecule will stick to a solid surface, as of an ► [interstellar dust](#) grain, is called the sticking coefficient.

Cross-References

► [Interstellar Dust](#)

Stink Damp

► [Hydrogen Sulfide](#)

Stirling Range Biota

Stefan Bengtson
Department of Palaeozoology, The Swedish
Museum of Natural History, Stockholm, Sweden

Keywords

Eukaryotes · Multicellular · Paleoproterozoic ·
Trace fossils

Definition

The Stirling Range biota is a Paleoproterozoic biota found in the Stirling Range formation of southwestern Australia and composed of disk-shaped fossils and trace-making organisms about 1.8–2.0 Ga old. The biota lived in a near-shore

marine environment and is thought to have included motile multicellular eukaryotes.

Overview

The Stirling fossils were discovered in southwestern Australia in the 1990s and were interpreted to represent metazoans (animals) belonging to the Ediacaran biota, less than 600 Ma old (Cruse and Harris 1994; Cruse et al. 1993). Subsequent radiometric dating of the sandstones containing the fossils showed that the Stirling Range biota is considerably older than the Ediacaran, between 1.8 and 2.0 Ga old (Rasmussen et al. 2004).

The biota contains disk-shaped fossils of unknown affinities (Fig. 1) and paired ridges interpreted as traces of moving organisms



Stirling Range Biota, Fig. 1 Discoidal fossil of uncertain affinity. (From Bengtson et al. 2007)

(Fig. 2). The traces have a characteristic hairpin shape, with one end closed and the other end usually slightly flaring. The tracemaker has been reconstructed as a motile multicellular or syncytial/multinucleate eukaryotic organism of unknown affinity (Bengtson et al. 2007; Rasmussen et al. 2002). The organism probably had a bulbous resting shape but stretched out into a more elongate body form, 1–2 mm in width, when in motion. Moving along the sea floor, the organism left sediment-entrained mucus ridges behind on both sides. The occasional presence of ridge pairs with crossed-over ridges suggests that the ridges represented two sides of a coherent band and that the organism laid down a string of mucus as it was crawling, much like today's ribbon worms or garden snails.

Because of its considerable age, more than three times that of the earliest uncontroversial trace fossils - made by metazoans - in the rock record, the interpretation of the Stirling structures as traces of moving organisms has been questioned (Budd and Jensen 2003; Conway Morris 2002; Seilacher 2007). No tenable alternative interpretation has yet been offered; however, a recent discovery of giant amoebas making similar traces on modern sea floors off the Bahamas has confirmed that other organisms than metazoans are able to make such traces (Bengtson and Rasmussen 2009; Matz et al. 2008).

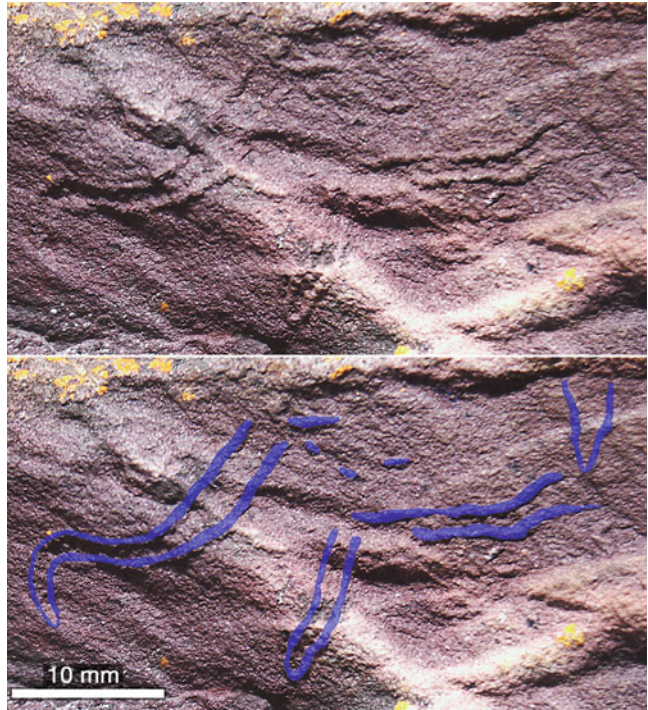
The Stirling Range biota, if correctly interpreted, represents early experiments into the energy-craving life mode of motile multicellular organisms. The question why it took more than a billion years before the multicellular life forms became an important component of the biosphere has yet to be convincingly answered but may be connected to the fluctuating oxygen levels of the ancient atmosphere.

Cross-References

- [Eukaryotes, Appearance and Early Evolution of](#)
- [Proterozoic Eon](#)
- [Stirling Range, Australia](#)

Stirling Range Biota,

Fig. 2 Hairpin-like structures interpreted as traces of motile, multicellular organisms. (From Bengtson et al. 2007)



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Stirling Range, Australia

Stefan Bengtson

Department of Palaeozoology, The Swedish Museum of Natural History, Stockholm, Sweden

Definition

The Stirling Range is a 60-km long range of hills in southwestern Australia, about 330 km SE of Perth. It is built up of a ca 1.6 km thick Paleoproterozoic sequence of siliciclastic sediments, the Stirling Range Formation. The sediments, mostly sandstones and shales, were deposited between

1.8 and 2 Ga ago along an ocean-facing shoreline influenced by storms, long-shore currents, and tidal currents. The rocks were subjected to low-grade metamorphism about 1.2 Ga ago. The Stirling Range Formation houses a fossil biota of disk-shaped and trace-making organisms, the ► [Stirling Range Biota](#).

Cross-References

► [Stirling Range Biota](#)

Stochasticity

► [Chance and Randomness](#)

Stone

André Brack and Frances Westall
Centre de Biophysique Moléculaire CNRS,
Orléans Cedex 2, France

Keywords

Artificial meteorites · Atmospheric entry ·
Biosignatures · Martian sedimentary rocks ·
Panspermia · Endolithic cyanobacteria

Synonyms

[Artificial meteorite](#)

Definition

STONE is a series of experiments to test the survivability of terrestrial sedimentary rocks, analogues of Martian sediments, embedded in the heat shields of Foton capsules during entry into the Earth's atmosphere at a velocity of 7.6 km/s (meteoritic entry speeds being higher at

12–15 km/s). At the same time, the ► [panspermia](#) hypothesis was tested with live endolithic microorganisms protected by 1–2 cm of rock thickness, as well as the survival of organic and morphological biosignatures encapsulated within the sediment. A dolomite, a siltstone, a volcanic sandstone, and a ► [basalt](#) control sample survived entry into the atmosphere, as did organic and morphological biosignatures away from the fusion crust. The ► [endolithic](#) microorganisms did not survive.

Overview

Of six STONE experiments, only three were successfully carried to completion. STONE-1 flown in 1999 tested a basalt (in flight control), a dolomite (sedimentary rock), and artificial Martian regolith. Only the dolomite sample survived, having lost 70% of its original thickness. Some kinetic isotopic fractionation accompanied the thermal degradation of the dolomite during reentry (Brack et al. [2002](#)). STONE-5, 2005, carried dolerite (an igneous rock), sandstone (a sedimentary rock), and gneissic impactite from Haughton Crater that were loaded with bacterial *Bacillus subtilis* spores, fungal *Ulocladium atrum* spores, and photosynthetic endolithic cyanobacteria *Chroococcidiopsis* sp. Despite intense ablation resulting in deeply eroded samples, all rocks in part survived atmospheric reentry. Temperatures attained during reentry were high enough to form fusion crusts on the exposed gneiss and dolerite surface, thus strengthening the link with real meteorites. None of the microorganisms survived, and it was concluded that atmospheric transit acts as a strong biogeographical filter to the interplanetary transfer of photosynthetic microorganisms (Brandstätter et al. [2008](#); Cockell et al. [2007](#)). STONE-6, 2007, tested a silicified volcanic sand, 3.446 ga old, containing cryptic traces of fossil life (Westall et al. [2006](#)), a Devonian mudstone containing organic biomarkers, and an Eocene basalt from Austria. The basalt was lost but the two sedimentary rocks survived, severely ablated. Mineralogical changes

indicated that entry temperatures exceeded $\sim 1800^\circ\text{C}$ that resulted in the fusion of both sediments. The 3.446-Ga-old microfossils survived furthest from the fusion crust while the organic carbon in the Devonian laminite sample was altered and thermally matured. Dried biofilms of *Chroococcidiopsis* pasted onto the underside of the rocks did not retain viability although the cells survived in a carbonized form (Foucher et al. 2010).

Although the speed of entry of these artificial meteorites was not as high as that of natural meteorites, 7.6 km/s as opposed to 12–15 km/s, it was close enough to produce fusion crusts on some of the sediments and to provide useful information relating to potential Martian sedimentary meteorites. Martian rocks having compositions typical of the terrestrial sediments tested could arrive on Earth as meteorites, providing they survive impact escape from Mars. Organic and morphological biosignatures in the Martian rocks could also survive. Heat flux calculations in the 3.446-Ga-old volcanic sand indicate that at least 5 cm rock thickness is necessary to protect extant organisms from heat shock.

Cross-References

- [ALH 84001](#)
- [Panspermia](#)

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Stopping Power

- [Linear Energy Transfer](#)

Stratigraphy

Felix M. Gradstein
University of Oslo, Oslo, Norway

Keywords

Correlation · Fossils · Geochronology · Geological strata · Sedimentary rocks

Definition

Stratigraphy is the scientific discipline dealing with the nature, relative order, and physical and paleontological content of the rock record on Earth. Stratigraphy (“description of strata”), like most geologic sciences, is essentially a natural philosophy rooted in a body of organized cumulative observations, governed by a series of accepted principles and rules, and has three main attributes: (1) The irreversible flow of time, often called the arrow of time; (2) superposition of successively younger strata, often referred to as Steno’s law, after the seventeenth century Danish scientist Nicholas Steno who first formulated this principle from observation in the hills of Italy;

(3) the evidence of events as fossilized in Earth's sedimentary record, and their spatial and temporal relations.

Overview

Correlation of the rock record plays a major role in stratigraphy. To the geologist such correlation often requires the hypothesis that correlated units have the same age. Without correlation, the rock record and its succession in time derived in a single area are unique, and contribute nothing to understanding the Earth history elsewhere. Stratigraphy has developed several main components or subdisciplines, each with their own scientific specialists (Rawson et al. 2002; Rey and Galeotti 2008): Lithostratigraphy, biostratigraphy, chronostratigraphy, magnetostratigraphy, cyclostratigraphy, organic and inorganic isotopic chemostratigraphy, and, in the subsurface, seismostratigraphy and well-log stratigraphy. Seismostratigraphy is a special type of lithostratigraphy using acoustic remote sensing and visualization; well-log stratigraphy uses specialized tools to record down-hole physical and chemical properties. All stratigraphies strive to assign (often unique) attributes to an individual rock unit that makes it distinguishable from lateral, underlying or overlying rock units, and thus assist with its correlation. When properly stacked, described, and correlated, the rock record in sedimentary basins, flat or hilly landscapes, and mountain ranges may thus reveal their history through geologic time.

Cross-References

- [Geochronology](#)
- [Geological Timescale](#)

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Stratosphere

Sébastien Lebonnois

Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, CNRS, Paris, France

Definition

In this region, as in the mesosphere (located above), the dominant mode of energy transfer is radiation, with a balance between the energy absorbed from the stellar irradiation by gaseous components and particles when present, and the energy reemitted by these components at infrared wavelengths. This balance in these regions is characterized by local thermodynamic equilibrium, which means that the energy distributions of the molecules are in equilibrium and follow the Boltzmann distribution.

The stratosphere starts above the tropopause and is characterized by an increase of temperature with altitude, a region that is not always present in the vertical structure of an atmosphere: no stratosphere are present in the atmospheres of Venus and Mars. This is due to a source of energy absorption. In the Earth atmosphere, heating is due to absorption of solar light by ozone molecules. For giant planets, it is due to methane, while in the atmosphere of Titan, the photochemical haze particles play a significant role in this heating. This positive temperature gradient is associated with a strong stability of the atmosphere, inhibiting vertical exchanges between atmospheric layers.

The upper boundary of the stratosphere is called the stratopause (at roughly 50 km altitude for the Earth).

Cross-References

- [Atmosphere, Structure](#)
- [Giant Planets](#)
- [Mesosphere](#)
- [Terrestrial Planet](#)
- [Troposphere](#)

Stratosphere Biology

David J. Smith¹ and Samantha M. Waters²

¹Space Biosciences Research Branch, NASA Ames Research Center, Moffett Field, CA, USA

²Universities Space Research Association, Space Biosciences Research Branch, NASA Ames Research Center, Moffett Field, CA, USA

Keywords

Microorganism · Aerobiology · Bioaerosol · Stratosphere · Aircraft · Balloon

Synonyms

Stratosphere microbiology; Upper atmosphere microbiology

Definition

Microbial biomass naturally transits through the Earth's ► [stratosphere](#) (roughly 12–50 km above the surface), a deadly environment sharing many conditions also present on the surface of ► [Mars](#), including cold temperatures, severe dryness, and strong solar radiation. To collect samples at extreme altitude and perform controlled exposure experiments in this ► [Mars](#) analogue site, investigators use mountaintop observatories, aircraft, and scientific balloons.

Overview

Earth's ► [stratosphere](#) is located approximately 12–50 km above the surface (depending on location and season) and is practically at the edge of space. At these extreme altitudes, atmospheric pressure is comparable to surface conditions on ► [Mars](#) (about 0.1–1 kPa), alongside ultralow temperatures (0–100 °C), intense ► [desiccation](#), and ► [extreme ultraviolet light](#) (~50 W·m²); the stratosphere is a compelling analogue for the Red Planet (Smith 2013; Smith and Sowa 2017).

Microbial ► [life](#) emanating from the Earth's surface (collectively known as *bioaerosols*) can reach stratospheric heights through strong convective forces such as thunderstorms, monsoons, and hurricanes (Griffin et al. 2017). Stratospheric intrusions also occur regularly alongside mountain ranges. Reaching the stratosphere is more probable for smaller bioaerosols (<1 µm), and particle size determines total residence time aloft. Although it is unknown how long ► [micro-organisms](#) can stay airborne in the Earth's stratosphere, non-biological ► [aerosols](#) (e.g., volcanic ash) can potentially remain drifting through the upper atmosphere for years before returning to the surface (Smith 2013).

Generally, the diversity of microbial taxa measured in the lower stratosphere matches proportional abundances found in surface and marine/freshwater environments; however, the concentration of biomass in the upper atmosphere is orders of magnitude lower (Smith et al. 2013). Since cold temperatures and severe dryness inhibit metabolic activities, microorganisms pass through the stratosphere in a state of dormancy. Yet, remarkably, viable microbes have been collected at stratospheric altitudes ranging from 12 to 41 km (Smith et al. 2009, 2018; Wainwright et al. 2003), with most surviving isolates captured as bacterial ► [endospores](#) specially adapted for dispersal and resistance to environmental insults. Exactly how some terrestrial microorganisms withstand the harsh stratosphere remains an open question in the field of ► [aerobiology](#), but shading from sunlight provided by co-transported dust or biomass debris is a leading explanation. While viable ► [fungi](#) also appear in stratosphere surveys (Smith et al. 2009, 2013), ► [bacteria](#) probably represent the most common form of stratospheric biomass due to smaller sizes. Modern microbiological expeditions in the stratosphere now rely upon molecular measurements, including fluorescent microscopy- and ► [DNA sequencing](#)-based detection assays (Bryan et al. 2014; Smith et al. 2018). These molecular approaches have revealed a surprising richness of microorganisms in the stratosphere, previously masked by limitations associated with culture-based methods

Stratosphere Biology,

Fig. 1 A stratosphere biology experiment, *Exposing Microorganisms in the Stratosphere* (*E-MIST*), flown to 31 km by Khodadad et al. (2017) onboard a large ▶ [NASA](#) scientific balloon



and biocidal atmospheric conditions that render most collected biomass dead, damaged, or destroyed.

Teams acquiring microbiological samples can use mountaintop observatories (Smith et al. 2013) and aircraft (Smith et al. 2009, 2018) for routine lower stratosphere access, as well as meteorological (Bryan et al. 2014) and large scientific balloons (Wainwright et al. 2003) for less frequent middle and upper stratosphere access. Considering the fundamentally low concentration of biomass in the stratosphere, regardless of sampling technique used, investigators must carefully monitor contamination control methods (Smith 2013; Griffin et al. 2017).

Along similar lines of research, ▶ [astrobiology](#) teams studying the probability of terrestrial ▶ [exposed surface bioburden](#) surviving on Mars have intentionally sent spacecraft-associated microorganisms to the Earth's stratosphere onboard balloons for exposure-based experiments relevant to the field of ▶ [planetary protection](#) (Fig. 1) (DasSarma and DasSarma 2018; Khodadad et al. 2017; Smith and Sowa 2017). Results from stratosphere exposure investigations demonstrate the vulnerability of endospore-forming bacteria to intense short wavelength ▶ [ultraviolet radiation](#) levels (100–280 nm) and can provide predictive measurements for terrestrial microbes inadvertently delivered to Mars with spacecraft missions.

Cross-References

- ▶ [Aerobiology](#)
- ▶ [Aerosols](#)
- ▶ [Astrobiology](#)
- ▶ [Bacteria](#)
- ▶ [Desiccation](#)
- ▶ [DNA Sequencing](#)
- ▶ [Endospore](#)
- ▶ [Exposed Surface Bioburden](#)
- ▶ [Extreme Ultraviolet Light](#)
- ▶ [Fungi](#)
- ▶ [Life](#)
- ▶ [Mars](#)
- ▶ [Mars Analogue Sites](#)
- ▶ [Microorganism](#)
- ▶ [NASA](#)
- ▶ [Planetary Protection](#)
- ▶ [Stratosphere](#)
- ▶ [Ultraviolet radiation](#)

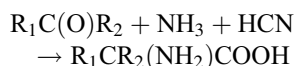
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Strecker found that the amino acid alanine had been synthesized. This represented the first successful demonstration of the synthesis of an amino acid in the laboratory.

The overall reaction sequence shown below is now generally referred to as the Strecker synthesis:



where in $\text{R}_1\text{C}(\text{O})\text{R}_2$, R_1 and R_2 may be either a proton (H) or various substituted or non-substituted alkyl chains. Thus, both aldehydes and ketones can be starting materials for the Strecker synthesis, and depending on the nature of the aldehyde or ketone, amino acid products with different R_1 and R_2 substitutions can be generated.

This is generally accepted to be one of the principle mechanisms by which amino acids are synthesized in prebiotic simulations such as Miller-Urey synthesis and is likely one of the pathways for amino acid formation in ► [carbonaceous chondrites](#).

Stratosphere Microbiology

- [Stratosphere Biology](#)

Stratospheric Ozone

- [Ozone Layer](#)

Strecker Synthesis

Jeffrey Bada
Scripps Institution of Oceanography, La Jolla,
CA, USA

Definition

The Strecker synthesis is a chemical reaction inadvertently discovered in 1850 by Adolph Strecker (Strecker 1850) during an attempt to synthesize lactic acid from a mixture of acetaldehyde, HCN, and ammonia. Instead of lactic acid, however,

Cross-References

- [Amino Acid](#)
- [Miller, Stanley](#)

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Strelley Pool Formation

Kenichiro Sugitani
Graduate School of Environmental Studies,
Nagoya University, Nagoya, Japan

Keywords

Stromatolite · Microfossil · Hydrothermal · Archean · East Pilbara Terrane · Pilbara Craton

Chemical Formula

$$\delta^{13}\text{C} = \left\{ \left(\frac{{}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}}{{}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}} \right) \times 1000 (\text{‰}) \right\}$$

$$\delta^{34}\text{S} = \left\{ \left(\frac{{}^{34}\text{S}/{}^{32}\text{S}_{\text{sample}} - {}^{34}\text{S}/{}^{32}\text{S}_{\text{standard}}}{{}^{34}\text{S}/{}^{32}\text{S}_{\text{standard}}} \right) \times 1000 (\text{‰}) \right\}$$

Definition

The Strelley Pool Formation (SPF) is a 3426–3350 Ma sedimentary succession that occurs in 14 greenstone belts in the East Pilbara Terrane (EPT) of the Pilbara Craton in Pilbara, Western Australia. The SPF is underlain and overlain unconformably by the dominantly volcanic Warrawoona and Kelly Groups, respectively. Its name is derived from a small pool known as the Strelley Pool occurring in the Pilgangoora Syncline. Its depositional area is assumed to cover more than 30,000 km², and the depositional environment ranges from shallow submarine to terrestrial. The SPF is known to contain morphologically diverse stromatolites and microfossils whose biogenicity has been extensively examined.

History

Identification of the sedimentary unit now assigned to the Strelley Pool Formation (SPF) dates back to 1972, when the unit was correlated to the Towers Formation (a term no longer used) of the Warrawoona Group. The SPF was previously called the Strelley Pool Chert (SPC), which Lowe (1980) introduced for outcrops at Strelley Pool in the Pilgangoora Syncline, approximately 30 km west of North Pole Dome. The SPF was once considered as a basal member of the Kelly Group (Van Kranendonk et al. 2004), but later reinterpreted as an independent formation separating the two major volcanic units of the Pilbara Supergroup, the Warrawoona, and the Kelly groups (Hickman 2008). The SPF is now identified in 14 greenstone belts in the East Pilbara Terrane (EPT) (Hickman *in press*).

Overview

The SPF is composed predominantly of sedimentary rocks such as sandstones, conglomerates, volcanoclastics, carbonates, evaporites, and cherts. Its depositional age is constrained by the ages of the underlying felsic volcanics of the Warrawoona Group (3433–3427 Ma) and the overlying basalts of the Euro Basalt of the Kelly Group (3350–3315 Ma) (Hickman, 2008). The basal unconformable contact includes a subaerial erosional unconformity (Van Kranendonk et al. 2006). Its thickness can be up to 1000 m. Lithostratigraphic subdivisions of the SPF, which were first proposed by Lowe (1983), ascend in the following stratigraphic order:

- Member 1, basal quartzose sandstone.
- Member 2, cherty unit of laminated flat stromatolite, conical stromatolite, and silicified evaporate.
- Member 3, stratified unit of stromatolite, black chert, silicified evaporite, and evaporate solution layer.
- Member 4, coarse, intraformational conglomerate and breccia.
- Member 5, cap unit of volcanoclastic debris.

As reported by Hickman (2008), on the other hand, this formation has significant lithostratigraphic variation both on regional and local scales. The SPF mostly represents shallow-water to subaerial environments, including shallow-water marine, coastal, and estuarine and non-marine such as lacustrine, fluvial, and sabkha (Hickman 2008; Allwood et al. 2006). Macroscopic biosignatures known as stromatolites have been identified as early as the 1980s. The SPF is also known to contain cellularly preserved microfossils of various morphologies and other biosignatures. These biosignatures are the focus of this contribution.

Basic Methodology

Studies of the SPF have been built on detailed fieldwork, including, for example, geological mapping, measuring sections, close examination

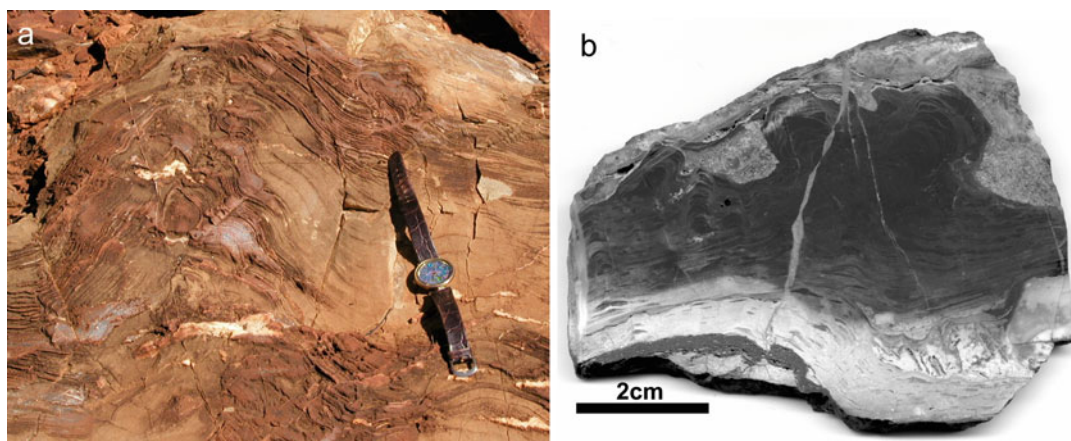
of outcrops, and careful collection of rock specimens with precise GPS (Global Positioning System) constraints. Reconstruction of local lithostratigraphy is essential for understanding paleoenvironment in which rocks containing potential biosignatures were formed. Collected hand specimens have been subjected to various analyses. Polished sections of hand specimen provide us with additional and detailed sedimentological information that could not be identified from outcrops. Microscopic examination of conventional petrographic thin sections is indispensable to make preliminary assessment of biogenicity of the fossil-like microstructures. Best targets for further analyses can be chosen only based on detailed and careful examination of petrographic thin sections. Representative further analyses include mineral and material identification, measurement of crystallinity of organic matter, elemental mapping, measurement of isotopic composition, and examination of nanoscale structures of putative microfossils and bulk rock chemical compositions. For these purposes, e.g., Raman Spectroscopy, Secondary Ion Mass Spectrometry (SIMS), Nanoscale Secondary Ion Mass Spectrometry (NanoSIMS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) are used.

Key Research Findings

Stromatolite

The first description of stromatolitic structures in the SPF was made by Lowe (1980), who reported finely laminated conical mounds in chert in the East Strelley greenstone belt, which were correlated to *Conophyton* common in the Proterozoic. An outcrop displaying extensive conical to pseudocolumnar stromatolitic structures composed of carbonate was later discovered by A.F. Trendall (the Trendall locality) (Fig. 1a) from the Panorama greenstone belt. Hofmann et al. (1999) emphasized that purely chemical processes were insufficient for explaining several features of the SPF carbonate-facies stromatolites such as (1) the combination of steeply conical forms modified by second-order corrugate lamination; (2) the coexistence of cones with branching pseudocolumns; and (3) the juxtaposition of uniform laminae in cones with uneven wispy, lenticular horizontal laminae in intercone areas. The authors also mentioned the morphological similarity of the SPF stromatolites to younger varieties such as *Jacutophyton* and *Thyssagetes* and suggested that microbial activity was involved in the formation of the SPF conical stromatolites.

Biogenicity of the SPF carbonate-facies stromatolites has been further confirmed by Allwood



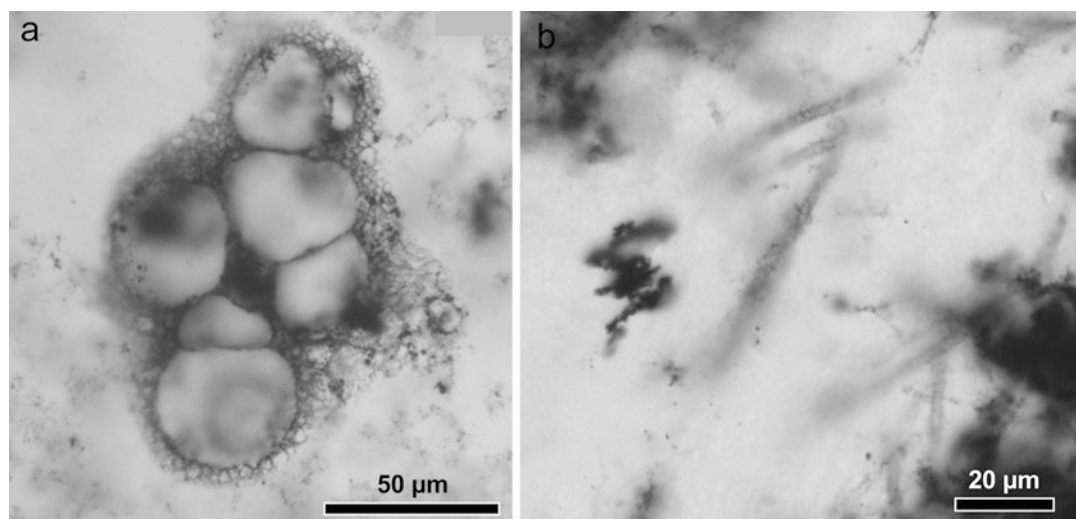
Strelley Pool Formation, Fig. 1 (a) Stromatolite cones at the Trendall locality in the Panorama greenstone belt, (b) silicified stromatolite-preserving organic laminae at the Waterfall locality in the Goldsworthy greenstone belt

et al. (2006), who described seven morphological types and related them to the variation in sedimentary environments determined through detailed mapping that covered several kilometers of outcrops. This macroscale analyses were combined with mesoscale to microscopic investigations of laminae architecture to successfully demonstrate the biogenicity of the SPF stromatolite. Habitat for the stromatolites was marine with some contributions of hydrothermal fluids (Allwood et al. 2010). The stromatolite locally preserves organic matter, whose carbon isotopic values are consistent with biogenicity and could further place some constraints on metabolism (Flannery et al. 2018). It was suggested that the reported large fractionation of carbon isotopes ($\delta^{13}\text{C} = -29 \sim -45\%$) between organic matter and associated carbonate reflected fixation and/or remobilization of carbon mediated by, for example, the Calvin-Benson-Bassham (CBB) cycle combined with the Wood-Ljungdahl pathway. From the SPF in the Goldsworthy greenstone belt, Sugitani et al. (2015b) reported siliceous stromatolites, in which carbonaceous laminae, trapped grains, and casts of possible evaporitic minerals are preserved. This newly described stromatolite varies in morphology from flat to columnar (Fig. 1b).

Carbon-isotopic compositions of carbonaceous laminae determined by SIMS are around 27‰. Habitat for these stromatolites was assumed to be nonmarine, based on rare-earth elements and yttrium systematics.

Cellularly Preserved Microfossils and Possible Microfossils

Fossil-like microstructures have been reported in several localities of the SPF. Schopf and Packer (1987) first described carbonaceous spheroids $\sim 20\ \mu\text{m}$ across and interpreted them as ensheathed colonial unicells. Sugitani et al. (2010, 2013, 2015a, b) and Schopf et al. (2017) reported morphologically diverse but basically identical assemblage of carbonaceous microstructures from the Panorama, Warralong, and Goldsworthy greenstone belts. The carbonaceous microstructures include spheroids, films, lenses, and filaments (Figs. 2 and 3): As such, the assemblage is basically similar to those reported from the contemporaneous ($\sim 3416\text{--}3330\ \text{Ma}$) Kromberg Formation in the Barberton greenstone belt, South Africa (Walsh 1992; Oehler et al. 2017) and from the ca. 3.0 Ga Farrel Quartzite in the Pilbara Craton (e.g., Sugitani et al. 2007). The SPF spheroid microstructures can be divided

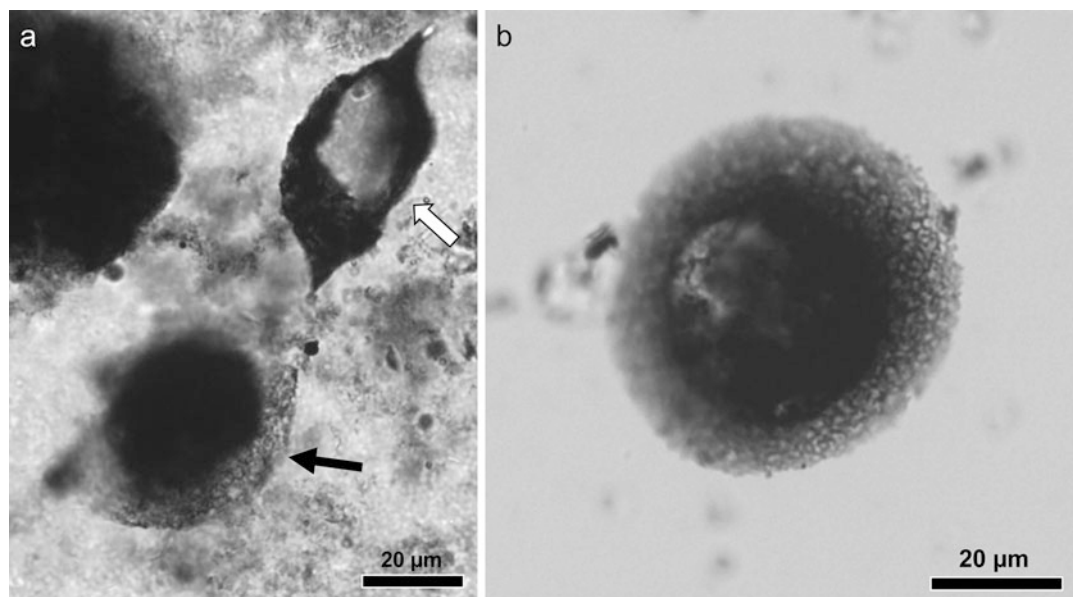


Strelley Pool Formation, Fig. 2 (a) Colony of large spheroids with foam-like envelop; (b) loose cluster of gently sinuous cylindrical and hollow filaments

into two diameter categories, including small ($<15\ \mu\text{m}$) and large ($>15\ \mu\text{m}$), both of which occasionally occur as colony-like clusters (Fig. 2a). Some of filament-like structures are also clustered and comprise biomat-like fabrics (Fig. 2b) (Schopf et al. 2017). Lenses are composed of central spheroid body and surrounding discoid flange (Fig. 3a), ranging mostly from 40 to 80 μm along the major dimension.

Biogenicity of the SPF microstructures discovered by Sugitani et al. (2010, 2013) was assessed based on several criteria such as carbonaceous composition, size distribution, taphonomic features, and supposed physical property. The preliminary claims for biogenicity were supported by several followed-up studies. Lepot et al. (2013) performed SIMS analyses on small spheroids and lenses and revealed that these two morphological types had significantly light and distinct $\delta^{13}\text{C}$ values. Sugitani et al. (2015a) also successfully extracted lenses from host rocks by conventional acid maceration (Fig. 3b), demonstrating that they were composed of continuous membranous carbonaceous matter. TEM analyses of the extracted specimens showed that the central body of lenses

had inner alveolar structures which were likely originated from cytological complexity. Alleen et al. (2018) detected nitrogen- and oxygen-rich organic molecules from film and lens exposed on freshly fractured surface of the SPF chert. X-ray adsorption near edge structure (XANES) spectra of these microstructures was similar to those of the best-preserved microfossils in the 1.9 Ga Gunflint cherts. NanoSIMS analyses also demonstrated high N concentrations and substantial presence of P for spheroids, films, and spheroids (Delarue et al. 2020). Sugitani et al. (2018) performed morphometrics of extracted lenses (total analyzed number > 800) from two remote localities in the Goldsworthy and Panorama greenstone belts. Cluster analyses using three parameters of the whole area, the flange ratio, and sphericity revealed that each population was composed of three subpopulations and that the Panorama population is dominated by elliptic specimens, whereas the Goldsworthy population by circular ones. Trace element geochemistry of host rocks and lithostratigraphy suggest that the two habitats were environmentally different, namely marine (the Panorama locality) and nonmarine (the



Strelley Pool Formation, Fig. 3 (a) Two lenticular microfossils. The white arrow indicates an equatorial view, whereas the solid arrow does an inclined polar

view; (b) a slightly inclined polar view of specimen extracted from host rock by acid maceration

Goldsworthy locality), although both were influenced by hydrothermal activities. This morphological variation may therefore be a result of adaptive and geographical diversification. Another implication of this study is that SPF lenticular microbes have a common ancestor. One possible candidate is lenticular structures described from the Dresser Formation, although these were interpreted as volcanic vesicles by the discoverer (Wacey et al. 2018a).

Another assemblage of microfossils was reported by Wacey et al. (2011a), who described three morphotypes of putative microfossils from the basal sandstone of the SPF in the East Strelley greenstone belt, including small coccoids (~10 μm in diameter), sheath-like tubes (~10 μm in diameter), and large envelope-like spheroids (~80 μm in diameter). The authors performed focused ion beam system (FIB)-TEM and SIMS analyses of these structures and suggested that the specimens were fossils of sulfur metabolizing bacteria inhabited in an Archean sandy coastal environment. Wacey et al. (2018b), however, reinterpreted the clustered large spheroids as probable volcanogenic in origin (volcanic vesicles) and in extension implied the possibility that some of the lenticular microfossils described above (e.g., Sugitani et al. 2010, 2013) were volcanic vesicles colonized by microbes (biofilm).

Pyrite and Kerogen

In addition to the above-described cellularly preserved microfossils, possible noncellular biosignatures have been reported also from the basal sandstone of the SPF. The biosignatures include (1) pristine micron-sized pyrite with a $\delta^{34}\text{S}$ spread of $-12 \sim +6\text{‰}$ and $\Delta^{33}\text{S}$ (deviation from $\delta^{34}\text{S}$ – $\delta^{33}\text{S}$ correlation) with both positive and negative values of $-1.65 \sim +1.43\text{‰}$ and (2) detrital pyrite grains with minute spherical pits and chains of pits. The former is associated with organic material coating the framework quartz grains and is interpreted to provide evidence for microbial sulfate reduction and microbial disproportionation of elemental sulfur, whereas the latter is likely the result of microbially mediated oxidation of pyrite (Wacey et al. 2010, 2011b). Prior to these works, Marshall et al.

(2007) analyzed kerogenous materials extracted from the SPF and examined them using several spectrometric methods, including Fourier-transform infrared spectroscopy (FTIR) and catalytic hydropyrolysis followed by gas chromatography mass spectrometry (HyPy–GC–MS). The authors reported similarities of molecular profiles of HyPy products between SPF kerogens and unequivocally biogenic kerogens from the Mesoproterozoic Roper Group (~1450 Ma), and they implied that the SPF kerogens were biogenic.

Future Directions

Although a few skepticisms still remain (e.g., Wacey et al. 2018a, b), it now seems evident that the SPF contains well-demonstrated and various types of Paleoarchean biosignatures, including stromatolites, cellularly preserved microfossils, molecular fossils, and isotopic data of carbon and sulfur. Although some ideas have been proposed (e.g., Kozawa et al. 2019; Flannery et al. 2018), lifestyles, metabolisms, and biological affinities of stromatolite-builders and cellularly preserved microfossils are still poorly known. For example, despite its upward-growing morphology, phototaxis of microbes that had constructed stromatolite has not yet been fully confirmed (e.g., Bosak et al. 2009). This issue could be addressed by further detailed organochemical studies on early silicified stromatolites such as those discovered from the Goldsworthy greenstone belt (Sugitani et al. 2015b) in which organic laminae are well preserved: Exploring microfossils in them is challenging but intriguing. Additionally, systematic paleontology of cellularly preserved microfossils, which is indispensable for the assessment of Paleoarchean microbial diversity, should be established. As it is probable that lenticular microfossils can be discovered from older successions, search for them and demonstrating their biogenicity can also be expected. Finally, biological affinity (eukaryotic vs. prokaryotic and/or oxygenic photosynthesis vs. nonoxygenic photosynthesis) of lenticular microfossils should be one of the most important future research targets, although this

difficult task may need to be addressed with the development of new methodologies.

Cross-References

- ▶ [Apex Chert](#)
- ▶ [Archaean Biosignatures](#)
- ▶ [Archean Environmental Conditions](#)
- ▶ [Archaean Traces of Life](#)
- ▶ [Barberton Greenstone Belt, Traces of Early Life](#)
- ▶ [Chert](#)
- ▶ [Early Earth](#)
- ▶ [Isotopic Traces of Life](#)
- ▶ [Microbialites](#)
- ▶ [Microfossils, Analytical Techniques](#)
- ▶ [North Pole Dome \(Pilbara, Western Australia\)](#)
- ▶ [Photosynthesis](#)
- ▶ [Rare Earth Elements](#)
- ▶ [Stromatolites](#)
- ▶ [Sulfur Isotopes](#)

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Stromatolites

Nicola McLoughlin

Department of Geology, Rhodes University,
Makhanda/Grahamstown, South Africa

Keywords

Laminated sedimentary structures · Microbial mats

Synonyms

Fossilized microbial mats; Living stromatolites; Microbialites; Modern stromatolites

Definition

Stromatolites are morphologically circumscribed accretionary growth structures with a primary lamination that is, or may be, biogenic. They form centimeter- to decimeter-scale domes, cones, columns, and planiform surfaces made of carbonate layers. Stromatolites accrete through a combination of microbially mediated sediment trapping and binding and by the precipitation of carbonate crusts that may be due to microbial mat growth and/or be purely ► [abiotic](#) in origin. Stromatolites provide the oldest macrofossil evidence of ► [life](#) on earth and sometimes host important ► [microfossil](#) occurrences. Images of macroscopically layered stromatolites obtained by rovers on other planetary surfaces may yet provide some of the first evidences of life beyond earth.

History

The term “stromatolith” was first used just over a century ago by Kalkowsky (1908) and derived from the Greek words *stroma* meaning bed, mattress, or layer, and *lithos* meaning stone. It was used to describe laminated limestones from the early Triassic, lacustrine deposits near the Harz Mountains of Northern Germany. Kalkowsky

attributed the formation of these structures to simple plant-like organisms, and the term was later popularized by Pia (1927) as a type of fossil produced by the calcium carbonate precipitation. The term was translated by Krumbein (1983) who stated that “stromatolites are organogenic, laminated, calcareous rock structures, the origin of which is clearly related to microscopic life, which in itself must not be fossilised.” It is now known that ► [prokaryotes](#) both photosynthetic and non-photosynthetic are largely responsible for stromatolite growth (Freytet and Verrecchia 1998), along with ► [heterotrophs](#), algae, and metazoans.

Overview

Stromatolites are the most abundant macrofossil in the ► [Precambrian](#) rock record and are volumetrically very significant components of Precambrian carbonate platforms. Stromatolites can be used to reconstruct sedimentary environments, especially paleobathymetry, paleoslopes, and current directions, and are used for biostratigraphic correlation within basins. Distinguishing the relative contribution of biological, physical, and chemical controls on stromatolite morphology can be difficult, and below the criteria that have been developed to assess the ► [biogenicity](#) of stromatolites are reviewed. The macro-morphology and especially microfabrics of stromatolites are archives of microbial evolution that together with their carbonate geochemistry record secular changes in seawater chemistry. This review focuses on how stromatolites grow and what they can tell us about the earliest microbial ecosystems on earth and perhaps beyond.

Basic Methodology

To study the microbial microtextures and carbonate mineralogy of stromatolites, light microscopy is widely applied. To investigate organic remains and the mineralogy, Laser Raman spectroscopy can be useful. If the samples are well-preserved with possible microbial remains, high-magnification microscopy techniques such as

scanning, and transmission electron microscopy, can be applied to rock samples and/or resin-impregnated nonlithified microbial mat remains. Geochemical information can be obtained on elemental abundances (major and trace), also isotopic ratios (see ► [Isotope Biosignatures](#)) using mass-spectrometry techniques, which may give bulk data from powdered samples, or in situ micro- to nanoscale data, if the mass spectrometer is coupled to a laser (laser ablation technique), or by using secondary ion mass spectrometry (SIMS).

Key Research Findings

What Is a Stromatolite?

The definition and meaning of the term stromatolite has been widely debated, especially whether the term should be used in a purely descriptive sense, to refer to laminated sedimentary structures, or should be used genetically to refer to structures that are demonstrably biogenic in origin; see reviews by, for example, Riding (1999), and Grotzinger and Knoll (1999). But herein lies the problem. There are many types of related geological structures that display some or all of the features of stromatolites, and are formed in a variety of environments, but with varying and sometimes debatable degrees of biological involvement. Such structures include hot spring travertines, nonmarine tufas, laminar caliche crusts, and speleothems. The possibility that abiotic processes may solely account for stromatolite growth was reasserted by Grotzinger and Rothman (1996) who used the Kardar-Parisi-Zhang (KPZ) equation of interface growth to show that the morphologies of some stromatolites can be modeled by abiotic processes alone. This was a significant study that reinvigorated the debate surrounding the biogenicity of Precambrian stromatolites in particular, and reemphasized the difficulties of disentangling biological, physical, and chemical controls on stromatolite growth. This remains a serious concern if we are 1 day to assess the biogenicity of laminated deposits imaged by rovers exploring other planetary surfaces.

A purely descriptive definition of a stromatolite was proposed by Semikhatov et al. (1979) and others: “an attached, laminated, lithified sedimentary growth structure, accretionary away from a point or limited surface of initiation.” Many sedimentologists favor this nongenetic definition to describe a laminated sedimentary structure with positive relief. This has resulted in the usage of terminology such as “abiogenic stromatolite” to stress the absence of compelling microtextural or morphological evidence for biological participation that is often lacking in many instances due to diagenetic alteration. Strictly speaking, however, this is a corruption of the original intention. The term stromatoloid has also been introduced by Buick et al. (1981) to refer to laminated sedimentary structures, the biogenicity of which is uncertain. An alternative approach to express the uncertainty surrounding the biogenicity of a given stromatolite is to add the prefix “probable” or “possible” or “dubio” stromatolite, as appropriate – this approach is applied to other biosignatures such as microfossils. Genetic definitions, on the other hand, have been proposed by, for example, Awramik and Margulis (1974), to mean an “organosedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes.” The evidence necessary to substantiate such a biogenic definition can be difficult to obtain in the rock record, especially in Precambrian sequences that have experienced diagenetic and metamorphic recrystallization – in this review, the term stromatolite is therefore used in the nongenetic sense.

Some workers, meanwhile, prefer the broader term *microbialite* that was introduced by Burne and Moore (1987) to describe both laminated and nonlaminated microbially mediated sedimentary structures. They defined microbialites as “organosedimentary deposits that have accreted as a result of benthic microbial community trapping and binding sediment and-or forming the locus of mineral precipitation.” Stromatolites are thus a subset of microbialites that also include nonlaminated deposits such as thrombolites (clotted) and dendrolites (branched) (Riding

1999). This term is perhaps most useful for describing modern microbial deposits that often exhibit varied internal structure and can be composite, including stromatolitic and other microbialite microfabrics. To add further confusion, the term stromatolite has also been applied to laminated microbial deposits that are not composed of carbonate, for example, laminated silica glazes or desert varnish crusts. Here, we will restrict our usage of the term stromatolite to carbonates.

Lithification of Recent Microbial Mats

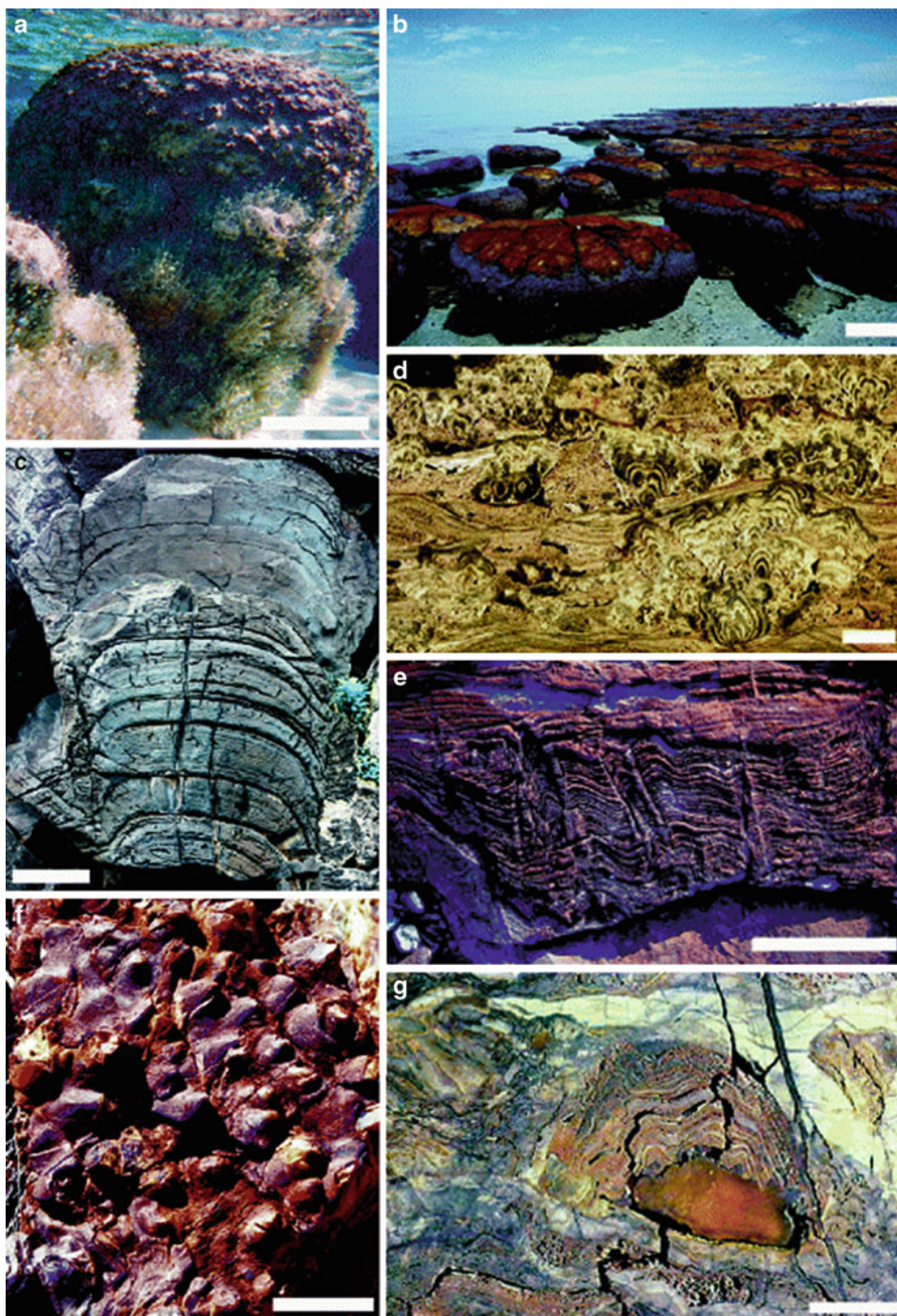
Studies of modern stromatolite analogues both in nature and the laboratory have been very informative for understanding mechanisms of stromatolite growth and lithification. Many modern stromatolites are known from hypersaline settings, for instance, Shark Bay in Western Australia (Fig. 1a, b), where the hypersalinity is thought to restrict grazing on the mats. Here the stromatolites accrete at an estimated rate of ≤ 3 mm per year with microbial trapping and binding of sediment being the predominant accretion mechanisms in the intertidal stromatolites and carbonate precipitation in the subtidal stromatolites (Reid et al. 2003). Several modern stromatolite-forming microbial mat systems are also known from Lake systems such as Lake Pavilion in British Columbia and Lake Thetis in Western Australia, where elevated carbonate saturation levels are thought to promote lithification of the microbial mats. The only known modern open-marine stromatolite system comes from the Bahamas where stromatolites occur in supra-, inter-, and subtidal settings (e.g., Reid et al. 2000). Studies have found that the microbial mats are spatially and temporally very dynamic systems, with the location of primary production and lithification changing on diurnal to seasonal and annual cycles and across depositional gradients (e.g., Reid et al. 2003; Visscher et al. 2000). The distinct microenvironments, steep geochemical gradients, and diverse processes that occur within modern microbial mats are described elsewhere in this volume. Modern systems are, however, imperfect analogues for the Precambrian rock record, especially prior to the evolution of eukaryotes and

metazoans, and in a water column that was anoxic for much of the Archaean and early Proterozoic. Nonetheless, the manipulation of model microbial mat systems both in the lab and in their natural environment has proved informative for better understanding the mechanisms that produce specific stromatolite features, for example, cell motility in reticulate mats and oxygenic [photosynthesis](#) in conical mats (see below).

Stromatolite Biogenicity Criteria

The rock record provides a testing ground for developing stromatolite biogenicity criteria that 1 day may be applied to laminated sedimentary structures on other planetary surfaces. The problem is that most of these criteria are so prescriptive that the majority of Precambrian stromatolites of widely regarded biogenic origin fail to qualify. Here, a brief review of the most widely applied stromatolite biogenicity criteria is given, drawing from the classic study of Buick et al. (1981) and additional criteria (points 9–11) proposed by Hofmann (2000):

1. “*The structures must occur in undoubted sedimentary or metasedimentary rocks.*” A viable sedimentary environment is a necessary first condition to demonstrate the biogenicity of a stromatolite.
2. “*It must be demonstrated that the structures are syndimentary.*” It is necessary to exclude soft sediment deformation and/or later structural deformation as contributing to the resulting stromatolite morphology.
3. “*There should be a preponderance of convex upwards structures.*” This is a useful but very qualitative criterion and is neither necessary nor sufficient to demonstrate biogenicity as, for example, abiotic self-organizing structures such as stalagmites and agate crusts can exhibit convex-upward morphologies.
4. “*Laminae should thicken over the crests of flexures.*” This qualitative criterion is designed to exclude abiotic, chemical crusts that are widely believed to exhibit laterally uniform thickness, i.e., be isopachous (e.g., Pope and Grotzinger 2000). However, freshwater *Phormidium* stromatolites, for



Stromatolites, Fig. 1 Examples of stromatolites: (a) submerged intertidal modern stromatolites from Shark Bay, Western Australia; (b) living domal stromatolites with an orange diatom-rich coating from the intertidal zone of Carbla Foreshore, W Australia; (c) large columnar

stromatolite with smooth, convex laminae from the Neoproterozoic lower Transvaal Supergroup of South Africa; (d) microdigitate stromatolites from 2.7 Ga Tumbiana Formation of W Australia; (e) pseudocolumnar stromatolites from the Trendall locality of the ~3.4 Ga Strelley Pool Chert of

example, are commonly isopachous and can be differentiated from abiological speleothem cements by being of uniform thickness around, for example, the entire circumference of coated tree branches, whereas abiological cement would be thicker on the undersides due to geopetal effects. In other words, crusts do not need to thicken – they may just maintain their thickness. Further discussion on the different types of stromatolite laminar geometries is given below, including the degree of vertical inheritance between laminae and their lateral continuity.

5. *“If the structures are laminated the laminations should be wavy, wrinkled and/or have several orders of curvature.”* Again, this qualitative criterion is designed to exclude abiogenic precipitated crusts that are thought to be more uniform, but no limits are placed on the extent of “crinkliness” or “curvature” which are also controlled by sedimentary rheology and overprinted by the degree of diagenetic modification.
6. *“Microfossils or trace fossils should be present within the structures.”* This is far too rigid as the preservation potential of microbial remains is extremely low, such that this criterion would exclude more than an estimated 90% of described fossil stromatolites. Also, the majority of recent stromatolites only contain microorganisms in their outermost layers. Furthermore, the presence of microfossils in a stromatolite does not confirm their active role in formation of the structure, as they may simply have been passively entombed by the accreting structure, as is seen, for example, in some silica sinter deposits.
7. *“Changes in composition of the microfossil assemblages should be accompanied by morphological changes in the stromatolite.”* This is an extension of criterion 6 and is extremely prescriptive as only a few instances are known where this criterion is satisfied, for example, stromatolites of the Gunflint Chert. Studies of modern stromatolites also suggest similar fabrics can be produced by more than one organism, such that morphological changes may not necessarily accompany changes in microfossil assemblage.
8. *“The fossils or trace fossils must be organised in a manner indicating trapping, binding or precipitation of sediment by the living microorganisms.”* Again, this would be desirable but is somewhat overoptimistic in many settings. Likewise, tufted microbial filaments, fenestrae, and/or micropores created by the growth and decay of now absent microbes would be useful but are only found when diagenesis is minimal (e.g., Turner et al. 2000a).
9. *“Brecciated mat chips accumulated in depressions between convexly laminated mounds.”* These are occasionally seen and have been highlighted in discussions surrounding early Archaean stromatolites, for example, from the Strelley Pool Chert (Hofmann et al. 1999). Such textures are most convincing if the mat fragments show laminated internal fabrics or microtextures that can distinguish them from fragments of brecciated seafloor crusts.
10. *“Thin, rolled-up fragments as indications of the existence of coherent flexible laminae that are reasonably interpreted as microbial mats.”* These are desirable and occasionally seen, for example, in the Paleoproterozoic Hamersley Group of Western Australia and in silicified microbial mat horizons, for example, the 3.4 Ga Buck Reef Chert of South Africa (Tice and Lowe 2004), but again require exceptional organic preservation.
11. *“Distinct compositional differences between the laminated growth structures and their surrounding matrix, such as carbonate*

Stromatolites, Fig. 1 (continued) W Australia; (f) plan view of simple coniform stromatolites on a bedding surface of silicified carbonate from the W Strelley locality of the Strelley Pool Chert; and (g) domal stromatolite in a

ferruginous carbonate with a silicified core from the ~3.5 Ga Dresser Formation of the North Pole Dome, W Australia. Scale bar (a) and (b) 15 cm, (c) 20 cm, (d) 1 cm, (e) and (g) 5 cm, and (f) 10 cm

stromatolites set within terrigenous detritus.”

This can be a helpful criterion, but there are numerous exceptions. For instance, many of the least controversial carbonate stromatolites are found in carbonate settings, and especially those formed by trapping and binding can have a similar composition to their surrounding matrix. Whereas, in terrigenous clastic settings laminated carbonates are not always a stromatolite: Many caliche crusts would meet this criterion.

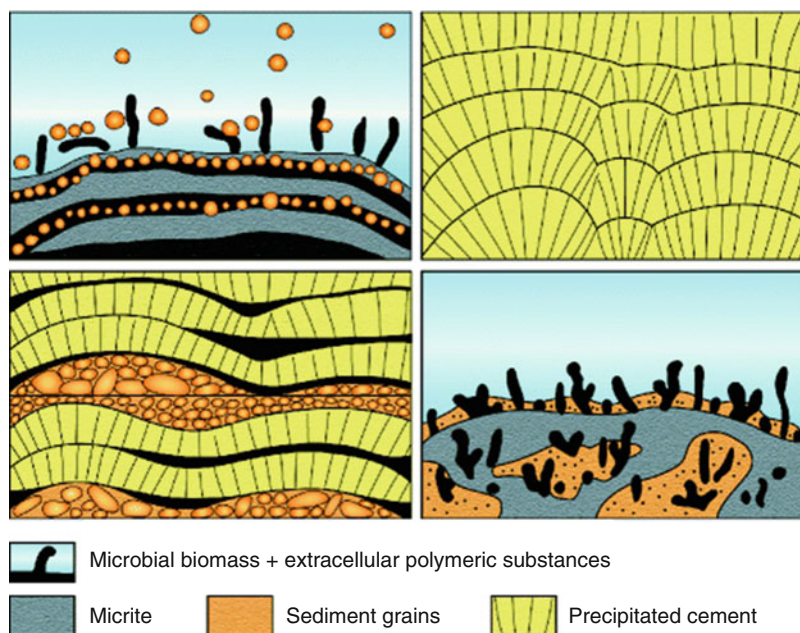
In summary, a biogenic origin is most likely for stromatolites that exhibit complex morphologies, laminae that show lateral and vertical variability (see discussion on microfabrics below), and organic bearing microfabrics. A more compelling case for a biogenic origin can be made, if it can also be shown that changes in both the macro- and microfeatures of the stromatolite correlate with biologically significant environmental gradients, such as light levels.

Mechanisms of Stromatolite Accretion

Here, the processes that contribute to stromatolite accretion are summarized, also the laminar geometries and microtextures that are thought to result. A schematic of these accretionary processes is shown in Fig. 2 (modified from Shapiro 2005); these are sediment trapping and binding (top left) producing often clotted or peloidal crusts, sometimes referred to as “fine-grained crusts”; chemical precipitation of carbonate (top right) producing laminae comprising “abiogenic sparry crusts”; a combination of these processes (lower left) producing composite crusts; and a skeletal stromatolite (lower right) formed by calcifying microorganisms, most commonly ► [cyano-bacteria](#). A more detailed review of this subject can be found in Riding (2008) that focuses on the microfabrics of Precambrian stromatolites.

Sediment Trapping and Binding

In recent stromatolites, the trapping and binding of suspended sediment particles is an important



Stromatolites, Fig. 2 Mechanisms of Stromatolite Accretion: (*top left*) sediment trapping and binding by microbial mats producing laminae with micritic, detrital, and/or peloidal layers; (*top right*) chemical precipitation of carbonate-producing laminae comprising “sparry crusts”;

(*lower left*) a combination of these processes producing composite crusts of alternating sparry, detrital, and organic layers; and (*lower right*) a skeletal stromatolite formed by calcifying microorganisms, for example, the cyanobacteria *Girvanella*. (Diagram modified from Shapiro (2005))

accretionary mechanism. This process is controlled by the slope of the accreting stromatolite interface, the grain size and density of the sediment particles, and the size and motility of the microbes (e.g., Riding (2000) and references therein). This process is countered by the movement of sediment down stromatolite flanks under the forces of gravity and current action that are most vigorous in high-energy settings and for stromatolites with steep flanks or significant relief. Sediment trapping and binding is thought to be facilitated by biofilms that have abundant “sticky” extracellular polymer and by microbes with high motility (e.g., Golubic et al. 2000). In addition, early cementation is necessary to prevent loss of this detrital sediment off the stromatolite flanks. These processes are thought to create nonisopachous laminae that show irregular uneven layering with low inheritance and limited lateral continuity. In petrographic thin section, preservation permitting the trapped and bound sediment grains should be visible, perhaps between the decayed remains of organic laminae that may have formed during more quiescent periods.

Trapping and binding processes are commonly associated with microbially induced carbonate precipitation (see below) that together result in so-called fine-grained crusts of Riding (2008). These can exhibit micritic, clotted, peloidal, or filamentous microfabrics and are especially abundant in the Neoproterozoic (e.g., Turner et al. 2000b). Additional support for microbial activity can come from microfossil remains, for example, in the 1.8 Ga stromatolites of the Gunflint (Awramik and Semikhatov 1978); or in the form of micropores interpreted to be the molds of decayed microbes (Bosak et al. 2004); or palimpsest fabrics comprising vertically aligned, decayed microbial filaments (e.g., Buick 1992). The mere presence of such microbial remains is insufficient, however, to demonstrate full microbial control on precipitation, as it needs to be shown that these remains were not just passively entombed but rather actively shaped by the accreting structure. In some stromatolites, the fine-grained crusts are interleaved with so-called crystalline or sparry crusts (see below) creating

alternating light and dark layers conferring a streaky appearance. These are interpreted to reflect the switching between dark, fine-grained essentially microbial-mediated layers and light-colored, possibly abiotically precipitated, spar layers that are common in many conical stromatolites termed *Conophyton* (e.g., Grotzinger and Knoll (1999), and references therein).

Abiotic Chemical Precipitation

Carbonate precipitation in microbial stromatolites not only can be induced by the activities of living and decaying microbes (e.g., Riding 2000), but also results from pore water supersaturation generated by abiotic processes such as degassing of CO₂ and evaporation. Abiotic chemical precipitation is responsible for the growth of abiotic laminated deposits, such as agates, botryoides, crystalline crusts, and cements. These can sometimes be recognized by the expansion and ultimate coalescing of neighboring crystal fans, or undulose layers with microfabrics clearly resulting from precipitation. These are termed “abiogenic sparry crusts” by Riding (2008). In discussions concerning the biogenicity of stromatolites, abiotic chemical precipitation is widely assumed to produce isopachous laminae, i.e., laminae of uniform thickness (e.g., Buick 1992). The synthetic stromatolite experiments reported in McLoughlin et al. (2008), however, together with several numerical modeling studies (e.g., Grotzinger and Rothman 1996), have shown that abiotic processes can also produce nonisopachous laminae, and therefore stromatolite imposters or pseudofossils. This is well known. For example, meteoritic cements formed in the phreatic zone, where void spaces are water filled, result in the precipitation of cements with isopachous laminae, whereas cements formed in the vadose zone have dripstone, i.e., nonisopachous geometries. Thus, the assumption that abiotic precipitation exclusively results in isopachous stromatolite laminae does not hold. This raises further concerns about our abilities to always identify abiotic laminated deposits confidently.

In the Precambrian rock record, stromatolitic growth by abiotic, surface-normal chemical precipitation is suggested by laminae that are

composed of radial fibrous crystals fans (Fig. 2c) (e.g., Grotzinger and Knoll 1999) or so-called sparry crusts (Riding 2008). These are characterized by isopachous laminae that show extreme lateral continuity and high degrees of vertical inheritance. Such structures are believed to form by direct carbonate precipitation on the seafloor and are devoid of clastic carbonate (e.g., Turner et al. 2000b; Pope and Grotzinger 2000). They are particularly abundant in Archaean and Paleoproterozoic sequences and are believed to be associated with times of high seawater carbonate supersaturation, often being associated with evaporitic sequences. They have been termed “chemical stromatolites” by Pope and Grotzinger (2000) who argued that they are largely abiotic in origin.

Biologically Induced Precipitation: Chemo- and Phototaxis

The thickening of laminae across the crests of stromatolite domes and cones is commonly believed to result from microbially accelerated growth in an upward direction due to chemo- or phototaxis. Coniform stromatolites are taken as indicators of phototactic microbial growth by analogy to modern-tufted and peak-shaped microbial mats (e.g., Walter et al. 1976; Batchelor et al. 2004). It is envisaged that phototactic biofilms strive to gain more light and that chemotactic biofilms aim to elevate themselves in the benthic boundary layer to access more nutrients. This accelerated upward growth is accomplished by microbial motility toward topographic highs termed “upslope diffusion” by Jogi and Runnegar (2005). The exact geometries of the resulting laminae, in particular, the degree of laminar thickening in the axial zone, are likely controlled by photic zone conditions, the thickness of the benthic boundary layer, and the nature of diffusive gradient both within and above the accreting surface. Recent laboratory investigations of reticulate cyanobacterial mats have found that it is cell motility and not phototaxis that controls the shape of the mat, because upward growth was observed even when illuminated from below (Shepard and Sumner 2010).

In addition to laminar geometries, there are other microfabric clues that may indicate the

phototactic growth of stromatolites. Recent laboratory experiments growing cyanobacterial-dominated microbial mats have identified the presence of contorted laminae in the axial zone of conical aggregates and preservation of enmeshed oxygen bubbles as indicators of oxygenic photosynthetic mat growth (Bosak et al. 2009). Such features are found in the central zones of well-preserved Proterozoic conical stromatolites from which these workers argue that oxygenic photosynthesis first appeared in the Paleoproterozoic. In outcrop, the observation of sinuous growth axes of 850 Ma stromatolites from the Bitter Springs Formation has also been argued to represent heliotropism, i.e., microbial mat growth that tracks the changing position of the sun (Vanyo and Awramik 1985) – this of course requires that the stromatolites were accreting and lithified at a sufficiently fast rate to record such annual variation.

Brief Review of Stromatolites Through Time

There have been many attempts to compute curves of stromatolite diversity and abundance through geological time; however, these efforts have been somewhat hampered by our inability to separate biological, chemical, and physical controls on stromatolite growth and to agree a universal definition of what constitutes a stromatolite taxon (Grotzinger and Knoll 1999). There are, nonetheless, long-term, first-order trends in stromatolite morphologies and microfabrics that record evolutionary and environmental changes that are summarized here.

First, there is a broad transition in the Precambrian from stromatolites formed predominantly by chemical precipitation in the Archaean with sparry microfabrics to stromatolites with fine-grained more microbially influenced microfabrics in the Neoproterozoic (Riding 2008). In the intervening Paleo and Meso-proterozoic interval, stromatolites with hybrid fabrics are most common, and this is argued to reflect growth by a combination of chemical precipitation and sediment trapping and binding. This transition has been suggested to represent a long-term decline in Precambrian seawater carbonate supersaturation (Grotzinger and Kasting 1993), with a consequent

switch in importance from chemical precipitation to microbial trapping and binding as the dominant mechanisms of stromatolite growth. This connection between seawater carbonate saturation and microbialite abundance has been further tested in the Phanerozoic with compilations of abundance data for calcified cyanobacteria and microbial carbonates (Riding and Liang 2005 and references therein) showing a positive correlation with marine carbonate saturation.

Second, distinctive new stromatolite morphologies and/or microfabrics can record major evolutionary events. For example, cyanobacterial biomineralization in the lower Cambrian (Riding and Voronova 1984) resulted in the formation of dendrolites and skeletal stromatolites, which are most abundant in the Cambrian and Lower Ordovician. Also thrombolites, with their clotted microfabrics, first appear in the Cambrian, and they are argued to represent “disturbed stromatolites,” in which the activities of animals and ► [algae](#) have disrupted and destroyed the laminae (Walter and Heys 1985). In addition, the abundance of microbial carbonates in the Phanerozoic is generally inversed to that of marine metazoan taxonomic diversity, supporting the view that metazoan competition has progressively limited the formation of microbial carbonates. Further, stromatolite morphologies that may be diagnostic of certain periods of geological time have been recognized, although their environmental and/or evolutionary significance is yet to be fully understood. For instance, many late Archaean carbonate sequences include fenestrate microbialites, netlike masses of irregular columns, or tent shapes composed of dark organic layers encased in irregular calcite cements (Sumner 1997), but their apparently restricted time distribution is yet to be fully explained.

Third, stromatolites have been suggested as disaster taxa, namely, organisms that in the aftermaths of mass extinction events show increased abundance due to the relaxation of ecological constraints. For example, in Lower Triassic strata following the end-Permian mass extinction that was particularly devastating to benthic biota, a time dominated by depositional systems reminiscent of the Neoproterozoic-Early Paleozoic has

been reported. In particular, this includes planar microbialites, small stromatolites, thrombolites, and microbial reefs developed extensively in normal marine carbonate environments. The proliferation of these so-called disaster taxa has been attributed to a reduction in trace fossil infaunalization and metazoan grazers. But there may be other environmental factors at play, including the enhanced carbonate saturation at this time as supported by the abundance of seafloor crystal fans that would promote the lithification of benthic microbial mats. A more recent study from the Phanerozoic of North America (Peters et al. 2017) found that the aftermaths of major mass extinction events are not well correlated with stromatolite resurgence. Instead, stromatolite occurrence is well-predicted by the prevalence of dolomite, and a shift in carbonate mineralogy that is sensitive to changes in water-column and pore-water chemistry occurring during continent-scale marine transgressive-regressive cycles. These findings again highlight the difficulties of separating physical, chemical, and biological controls on stromatolite growth and abundance.

The Oldest Stromatolites on Earth

The oldest known stromatolites are described from silicified carbonates of the Pilbara Craton, Western Australia. Archaean ► [traces of life](#) are reviewed elsewhere in this volume, and here the focus is on the macrofossil evidence provided by stromatolites. A comprehensive summary of all reported Archaean stromatolite occurrences can be found in Table 1 of Hofmann (2000). The oldest candidate stromatolites come from the <3.49 Ga Dresser Formation of Western Australia and include wrinkled planiform surfaces, broad domes, and columnar forms (Fig. 1g). These occur at several localities in the North Pole Dome both in syn-depositional barite mounds and hydrothermal dykes and in silicified and hydrothermally altered ferruginous carbonates (Wacey 2009 and references therein). Early studies supported a biological explanation from these structures based on macromorphological similarities to younger, unambiguously biological stromatolites (Walter et al. 1980). However, Lowe

(1994) reinterpreted these structures as soft sediment deformation features, and Buick et al. (1981) concluded that they were only “*probable or possible*” biogenic stromatolites because they failed to satisfy many of their biogenicity criteria reviewed above. More recent studies have argued largely on the basis of field relationships that these stromatolites are primary features that were constructed by hyperthermophilic microbes (Van Kranendonk 2007). The depositional environment has also been variously interpreted as a seafloor hydrothermal “white smoker” type deposit, and more recently as a terrestrial hot-spring biogenic geyserite deposit (Djokic et al. 2017). A variety of other candidate microbial biosignatures have been described and debated from the North Pole locality, including microfossils, C-isotope and fluid inclusion evidence, microbially induced sedimentary structures, and S isotopes on sulfide minerals that are discussed in a separate entry: ► [Dresser Formation, Traces of Life](#).

Some of the next oldest putative stromatolites are described from the <3.4 Ga Strelley Pool Chert of Western Australia; the most abundant forms are simple unbranched cones (Fig. 1f) that were initially interpreted as biogenic in origin, but this interpretation was later rescinded in favor of an origin by abiogenic evaporitic precipitation (Lowe 1994). The discovery of large coniform stromatolites with rare flank structures and domal and laterally linked pseudocolumnar morphologies (Fig. 1e) at the Trendall locality in the North Pole Dome led to a biological origin for these structures being readvanced (Hofmann et al. 1999). This was argued for based on morphological and sedimentological evidence, especially the steep-sided cones argued to require cohesive microbial mats, the presence of detrital sediment taken to imply microbial tapping and binding, the wrinkly nature of the laminae, and microfabric differences between the stromatolites and intervening nonstromatolitic sediments (Hofmann et al. 1999). Subsequently, detailed mapping of the stromatolite macromorphologies and investigation of rare outcrops with relatively good microtextural preservation have found evidence for a spatiotemporal correlation between

stromatolite morphology and microfabric and depositional environment. This has been taken to support a shallow-water carbonate platform depositional model for the Strelley Pool Chert and a phototrophic origin for the stromatolites (Allwood et al. 2009). Regionally, however, the more typical, small, unbranched coniform stromatolites of the Strelley Pool Chert do not show unambiguous biological characteristics or depth-controlled distribution and/or changes in morphology with depth (Wacey 2010). In addition, their close interrelationship with crystal fan arrays upon which they can be seen to nucleate emphasizes a strong chemical component to their growth, and their intergradation with linguoid current ripples highlights the importance of physical controls on their accretion. In short, the Strelley Pool Chert includes a spectrum of stromatolitic structures, only some of which are confidently interpreted as biogenic.

Older still, convex-up structures initially interpreted as stromatolites were described from 3.7 Ga metasediments of the Isua Supracrustal Belt (Nutman et al. 2016). These structures occur in tightly folded rocks and comprise both convex-up structures adjacent to convex-down structures and, therefore, fail the requirements for syn-sedimentary structures, with a predominance of convex-up morphologies, and so were reinterpreted as deformation features (Allwood et al. 2018). In addition, the depositional setting of these rocks has been questioned, with major and trace element geochemistry suggesting that the carbonate is more likely secondary (metasomatic/metamorphic) in origin and not primary seafloor deposits (Allwood et al. 2018).

Applications

In the near future, images of layered extraterrestrial sediments will be collected by rovers or landers on other planetary surfaces, most immediately Mars. We therefore require tools for assessing if these deposits were microbially shaped and/or if their mineralogy reflects microbial involvement. One approach involves quantitative image processing tools to measure the

degree of ► [complexity](#) in images of laminated deposits (Wagstaff and Corsetti [2010](#)) that may help select targets that are most likely biogenic, and perhaps promising for sample return missions. Currently, NASA's Mars Perseverance rover is deploying the PIXL (Planetary Instrument for X-ray Lithochemistry), which is a micro-focused X-ray fluorescence spectrometer mounted on a robotic arm (Allwood et al. [2020](#)). This instrument contains a powerful 120 μm -diameter X-ray beam with enough sensitivity to detect major and minor rock-forming elements, as well as many trace elements. This instrument can map the distribution and abundance variations of chemical elements making up a rock, tied to the physical texture and structure of the rock, which would be especially useful for assessing the origin of laminated deposits, particularly stromatolites. Other instruments that can be mounted on rovers and might be developed for future missions to investigate the carbonate mineralogy, and/or organic carbon content of stromatolites, include Raman spectrometers (Rividi et al. [2010](#)).

Future Directions

Stromatolites provide one of the most abundant and richest records of microbial evolution on our planet, but we are yet to fully decode the physical, chemical, and biological processes that are encoded in their diverse shapes and microfabrics. Promising approaches that are being developed include nanoscale elemental and isotopic signatures of organic matter found in well-preserved stromatolites (Lepot et al. [2009](#); Wacey et al. [2010](#)). Also, radiogenic and stable isotopes techniques are being revisited and further developed to directly date stromatolites and determine the source of elements in ancient stromatolite environments (radiogenic isotopes), and to understand redox conditions, metal availability, and (biogenic) metal cycling processes in microbial habitats (stable isotopes) as recently reviewed by Hohl and Viehmann ([2021](#)). Together with studies that manipulate living microbial mat systems to investigate the resulting morphological and chemical signatures produced in lithified stromatolites,

we are becoming better prepared to assess the biogenicity of stromatolites that may someday soon be found on other planetary surfaces.

Cross-References

- [Algae](#)
- [Archaean Traces of Life](#)
- [Belcher Group, Microfossils](#)
- [Biogenicity](#)
- [Biomarkers, Morphological](#)
- [Chemotaxis](#)
- [Chemotroph](#)
- [Complexity](#)
- [Cyanobacteria](#)
- [Dresser Formation, Traces of Life](#)
- [Eukarya](#)
- [Heterotroph](#)
- [Isotope Biosignatures](#)
- [Microbial Mats](#)
- [Microbially Induced Sediment Structures \(MISS\)](#)
- [Microfossils](#)
- [Photosynthesis](#)
- [Phototroph](#)
- [Precambrian](#)
- [Shark Bay, Stromatolites of](#)
- [Syngenecity](#)
- [Tumbiana Formation \(Pilbara, Western Australia\)](#)

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Structure and Chemistry of Microfossils

► Microfossils, Analytical Techniques

Subduction

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

A basic tenet of ► [plate tectonics](#) is that ► [oceanic crust](#) forms at ► [mid-ocean ridges](#) and cycles back into the mantle, usually at the margins of ocean basins (called *convergent margins* because plates converges, one subducting beneath another). The latter process is called subduction, and the regions where it happens are called subduction zones. At mid-ocean ridges, seawater penetrates the basaltic crust and converts the upper portions of the crust to an assemblage of hydrous minerals; as temperature and pressure increase during subduction, these hydrous minerals are destabilized. The released aqueous fluid triggers melting in the mantle overlying the subduction zone (the so-called mantle wedge) to yield calc-alkaline magmas and explosive volcanism producing *volcanic arcs* above subduction zones. Subducting plates correspond also to an inclined zones of earthquakes – the so-called Wadati-Benioff zone from the name of the discoverers – at the contact between the subducting plate and the overlying mantle. Evidence of past subductions are rare for the other telluric planets of our Solar system. It has

been suggested that the Tharsis rise on Mars could have been triggered by subduction of Martian crust provoked by large asteroidal impacts (Yin 2012).

Cross-References

- [Mid-Ocean Ridge](#)
- [Oceanic Crust](#)
- [Plate Tectonics](#)
- [Tharsis](#)

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Subglacial Antarctic Lake Vostok

- [Vostok, Subglacial Lake](#)

Subglacial Environments

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Subglacial is a term defining environments in a glaciated area, which lie directly beneath an ice mass and in close contact with the overlying ice. These environments include cavities and channels beneath the ice that are not influenced by subaerial processes (i.e., processes that take place in open air or adjacent to the land surface). Subglacial lakes, such as Vostok Lake in Antarctica, are subglacial environments. In astrobiology, these

environments are studied to understand how life survives in extremely cold habitats and often under suboxic conditions. Subglacial lakes seem to be present beneath the Mars' Southern Pole and possibly exist on icy moons Europa and Enceladus.

Cross-References

- [Antarctica, Natural Analogue Site](#)
- [Enceladus](#)
- [Europa](#)
- [Glaciation](#)
- [Icy Moons Chamber](#)
- [Mars](#)
- [Permafrost](#)
- [Vostok, Subglacial Lake](#)

Sublimation

Mark Dörr

University of Southern Denmark, Odense M, Denmark

Definition

Sublimation (Lat.: *sublimis* = “elevated,” “lofty”) is a special phase transition of an element or compound: the transition from a solid phase to a gas phase without intermediate liquid stage.

Sublimation is usually an ► [endothermic](#) phase transition that occurs at temperatures and pressures below the ► [triple point](#) of a substance. The opposite of *sublimation* is *deposition*. The formation of rime is an example of meteorological *deposition*, and its sudden disappearance at temperatures below the freezing point of ► [water](#) is an example of *sublimation*.

Cross-References

- [Endothermic](#)
- [Triple Point](#)
- [Water](#)

Subliths

► [Hypolithic](#)

Submarine Hot Spring

► [Black Smoker, Organic Chemistry](#)

Submillimeter Wave Astronomy Satellite

Ronald L. Snell
Department of Astronomy, 517 K Lederle
Graduate Research Center, University of
Massachusetts, Amherst, MA, USA

Synonyms

[SWAS](#)

Definition

The Submillimeter Wave Astronomy Satellite (SWAS) was a ► [NASA](#) mission dedicated to the study of interstellar chemistry. SWAS was launched in 1998 December and acquired data until 2004 July. SWAS was reactivated in 2005 June for a 3-month period to provide support for the Deep Impact mission. SWAS was comprised of a 54×68 cm off-axis Cassegrain telescope feeding two independent passively cooled heterodyne receivers. SWAS observed simultaneously the transitions of four astrophysically important species: O_2 (487.2 GHz), neutral atomic carbon (492.2 GHz), ^{13}CO (550.9 GHz), and H_2O (556.9 GHz) and it could also be tuned to observe $H_2^{18}O$ (547.7 GHz). The spectra were recorded using an Acousto-Optical Spectrometer (AOS) which provided a total bandwidth of 1400 MHz for the four lines of primary interest. Observations of over 200 targets in more than 5000 lines of

sight were obtained over its lifetime and were used to study the chemistry of interstellar molecular clouds, circumstellar envelopes of evolved stars, planetary atmospheres, and comets.

Cross-References

► [Deep Impact](#)
► [Odin](#)

Suboxic

Daniele L. Pinti
Geotop, Research centre for the dynamics of the
Earth system, Université du Québec à Montréal,
Montréal, QC, Canada

Synonyms

[Poorly oxygenated](#)

Definition

Suboxic is an adjective used for describing the oxygen concentration in the water column or any other environment (pore water, sediments, etc.) where oxygen is strongly limited and shows no perceptible vertical gradients. The boundary between hypoxic and suboxic conditions is widely taken as $10 \mu M$ of O_2 . This level probably corresponds to the biochemical threshold below which the dominant electron acceptors are oxidized species of N (nitrate, nitrite) or of metals [Mn(IV), Fe(III)], while dissolved oxygen becomes an auxiliary oxidant. Suboxic zones favor denitrification which in turn removes many essential nutrients from the water column. In astrobiology, suboxic environments are of interest because they could yield clues on the development of metabolic pathways in which oxidants were limited (e.g., nitrification/denitrification), possibly the case of stepwise oxygenating Proterozoic oceans.

Cross-References

- [Denitrification](#)
- [Electron Acceptor](#)
- [Heterotroph](#)
- [Iron Reduction](#)
- [Manganese Reduction](#)
- [Metabolism](#)
- [Methanogenesis](#)
- [Nitrogen Cycle, Biological](#)
- [Oxic](#)
- [Oxic Sediments](#)
- [Reduction](#)
- [Suboxic Sediments](#)
- [Sulfate Reduction](#)

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Suboxic Sediments

Rosalie Tostevin¹ and Simon W. Poulton²

¹Department of Earth Sciences, University of Oxford, Oxford, UK

²School of Earth and Environment, University of Leeds, Leeds, UK

Keywords

Oxygen · Redox · Diagenesis · Organic carbon · Microbes · Respiration · Pore waters

Definition

The suboxic zone lies between the oxic and anoxic zones, where the concentrations of both dissolved oxygen and sulfide are low. Sediment pore waters are generally driven to suboxic

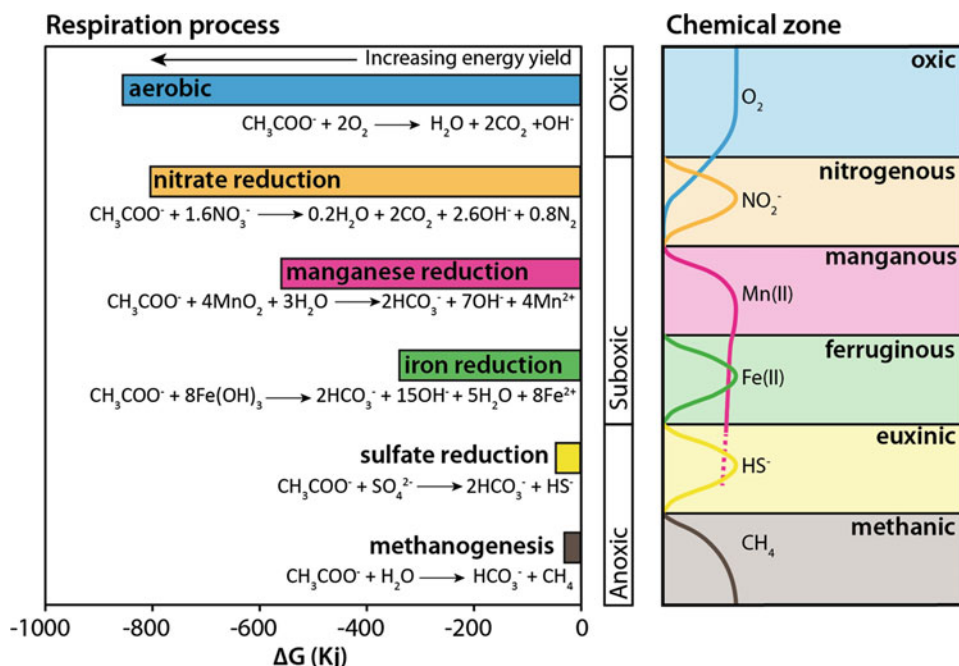
conditions via microbial degradation of organic matter, and these intermediate waters commonly host the biogeochemical cycling of nitrogen, manganese, and iron. Suboxic pore waters modify the chemistry and mineralogy of sediments between their deposition and eventual burial and represent an important component of early diagenesis.

History

A classification scheme for suboxic sediments was originally outlined by Froelich et al. (1979), based on chemical profiles of pore waters within marine sediments. These sediments were deposited below oxygenated bottom waters, but contained sufficient organic carbon to consume oxygen (via aerobic respiration) from pore waters. Froelich et al. (1979) defined suboxic sediments as those which support the reduction of nitrate, manganese, and iron before the onset of sulfate reduction and methanogenesis (Fig. 1). A later classification scheme outlined by Berner (1981) proposed the term “post-oxic” as an alternative to suboxic, and this equivalent term is sometimes seen in the literature.

The term suboxic has since become popular among biogeochemists, but is often applied rather randomly, with different intended meanings. For example, the term suboxic is sometimes used to imply low, but significant, oxygen levels (e.g., 1–10 μM , Oakley et al. 2007). However, the concentration of O_2 at which nitrate, manganese, and iron reduction occur is variable, and this O_2 range risks incorporating the process of aerobic respiration of organic matter (Christensen et al. 1989). Furthermore, iron reduction has historically been included as a suboxic process despite occurring under strictly anaerobic conditions. As such, suboxic conditions cannot be defined based on oxygen levels alone.

Another source of confusion has been the application of the term suboxic to describe sediments. This can variably refer to sediments deposited beneath suboxic bottom waters or to suboxic pore waters within the sediment pile. It is important to distinguish between these two meanings, given that with a sufficient supply of organic matter, pore waters are commonly driven to suboxic and anoxic conditions even below well-oxygenated bottom



Suboxic Sediments, Fig. 1 Generalized scheme showing the energy yield (ΔG) for each respiration processes (left) and the associated sedimentary chemical zone (right). Relative concentrations of oxidized species, such as

oxygen (in blue), and reduced metabolic products, such as nitrite (orange), Mn^{2+} (pink), Fe^{2+} (green), sulfide (yellow), and methane (brown), are shown in cartoon form on the right. (Adapted from Froelich et al. 1979)

waters. This distinction may be clarified by using the terms “sediments deposited below suboxic waters” or “suboxic pore waters.”

While geochemists use the term suboxic to refer to specific biogeochemical processes, sedimentologists commonly apply the term to describe paleoenvironments on the basis of mineral assemblages in sedimentary rocks. For example, minerals such as glauconite can indicate that oxygen was present intermittently (Berner 1981).

To ameliorate this confusion, a new scheme was outlined by Canfield and Thamdrup (2009). They proposed that the nebulous term suboxic is, where possible, replaced with a description of the individual metabolic zone, identified by its chemical signature. However, the term suboxic has persisted in the literature and can be useful when collectively referring to the biogeochemical cycling of nitrate, manganese, and iron.

Overview

The microbial oxidation of organic carbon can be coupled to the reduction of oxygen or to a series of

alternative oxidized species with lower reduction potentials, each one liberating less energy than the last. In general, microbes do not begin to respire the next species in the hierarchy until the more desirable one has been significantly depleted. This is reflected in the sediments, where pore waters become stratified into distinct chemical zones with depth.

The first alternate metabolic zone is the nitrogenous zone, which hosts nitrate reduction (or denitrification). This involves the reduction of nitrate to nitrite, which is then converted to N_2 gas or ammonia. The nitrogenous zone can be detected by the associated nitrite peak in pore waters. The second alternate metabolic zone is the manganous zone, where $\text{Mn}(\text{IV})$ oxide minerals are reduced to aqueous Mn^{2+} . The onset of manganese reduction occurs below the nitrite peak, but commonly overlaps with the base of the nitrogenous zone. In sediments, the top of the manganous zone is often marked by a distinct layer of MnO_2 , as upward-diffusing Mn^{2+} encounters nitrate or O_2 . In practice, the manganous zone is often insignificant due to the low

abundance of Mn oxide minerals in most sedimentary systems (Calvert and Pedersen 1996).

Below the manganous zone is the ferruginous zone, where Fe(III) oxide minerals are reduced to ferrous iron, Fe^{2+} . Iron reduction proceeds first with highly reactive ferric hydroxides, but as these become depleted, microbes utilize more crystalline phases such as hematite, goethite, or magnetite. Some of the Fe^{2+} generated may diffuse upward and be re-oxidized via reactions with MnO_2 , NO_3^- , or O_2 . As such, Fe^{2+} only accumulates under fully anoxic conditions.

The term suboxic is used to collectively refer to the nitrogenous, manganous, and ferruginous zones. In practice, it is often easier to identify the metabolic zone by the impact it has on pore water chemistry, rather than by detecting the activity of the responsible microbes. As such, the zones are defined by the loss of reactants, such as nitrate, or the buildup of aqueous products, such as Mn^{2+} or Fe^{2+} . Where metabolic zones overlap, the zone should be assigned according to whichever metabolic product is most abundant (Canfield and Thamdrup 2009).

The dominant microbial metabolisms and their chemical fingerprints do not always perfectly overlap. Firstly, chemical products may persist in the absence of active metabolic production. For example, Mn^{2+} removal is governed by the precipitation of Mn carbonate minerals, such as kutnohorite and rhodochrosite, and thus Mn^{2+} -enriched pore waters may persist below the zone of active production and well into the anoxic zone. The manganous zone must therefore be defined by the accumulation of Mn^{2+} in the absence of other anaerobic metabolic products. Secondly, reactions other than anaerobic respiration may produce nitrite, Mn^{2+} , or Fe^{2+} as a by-product. For example, chemolithoautotrophic bacteria may drive manganese reduction coupled to the oxidation of iron sulfide minerals. While the chemical fingerprint may be similar, Mn^{2+} buildup under these conditions is differentiated by context.

In contrast, chemical products may not be detectable despite active metabolic production. For example, sulfide produced through sulfate reduction can be rapidly oxidized by iron oxide minerals, pushing the top of the sulfidic zone to

greater depths than the onset of active sulfate reduction (e.g., Canfield et al. 1992). In this case, active sulfate reduction may either be measured directly using radiolabeled $^{35}\text{S}\text{-SO}_4$ or indirectly indicated by the formation of iron sulfide minerals (e.g., pyrite, FeS_2). Thus these metabolic processes would often go undetected using traditional geochemical techniques, and yet they play an important role in energy fluxes and elemental cycling.

Cross-References

- [Aerobic Respiration](#)
- [Bacteria](#)
- [Carbon Cycle, Biological](#)
- [Denitrification](#)
- [Diagenesis](#)
- [Dissimilative Metabolism](#)
- [Electron Acceptor](#)
- [Heterotroph](#)
- [Iron Reduction](#)
- [Manganese Reduction](#)
- [Metabolism](#)
- [Methanogenesis](#)
- [Microorganism](#)
- [Nitrogen Cycle, Biological](#)
- [Oxic](#)
- [Oxic Sediments](#)
- [Reduction](#)
- [Respiration](#)
- [Suboxic](#)
- [Sulfate Reduction](#)

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Substellar Objects

► [Brown Dwarf](#)

Substrate

Armen Y. Mulkidjanian^{1,2} and
Henderson James (Jim) Cleaves^{3,4,5}

¹School of Physics, University of Osnabrueck, Osnabrueck, Germany

²Moscow State University, Moscow, Russia

³Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

⁴Blue Marble Space Institute of Science, Washington, DC, USA

⁵Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

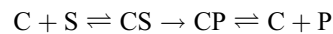
Synonyms

[Substratum](#)

Definition

In chemistry, a substrate is a substance that is acted upon by a ► [catalyst](#). The word substrate is a composite of the Latin terms *sub* “below” and *stratum* “layer.” In modern organisms, protein- or RNA-based polymers (enzymes and ribozymes, respectively) serve as catalysts that act upon various substrates, or reactants, which can be organic or inorganic. Substrates and catalysts are usually distinct entities, and depending on the reaction in question, a catalyst may react with two substrates together simultaneously or act promiscuously on various structurally related substrates.

In the case of a single substrate, the substrate binds with the enzyme or catalyst ► [active site](#), and a catalyst-substrate complex is formed. The substrate is then catalytically transformed into one or more products, which are then released from the active site.



where C is the catalyst (a surface, enzyme, ribozyme, or other species), S is the substrate (or substrates), and P is the product (or products).

In cases with more than one substrate, these may need to be bound in a particular order, before reacting together to produce products.

In the context of astrobiology, the clear discrimination between substrates and catalysts is difficult since complex catalysts such as enzymes and ribozymes were likely not present during the first stages of chemical evolution. Accordingly, the emergence of the first substrates and catalysts can be envisioned as their annealing from an initial network of diverse interactions between various small molecules.

Cross-References

- [Catalyst](#)
► [Chemical Reaction Network](#)

Keywords

Catalysis · Enzyme · Metabolite

- [Citric Acid Cycle](#)
- [Metabolism](#)
- [Organic Molecule](#)
- [Prebiotic Chemistry](#)

Substratum

- [Substrate](#)

Subsurface Biota

- [Deep Subsurface Microbiology](#)

Succinic Acid

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

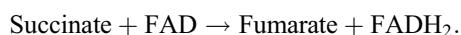
Synonyms

[Butanedioic acid](#)

Definition

Succinic acid ($\text{HOOCCH}_2\text{CH}_2\text{COOH}$) is a ► [dicarboxylic acid](#) which plays an important role in the ► [citric acid cycle](#). The name comes from Latin *succinum*, meaning amber, from which the acid was first isolated. The carboxylate anion is called succinate. Succinic acid has a melting point of 185 °C and a boiling point of 235 °C.

In the citric acid cycle, succinic acid donates electrons to FAD (flavin adenine dinucleotide) and ultimately to the electron transport chain by the reaction



This reaction is catalyzed by the enzyme succinate dehydrogenase.

Succinic acid has been produced in various prebiotic experiments and has been found in carbonaceous chondrite meteorites.

Cross-References

- [Citric Acid Cycle](#)
- [Dicarboxylic Acid](#)
- [Krebs Cycle](#)

Sudbury Impact Structure

Christian Koeberl
Department of Lithospheric Research, University
of Vienna, Vienna, Austria

Keywords

Sudbury · Impact structure · Canada

Definition

Sudbury crater is a large impact structure, originally about 200–250 km in diameter and 1.86 billion years old.

History

The almost two-billion-year-old Sudbury impact structure in Canada is one of the oldest known impact structures on Earth. Collisions and impact processes have been important throughout the history of the solar system, including that of the Earth. Small bodies in the early solar system, the planetesimals, grew through collisions, ultimately forming the planets. The Earth started growing about 4.56 billion years ago in this way. During the first several hundred million years, the Earth must have been subjected to an intense early impact flux, the (late) heavy bombardment period.

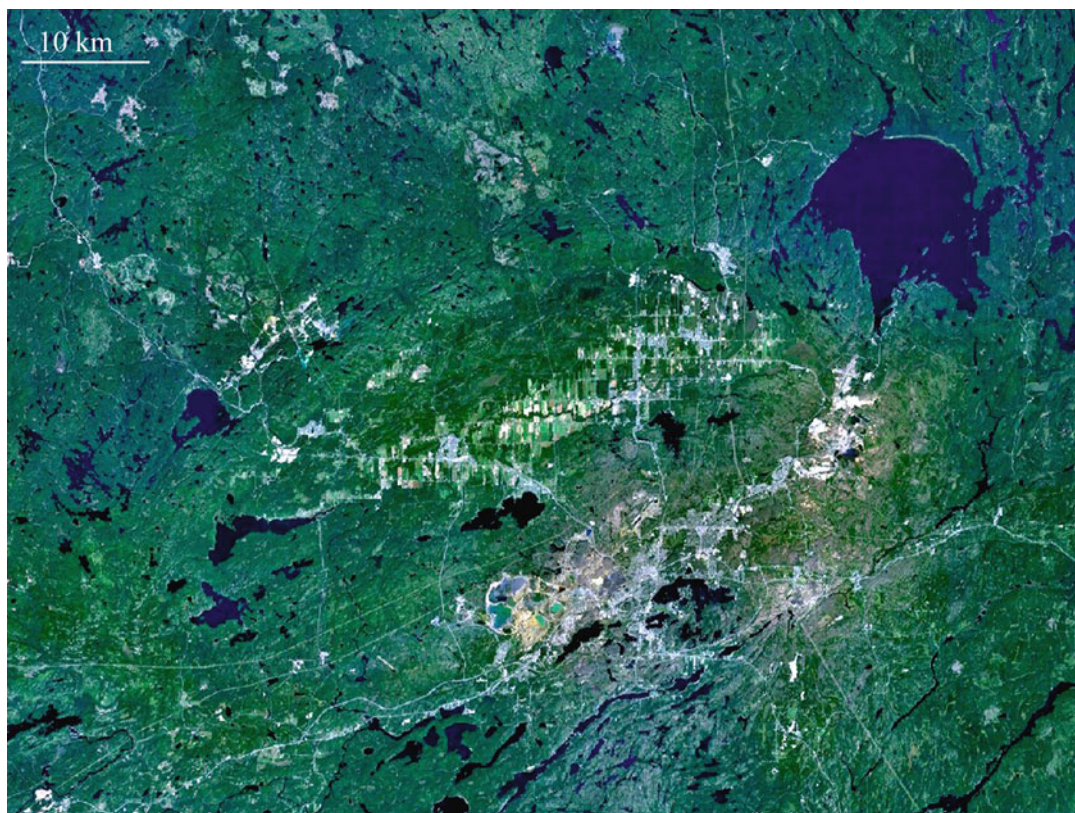
In terms of evidence for impact on Earth, the first solid evidence exists in the form of various impact-derived spherule layers found in South Africa and Australia with ages between about 3.4 and 2.5 Ga; these layers represent several (the exact number is still unknown) large-scale impact events. The oldest documented (and preserved) impact structures on Earth have ages of 2.23, 2.02 and 1.85 billion years. Thus, the impact record for more than half of the geological history of the Earth is incomplete and not well preserved, and we mostly have only indirect evidence regarding the impact record and its effects during the first 2.5 billion years of Earth history.

Overview

The currently visible structure is deeply eroded and highly deformed (Fig. 1). The term Sudbury

Structure collectively refers to the brecciated country rocks of the Superior and Southern provinces of the Canadian Shield in the environs of the Sudbury Igneous Complex, the SIC with its ore deposits, and the interior Sudbury Basin. Its origin has been debated for more than 100 years since its discovery in the late nineteenth century. An impact origin for Sudbury was first proposed in 1962, and confirmed by Dietz (1964) from the presence of shatter cones (see also Fig. 2). Later, microscopic planar deformation features (PDFs) were found in quartz in clasts of the Onaping Formation; such microstructures are unambiguous evidence of shock metamorphism and thus an origin by impact.

World-class Ni-Cu sulphide deposits, also containing noteworthy platinum group metal mineralization, are associated with the Sudbury Igneous Complex (SIC) in the central part of the Sudbury Structure (e.g., papers in Pye et al.



Sudbury Impact Structure, Fig. 1 The kidney-shaped Sudbury Basin, the eroded and highly deformed remnant of the Sudbury impact structure, is visible in the center of

the image, whereas on the upper right the (much younger) Lake Wanapitei impact structure can be seen (NASA Landsat image, Wikipedia, public domain)



Sudbury Impact Structure, Fig. 2 Shatter cones within the Sudbury impact structure; such features are uniquely characteristic of shock metamorphic processes and thus confirm an impact origin of the structure (image width ca. 50 cm; photo: C. Koeberl 2003)

1984; Naldrett 2003). The SIC is ca. 2.5 km thick and forms an elliptical body of about 27×60 km extent. The entire Sudbury Structure covers a much larger area, of some 15,000 km². This includes, besides the SIC, the fractured, brecciated, and shocked footwall rocks of the structure, namely the Archean basement to the north and east of the SIC, and the supracrustal rocks of the Proterozoic Huronian Supergroup south of the SIC, and the impact breccias, mudstones, and graywackes of the Whitewater Group in the Sudbury Basin, overlying the SIC (e.g., Dressler et al. 1991). The original diameter of the Sudbury impact structure, before deformation, has been estimated at around 200–250 km, making it the second largest currently known impact structure on Earth. For economic reasons, the SIC has been the focus of much of the past investigations in the Sudbury Structure (cf. Reimold et al. 2005). The Ni and other related mineralizations are of terrestrial

origin, and at least in the mineralized samples, no chemical or isotopic traces of the asteroid were found. Only from siderophile element (including platinum group elements, PGEs) analyses of samples from the Onaping Formation did Petrus et al. (2015) find evidence for an ordinary or enstatite chondrite as the most probable source of meteoritic material in the Sudbury crater fill.

Ejecta from the Sudbury impact were only recently discovered. A small number of studies have examined ejecta from the impact; for example, Addison et al. (2005) first described the ejecta and constrained the age of the deposits, and Cannon et al. (2010) examined a variety of known sites across Michigan, the USA, examining geochemistry and petrography, whereas Huber et al. (2014) found elevated abundances of PGEs from three sites and examined the detailed petrography of melts in the ejecta, confirming indications of evidence of a possible chondritic component in the ejecta. Chromium-isotope data on Sudbury ejecta record a complex meteoritic signature that could indicate the impact of a heterogeneous chondritic body (Mougel et al. 2017).

Meteorite impact-generated accretionary lapilli are not well studied. (Accretionary lapilli are millimeter- to centimeter-sized objects that are usually known from volcanic eruptions, where rounded pellets form by the accretion of ash or dust around moisture droplets, and they often show concentric rings; similar objects can also form in impact ejecta clouds.) The recently discovered distal ejecta from the 1850 Ma Sudbury impact event contain abundant accretionary lapilli generated during the impact and deposited at great distances from the crater. Huber and Koeberl (2017) petrographically and geochemically examined lapilli from five sites (McClure; Connors Creek; Hwy 588; Pine River; and Grand Trunk Pacific, ca. 480–750 km from the center of the Sudbury structure). In these studies, it was found that the compositions of quartz, K-feldspar, calcite, biotite, and chlorite minerals are similar to each other in all of the samples, although the relative proportions of the minerals vary from site to site. The lapilli occur in a matrix of coarse-grained quartz, carbonate, and feldspar grains. Zonation within lapilli appears to be due to grain size distribution rather than compositional

variation. The inner zones are coarser grained than outer zones. The relative abundances of calcite, phyllosilicates, and feldspars are similar in each zone within individual lapilli. The presence of a meteoritic component is indicated by up to 1.8 ppb Ir in one lapillus from the Pine River site; in addition, for many of the lapilli Ni to Cr ratios plot on a chondritic trendline. Current mechanisms previously proposed for the formation of accretionary lapilli during an impact event seem somewhat inadequate to explain deposition of distal accretionary lapilli resulting from impact events. A new mechanism for upper atmospheric accretion is proposed, whereby ash ejected from impact events concentrates at altitudes of neutral buoyancy, where it then accretes and is deposited later than ballistically emplaced particles. It is likely that a variety of different processes operated in the chaotic postimpact environment. Similar accretionary lapilli as in Sudbury are rare among impacts on Earth and thus deserve further study. Also, the ejecta may offer a better way to constrain the nature of the impacting body, rather than the (altered) fallback breccia within the structure.

Recently, carbon-rich microfossils were discovered in the breccias of the Onaping Formation, Sudbury impact structure; this suggests the presence of a previously unknown complex algal flora that inhabited the preimpact sea before the impact event 1.85 billion years ago at the very end of the Paleoproterozoic (Gurov et al. 2020).

Cross-References

- [Crater, Impact](#)
- [Impact Basin](#)
- [Impact Melt Rock](#)

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Suevite

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montreal, QC, Canada

Synonyms

[Mixed breccia](#); [Suevite breccia](#); [Suevitic impact breccia](#)

Definition

A suevite or suevite breccia refers to a polymictic impact breccia with clastic matrix and mineral clasts, unshocked or in various stages of shock metamorphism, including cogenetic glassy or crystallized impact melt particles. The clasts represent the composition of the target lithologies. Initially identified in the Ries crater (Germany), it is now a generalized term commonly used to describe brecciated rocks (impactites) produced by meteorite impacts and found in several other structures, worldwide. Suevite can occur within the crater or as proximal ejecta surrounding the structure.

Cross-References

- [Crater, Impact](#)
- [Impact Basin](#)
- [Impact Melt Rock](#)
- [Impactite](#)
- [Monomictic Breccia](#)
- [Polymictic Breccia](#)

Suevite Breccia

- [Suevite](#)

Suevitic Impact Breccia

- [Suevite](#)

Sulcus, Sulci

Roland J. Wagner
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Synonyms

[Groove](#)

Definition

Sulci are surface features found on ► [Mars](#) and on icy satellites in the outer ► [Solar System](#). Sulci are subparallel grooves and ridges, generally within a structural unit that can be bounded by a major trough. On ► [Ganymede](#) (► [Jupiter](#)), numerous parallel grooves form the so-called grooved terrain on this satellite. Other icy satellites featuring sulci are ► [Enceladus](#) (► [Saturn](#)), ► [Miranda](#) (► [Uranus](#)), and ► [Triton](#) (► [Neptune](#)). Sulci are created by extensional tectonism, involving a brittle-ductile transition at comparably shallow depths (order of a few kilometers) in icy satellites.

Cross-References

- [Chasma, Chasmata](#)
- [Enceladus](#)
- [Fossa, Fossae](#)
- [Ganymede](#)
- [Jupiter](#)
- [Mars](#)
- [Miranda](#)
- [Neptune](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Solar System, Inner](#)
- [Triton](#)
- [Uranus](#)

Sulfaniumylidene

- [Sulfur Hydrides in the Interstellar Medium](#)

Sulfanyl

- [Sulfur Hydrides in the Interstellar Medium](#)

Sulfanylium

- [Sulfur Hydrides in the Interstellar Medium](#)

Sulfate Minerals

Nicholas Arndt

Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

Definition

Sulfates are a class of minerals which include the sulfate ion SO_4^{2-} within their structure. Sulfate minerals occur in evaporitic environments, in hydrothermal veins, and as secondary minerals in the oxidizing zone of sulfide mineral deposits. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4) are common minerals in evaporitic environments; barite (BaSO_4) precipitates from hydrothermal fluids; and anglesite (PbSO_4) is an alteration product of lead sulfide ores. The identification of ► [jarosite](#), a potassium iron sulfate hydroxide, magnesium sulfates, and possible relicts of gypsum at the Meridiani Planum landing site on ► [Mars](#) is suggested to be evidence of wet, oxidizing conditions in the early history of the red planet.

Cross-References

- [Jarosite](#)
- [Mars](#)

Sulfate Reducers

Felipe Gomez

Centro de Astrobiología (CSIC/INTA), Instituto Nacional de Técnica Aeroespacial, Madrid, Spain

Synonyms

[SRB](#)

Definition

Sulfate reducers are prokaryotic microorganisms that are able to reduce sulfate or partially oxidized

sulfur compounds, such as sulfite and thiosulfate, in a non-assimilatory manner in order to obtain energy through ► [anaerobic respiration](#). Sulfate reducers couple the oxidation of propionate, butyrate, lactate, and ethanol among other electron donors with the reduction of sulfate to sulfide. They are obligate anaerobes and include heterotrophs as well as autotrophs. The best known are Gram-negative bacteria, but *Desulfotomaculum* is a Gram-positive spore-forming sulfate-reducer genera closely related to *Clostridium*. There is a phylum which includes thermophilic sulfate reducers, including Thermodesulfobacteria. Different archaea, e.g., *Archaeoglobus*, are able to use sulfate as an ► [electron acceptor](#) for anaerobic respiration. Sulfate-reducing microorganisms are fundamental elements of the sulfur cycle.

Cross-References

- [Anaerobic Respiration](#)
- [Biogeochemical Cycles](#)
- [Electron Acceptor](#)
- [Energy Conservation](#)
- [Respiration](#)
- [Sulfur Cycle](#)

Sulfate Reduction

Maya Gomes¹, William Leavitt² and Derek Smith³

¹Johns Hopkins University, Baltimore, MD, USA

²Dartmouth College, Hanover, NH, USA

³Case Western Reserve University, Cleveland, OH, USA

Keywords

Anaerobic respiration · Organic matter remineralization · Sulfur isotope effects · Anaerobic oxidation of methane

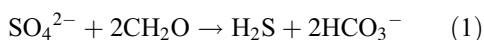
Definition

Sulfate reduction is a redox reaction in which the divalent anion sulfate (SO_4^{2-}) is reduced to

sulfide (S^{2-}) following the addition of eight electrons. This reaction can be coupled to the oxidation of other chemical species including a variety of organic compounds (e.g., acetate, pyruvate, methane) or inorganic compounds such as hydrogen (H_2). It is an important diagenetic process that oxidizes organic carbon generated by photosynthesis. Therefore, sulfate reduction is essential to regulating oxidant budgets in Earth's oceans and sediments. Sulfate reduction is one of the oldest metabolisms identifiable in the geological record as indicated by sulfur isotope signatures in sulfate- and sulfide-bearing minerals from Archean-aged rocks (see review in Fike et al. 2015).

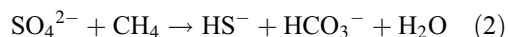
Overview

Microbial sulfate reduction (MSR) is a form of energy metabolism catalyzed by members of the Archaeal and Bacterial domains of life (Pereira et al. 2011; Rabus et al. 2013). The reaction can be summarized as:



MSR is thermodynamically less favorable than other anoxic energy metabolisms that use terminal electron acceptors such as nitrate, manganese, or iron oxides. Nonetheless, approximately half of the organic matter in shallow marine sediments is oxidized back to inorganic carbon through sulfate reduction (Jorgensen 1982). This is due, in part, to the abundance of sulfate in seawater, where it holds thirteen times the oxidizing capacity of all oxygen in the atmosphere (Hayes and Waldbauer 2006). MSR can also be coupled to the anaerobic oxidation of methane (AOM) via a process catalyzed by communities of anaerobic

methanotrophic archaea and sulfate-reducing *Deltaproteobacteria*:



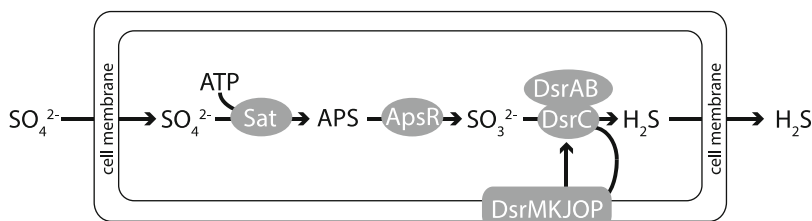
The AOM coupled to MSR was first observed at the sulfate-methane transition zone in marine sediments but has since been found in freshwater systems (see review in Knittel and Boetius 2009). MSR coupled to the AOM consumes approximately 90% of methane in diffusive marine sediments. Although MSR primarily occurs in anoxic environments, sulfate-reducing microbes have been found in oxic environments where rapid reoxidation of sulfide inhibits its accumulation. This so-called “cryptic” sulfur cycling is thought to play a role in fixed nitrogen loss from the ocean (Canfield et al. 2010; Johnston et al. 2014). In addition to being a major component of the sulfur cycle, sulfate reduction plays a key role in the global carbon, oxygen, nitrogen, iron, and other nutrient and element cycles.

Abiotic sulfate reduction to sulfide is kinetically inhibited at the low temperatures of Earth's surface conditions. As such, sulfate reduction is normally catalyzed by microorganisms using a reaction network with four key enzymatic steps (Fig. 1). The import of sulfate into the cell is the first step. This is done by sulfate transporters that operate as symporters transferring sulfate into the cytoplasm along with cations; the latter are generally protons in freshwater and sodium ions in seawater (Cypionka 1995). The second step is the activation of sulfate to an unstable intermediate adenylyl 5'-phosphosulfate (APS) by the enzyme sulfate adenylyl transferase (Sat, EC 2.7.7.4, also called ATP sulfurylase). Sulfate activation to APS requires energy derived from one molecule of adenosine triphosphate (ATP) per sulfate. The third step is the reduction of APS to sulfite

S

Sulfate Reduction,

Fig. 1 Schematic of the microbially mediated sulfate reduction pathway. All steps in the pathway are reversible. See text for definition of acronyms



(SO_3^{2-}) by adenylyl-sulfate reductase (ApsR, EC 1.8.992., also called APS reductase). The details of the final step, the reduction of sulfite to sulfide, have been the subject of much debate (see reviews by Bradley et al. 2011 and Rabus et al. 2013). Initial models invoked either a stepwise reduction of sulfite to sulfide through intermediates trithionate ($\text{S}_3\text{O}_6^{2-}$) and thiosulfate ($\text{S}_2\text{O}_3^{2-}$) or a direct six-electron reduction of sulfite to sulfide (Harrison and Thode 1958; Peck 1962). Recent work demonstrates that the reduction of sulfite to sulfide is carried out by dissimilatory sulfite reductase (Dsr), which is a multi-subunit enzyme consisting of DsrA and DsrB with the assistance of a separate sulfur transfer protein, DsrC (Santos et al. 2015). In this model, DsrAB reduces sulfite with two electrons where S^0 is bound to a reduced DsrC. After DsrC-bound S^0 dissociates from the DsrAB, the reduced cysteines of DsrC donate electrons to form a DsrC-trisulfide complex. Finally, the DsrC-trisulfide reacts with the membrane-bound DsrMKJOP complex, receiving the final two electrons, releasing H_2S , and re-reducing DsrC. These final steps of DsrC scavenging S from DsrAB and the reaction with DsrMKJOP were only recently recognized and complete core biochemistry of MSR (Santos et al. 2015). The reaction with DsrC/DsrMKJOP couples terminal sulfide production to membrane-bound electron transport and, critically, energy conservation.

The fractionation of sulfur isotopes during microbial sulfate reduction influences sulfur isotope signatures of sulfate and sulfide in both open marine and sediment pore waters. Those isotopic signatures can then be preserved in sulfate and sulfide minerals that are used in global biogeochemical models to reconstruct atmospheric O_2 levels (e.g., Kump and Garrels 1986) or environmental change (e.g., Leavitt et al. 2013) throughout Earth history. Sulfur isotopes are expressed in delta notation ($\delta^{34}\text{S}$) as permil (‰) deviations in the ratio of ^{34}S to ^{32}S from the Vienna-Canyon Diablo Troilite standard. The theoretical equilibrium sulfur isotope fractionation between sulfate and sulfide is approximately 70‰ at 25 °C (Farquhar et al. 2003). Fractionations approaching this limit have been observed

experimentally in batch and continuous cultures of sulfate-reducing bacteria grown at very slow sulfate reduction rates (Sim et al. 2011; Leavitt et al. 2013). Several models have been proposed to explain these fractionations (reviewed in Bradley et al. 2016). Each of these models suggests that critical parameters affecting fractionation include ambient sulfate and sulfide concentrations, cell-specific sulfate reduction rate, and the reversibility in each step of the sulfate reduction pathway. Although the general trend is that sulfur isotope fractionation is inversely related to sulfate reduction rate, transport processes (e.g., Chanton et al. 1987) and reservoir effects (e.g., Gomes and Hurtgen 2013) also influence the offset between $\delta^{34}\text{S}$ values of sulfate and sulfide minerals (i.e., barite or calcium-sulfate minerals and pyrite, respectively) because they determine if $\delta^{34}\text{S}$ patterns can be described by open-system versus closed-system models (i.e., Rayleigh fractionation). Open-system models, which favor full expression of biological sulfur isotope fractionations, are more appropriate for low-oxygen, anoxic, or euxinic settings because the sulfate reservoir is more likely to be well-mixed. Well-oxygenated settings where sulfate reduction occurs deep in the sediment are more similar to closed-systems, where progressive consumption of the sulfate reservoir inhibits the expression of biological sulfur isotope fractionation. Thus, sulfur isotope signatures can be used to investigate sulfur cycling processes in modern and ancient settings.

The sedimentary record of sulfate reduction extends through the majority of Earth history and tracks the oxygenation of its surface environments. The earliest evidence for sulfate reduction comes from $\delta^{34}\text{S}$ values of microscopic pyrite grains, which are 21‰ lower than associated barites from the 3.5 Ga Dresser Formation of the Warrawoona Group, Pilbara Craton (AU) (Shen et al. 2001). This 21‰ fractionation is consistent with high rates of microbial sulfate reduction, given the low temperature origin of these sediments and intimate association of pyrite grains with organic carbon. Despite this early evidence for microbial sulfate reduction, $\delta^{34}\text{S}$ variability of sulfides extracted from bulk sedimentary rocks is

mutated to below 10‰ for the majority of the Archean (Canfield and Farquhar 2009), although individual pyrite grains have larger $\delta^{34}\text{S}$ variability (e.g., Fischer et al. 2014). After the Great Oxidation Event at ~2.4 Ga, increasing marine sulfate concentrations led to an increase in the range of sedimentary sulfide $\delta^{34}\text{S}$ values of up to ~50‰ because the reservoir effect no longer limited preserved fractionation values. Contemporaneous with increased oxygenation, a second rise in the range of sedimentary sulfide $\delta^{34}\text{S}$ values to >70‰ is recorded in the late Neoproterozoic (see Lyons et al. 2014 for a review).

In summary, sulfate reduction is a ubiquitous microbially mediated process in marine and freshwater systems where the reduction of sulfate to sulfide is coupled to the oxidation of organic matter, hydrogen, or methane. Sulfate reduction plays an important role in the global biogeochemical cycles of sulfur, carbon, and oxygen on Earth now and over billions of years and therefore may also play an important role in these cycles on other Earth-like planets.

Cross-References

- [Anaerobic Respiration](#)
- [Methane Oxidation](#)

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Sulfates, Extraterrestrial

Daniela Tirsch

German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

Definition

Expression used for hydrated ► [minerals](#) that have been developed through the reaction of sulfuric acid with metal ions (Salt of Sulfuric Acid, containing the sulfate ion SO_4^{2-}). These minerals primarily form in thick sedimentary beds by evaporation of ► [water](#), in hydrothermal environments or as secondary minerals by the oxidation of sulfide minerals. The detection of sulfates on planets implies an acidic environment and the existence of liquid water at the time of mineral formation, but does not necessarily imply the long-term availability of liquid water. Typical sulfates found on ► [Mars](#) are, for example, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) and jarosite ($\text{KFe}^{3+}_3(\text{SO}_4)_2(\text{OH})_6$). Typical sulfate detections on ► [Mars](#) are reported from Meridiani ► [Planum](#) and the Interior Layered Deposits at the ► [Valles Marineris](#).

Cross-References

- [Carbonate, Extraterrestrial](#)
- [Mars](#)
- [Mineral](#)
- [Phyllosilicates, Extraterrestrial](#)
- [Water](#)

Sulfide Oxidation

Gordon Southam

The University of Queensland, St. Lucia, QLD, Australia

Keywords

Acidophiles · Lithotroph · Phototroph · Sulfate · Weathering

Synonyms

[Biooxidation of sulfur](#)

Chemical Formula



Acronyms

S_{ox}

Definition

The biooxidation of sulfur concerns the biological (enzymatic) pathway that extracts energy from chemically reduced forms of sulfur, typically producing sulfate as a by-product of metabolism.

History

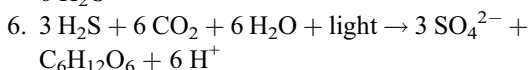
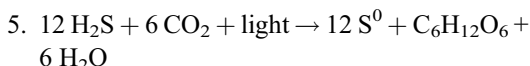
The biooxidation of sulfide was first demonstrated by Winogradsky (1887), who fed a culture of *Beggiatoa* with H_2S , demonstrating the formation of elemental sulfur granules. Nathansohn (1902) first isolated a member of the bacterial genus *Thiobacillus*, noted for its ability to oxidize elemental sulfur, which was followed by Waksman and Joffe (1921) who isolated *Thiobacillus*

thiooxidans, an acidophilic sulfur-oxidizing bacterium.

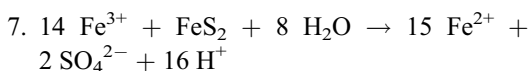
Overview

The oxidation of sulfur can proceed through a range of potentially complex biogeochemical and abiotic reaction pathways (Schmidt et al. 1987). For example, the biogeochemical oxidation pathway for “sulfur,” producing sulfate, can begin with diverse substrates, including hydrogen sulfide (H_2S ; link to *Sulfate reduction*), elemental sulfur (S^0), thiosulfate ($\text{S}_2\text{O}_3^{2-}$), and tetrathionate ($\text{S}_4\text{O}_6^{2-}$) (see reactions 1–4). In these reactions, the production of sulfate reflects the complete oxidation of each substrate, where all of the available energy has been “extracted.” While sulfur oxidation is most active under aerobic conditions (Knickerbocker et al. 2000), phototrophic purple and green sulfur bacteria can oxidize H_2S to S^0 or SO_4^{2-} (reactions 5 and 6) under anaerobic conditions via anoxygenic photosynthesis (Pfennig 1975; link to *Anaerobic photosynthesis*). They can also utilize other reduced sulfur compounds such as thiosulfate and sulfite.

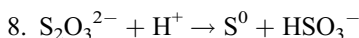
1. $\text{H}_2\text{S} + \frac{1}{2} \text{O}_2 \rightarrow \text{S}^0 + \text{H}_2\text{O}$
2. $\text{S}^0 + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{SO}_4^{2-} + 2 \text{H}^+$
3. $\text{S}_2\text{O}_3^{2-} + 2 \text{O}_2 + \text{H}_2\text{O} \rightarrow 2 \text{SO}_4^{2-} + 2 \text{H}^+$
4. $\text{S}_4\text{O}_6^{2-} + 3\frac{1}{2} \text{O}_2 + 3 \text{H}_2\text{O} \rightarrow 4 \text{SO}_4^{2-} + 6 \text{H}^+$



The biooxidation of sulfur does not necessarily proceed through the direct oxidation pathways seen and can be closely linked to sulfur reduction under “aerobic” (Norlund et al. 2009) and anaerobic conditions (Pfennig 1975). The oxidation of sulfur can also occur chemically via ferric iron oxidation, catalyzing the formation of sulfate via an abiotic mechanism (reaction 7), with the biogeochemical oxidation of iron (link to *Iron oxidation*) accelerating this reaction (Singer and Stumm 1970).



This summary reaction, transferring 14 electrons from pyrite- (FeS_2) producing sulfate as a by-product, ignores the diverse sulfur intermediates, for example, thiosulfate, in this acid system. Under acid conditions, the biooxidation of sulfur is further complicated by additional abiotic processes, for example, the disproportionation of thiosulfate into elemental sulfur and sulfurous acid (reaction 8).



Sulfide Oxidation, Fig. 1 Photographs of the Rio Tinto River, Spain (a), and Basque Lake #2 Canada (b) highlight the presence of jarosite ($\text{KFe}_3(\text{OH})_6(\text{SO}_4)_2$; see Loiselle et al. 2018; link to *Iron oxidation, Rio Tinto*) and epsomite

($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$; see Foster et al. 2010), respectively, two sulfate-bearing minerals that can entrap bacteria on Earth, making them prime targets in the search for inorganic and organic, extraterrestrial biomarkers

In addition to the production of a range of aqueous and solid (elemental) sulfur intermediates, there are a wide range of sulfate minerals such as jarosite, formed under acid conditions, and epsomite, which is found in weathered terrains where the acid from sulfur oxidation (reactions 2–4) has been buffered by ultramafic materials, releasing magnesium (Mg^{2+}) (Fig. 1).

From an astrobiology perspective, differentiating between these biotic versus abiotic processes is critical to identifying the biological contributions to these reactions and to the search for life beyond Earth. Sulfate is a particularly important target given the high sulfate content (~10–15%) of Martian soil (Clark et al. 1976). The formation of sulfate minerals during bacterial colonization of meteorites on Earth (Tait et al. 2017) raises interesting questions about the potential for these materials on Mars.

Cross-References

- [Anaerobic Photosynthesis](#)
- [Iron Oxidation](#)
- [Rio Tinto](#)
- [Sulfate Reduction](#)

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Sulfidic Oceans

Donald E. Canfield
Institute of Biology, University of Southern
Denmark, Odense, Denmark

Keywords

Anoxic · Chemocline · Nitrogen fixation ·
Oxygen minimum zone · Sulfate reduction ·
Sulfide

Synonyms

[Anoxic ocean](#); [Euxinic ocean](#)

Definition

A sulfidic ocean defines a condition where dissolved sulfide is found stably in measurable concentrations within the marine water column. Such waters contain no dissolved oxygen but are typically found below the oxygen-containing region of the upper water column. Dissolved sulfide may or may not extend to the seafloor.

Overview

Sulfidic water-column conditions are found in permanently stratified basins such as the Black Sea and the Cariaco Basin, and in numerous stratified fjords and other coastal embayments. Examples include Mariager Fjord in Denmark, Saanich Inlet in the USA, and Byfjorden in Sweden. Sulfide also accumulates in deep depressions such as the Gotland Deep in the Baltic Sea. Sulfide accumulates when the flux of oxygen by advection and diffusion is outpaced by the flux of reactive organic carbon from sinking marine biomass. The oxidation of the reactive carbon consumes all the oxygen and then the available nitrate, after which sulfate reduction ensues producing sulfide. Sulfide reacts with available iron oxides, and sulfide accumulates when the iron oxides are consumed. Although a rare condition today, if there is insufficient sulfide to consume the reactive iron oxides, dissolved ferrous iron may accumulate creating ferruginous water column conditions. Sulfidic conditions are often associated with enhanced water-column stratification, as this limits the oxygen flux.

While they are oxygen-free and thermally stratified, sulfide is rare in oxygen minimum zones of the global ocean. This is due to a feedback loop involving the nitrogen cycle. This feedback loop checks the microbial loss of nitrate to N_2 gas in the oxygen-free waters, maintaining the waters nitrate-rich and sulfide-free. Sulfide can accumulate if ► [nitrogen fixation](#) (microbial conversion of N_2 to organic nitrogen) balances the loss of nitrate to N_2 , but for reasons not well understood, nitrogen fixation is limited in these regions.

Sulfidic ocean conditions were very rare or absent in the distant geologic past when the Earth's atmosphere was anoxic. With no oxygen, mineral sulfides were not oxidized to sulfate on land, limiting the delivery of sulfate to the oceans and thereby limiting sulfate reduction in the oceans. The earliest reported sulfidic marine water column was 2.5 billion years ago in association with an early rise in atmospheric oxygen concentrations. Sulfidic water column conditions became more prevalent after this and from about

1.8 to about 1.0 billion years ago, sulfidic waters were not uncommon, sharing marine anoxic waters with ferruginous conditions. For reason not well understood, sulfidic marine waters became rare in the time window of about 1.0–0.55 billion years ago when marine anoxic waters were dominantly ferruginous.

Over the last 550 million years, anoxic marine waters were far more often sulfidic than ferruginous, likely due to a rise in seawater sulfate concentrations driving more sulfate reduction under anoxic water column conditions. Overall, however, marine anoxia has been less extensive over the last 550 million years likely due to elevated atmospheric oxygen levels. Still, major episodes of water column sulfide accumulation have been documented from sedimentary rocks throughout this period, and at least during some periods of time, sulfidic conditions were much more extensive than today. The frequency and intensity of water column sulfide accumulation over the last 550 million years have likely resulted from an interplay between atmospheric oxygen levels, paleogeography, and climate.

Cross-References

- [Anoxic Ocean](#)
- [Archaea](#)
- [Denitrification](#)
- [Nitrogen Fixation](#)
- [Precambrian](#)
- [Sulfate Reducers](#)

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Sulfur

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Keywords

Sulfide · Sulfate

Synonyms

Sulphur

Chemical Formula

S

Definition

Sulfur is a chemical element with the atomic number 16 denoted by the symbol S. It is a naturally

abundant, multivalent nonmetal. In its native form, at room temperature and pressure, sulfur is a soft bright yellow crystalline solid. In nature, it can be found as the pure element and in the form of sulfide and sulfate minerals. It is found in two of the coded protein amino acids: ► [cysteine](#) and ► [methionine](#).

Overview

The strong smell of sulfur is usually due to the presence of ► [hydrogen sulfide](#) (H₂S) or organosulfur compounds. Elemental sulfur is fairly insoluble in water. Common oxidation states of sulfur include −2, +2, +4, and +6. Sulfur forms stable compounds with most elements. Sulfur forms more than 30 solid allotropes, more than any other element. Besides S₈, several other rings are known. Elemental sulfur is an equilibrium mixture of S₈, S₇, and small amounts of S₆.

Sulfur is unusual in that its viscosity in its molten state, unlike most other liquids, increases above temperatures of 200 °C (392 °F) due to the formation of polymers. Molten elemental sulfur is dark red above this temperature. At higher temperatures, its viscosity decreases as depolymerization occurs. The distinctive colors of Jupiter's volcanic moon, Io, are from various forms of molten, solid, and gaseous sulfur.

Sulfur has 25 known isotopes, 4 of which are stable – ³²S, ³³S, ³⁴S, and ³⁶S – with natural terrestrial abundances of 95.02%, 0.75%, 4.21%, and 0.02%, respectively. Aside from ³⁵S, all of the radioactive isotopes of sulfur are short-lived.

Common naturally occurring sulfur compounds include sulfide minerals such as pyrite (iron sulfide, FeS), galena (lead sulfide, PbS), and sphalerite (zinc sulfide, ZnS), and sulfate minerals, such as gypsum (calcium sulfate, CaSO₄ · H₂O) and barite (barium sulfate, BaSO₄). Sulfur occurs naturally in volcanic emissions.

Sulfur is present in many types of meteorites. Ordinary chondrites contain an average of 2.1% sulfur, and carbonaceous chondrites may contain

as much as 6.6% sulfur. Sulfur in meteorites is normally present as troilite (FeS), but other sulfides are found in some meteorites, and carbonaceous chondrites contain free sulfur, sulfates, and possibly other sulfur compounds, including organosulfonates.

Sulfur is created in extremely large, extremely hot (nuclear temperature over 2.5 billion kelvin) stars, by the fusion of silicon with helium.

Organosulfur compounds include thioethers (with the generic formula $R - S - R$), thiols (also known as mercaptans, with the generic formula $R - SH$), thiolates (the conjugate bases of thiols, with the generic formula $R - S^-$), sulfoxides (with the generic formula $R - S(=O) - R'$), and sulfones (with the generic formula that has the form $R - S(=O)_2 - R'$).

Many organisms are able to use sulfur in its various redox states as a source of energy. Some bacteria use hydrogen sulfide (H_2S) in the place of water as an electron donor in the form of photosynthesis in which oxygen is the electron acceptor. The photosynthetic green and purple sulfur bacteria use elemental oxygen to oxidize hydrogen sulfide to elemental sulfur. Some bacteria which live around deep-sea hydrothermal vents oxidize hydrogen sulfide in this way. Sulfur bacteria use sulfate as an electron acceptor instead of oxygen and reduce various oxidized sulfur compounds to sulfides.

There are numerous sulfur-containing metabolites which are important in biochemistry, most notably the protein amino acids methionine and cysteine. Glutathione is an important sulfur-containing compound which plays a cellular role as a source of reduction potential. Several coenzymes have $-SH$ moieties to handle reactions involving acyl-containing biochemicals, for example, coenzyme A and alpha-lipoic acid.

Some theoretical models for the origin of life have emphasized the role of sulfur compounds, for example de Duve's thioesters, with a role in an early energy transduction mechanism, or the anaerobic synthesis of pyrite from hydrogen sulfide and ferrous sulfide as the earliest source of energy and electron in primitive metabolisms as postulated by Wächtershäuser.

Cross-References

- ▶ [Anaerobic Respiration](#)
- ▶ [Biogeochemical Cycles](#)
- ▶ [Cysteine](#)
- ▶ [Disulfide Bond](#)
- ▶ [Green Bacteria](#)
- ▶ [Hydrogen Sulfide](#)
- ▶ [Hydrothermal Vent Origin of Life Models](#)
- ▶ [Methionine](#)
- ▶ [Sulfate Reducers](#)
- ▶ [Sulfates, Extraterrestrial](#)
- ▶ [Sulfidic Oceans](#)
- ▶ [Sulfur Cycle](#)
- ▶ [Sulfur Isotopes](#)
- ▶ [Sulfur Monoxide \(SO\)](#)
- ▶ [Thioester](#)
- ▶ [Thioformaldehyde \(\$H_2CS\$ \)](#)
- ▶ [Thiol](#)

Sulfur Chemistry

Romane Le Gal

Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

Keywords

Molecular astrophysics · Astrochemistry · Interstellar molecules · Interstellar medium · Protostars · Proto-planetary disks · Solar system · Planetary systems · Abundances · Radio-astronomy · Numerical methods

Chemical Formula

S

Definition

Sulfur is the tenth most abundant element in our local universe. As of today, ~35 different sulfur-bearing species have been observed in space, from

Sulfur Chemistry, Table 1 S-bearing species detected in space and comets so far (not including isotopologues)

1 atom	2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	> 6 atoms
S	CS	H ₂ S	H ₂ CS	HC ₃ S ⁺	CH ₃ SH	CH ₃ CH ₂ SH
S ⁺	SO	OCS	HNCS	H ₂ CCCS	C ₅ S	
	SO ⁺	SO ₂	HSCN	C ₄ S	H ₂ CCCS	
	SH	C ₂ S	C ₃ S			
	SH ⁺	S ₂ H	S ₄			
	SiS	HCS ⁺	HCCS			
	NS	HCS				
	NS ⁺	HSC				
	S ₂	S ₃				
		NCS				
		CS ₂				

atomic S up to 9 atom molecules (CH₃CH₂SH) (see Table 1). They are routinely observed in a wide variety of astrophysical objects from extragalactic sources to our own solar system. Commonly used to constrain the physical conditions of the environment in which they thrive, the S-chemistry also plays an important role in the formation of life building blocks (Chen et al. 2015) and planet habitability (Ranjan et al. 2018; Ruf et al. 2019). Sulfur is thus an important element linking the physics, the chemistry, and ultimately the biology of its environment.

Overview

Despite all the astronomical observations of sulfur-bearing species, the chemistry of sulfur in space remains one of the least understood. This is mainly due to the fact that we still do not know the nature and identity of its chemical reservoir(s). In the diffuse interstellar medium (ISM) and photon-dominated regions (PDR), the total amount of sulfur is close to the value measured in the Sun photosphere of S/H $\sim 1.5 \times 10^{-5}$ by Asplund et al. (2009) (e.g., Goicoechea et al. 2006; Howk et al. 2006). This is in contrast with dense molecular gas, where the total amount of sulfur is found to be strongly depleted. No more than $\sim 1\%$ of the sulfur cosmic abundance is observed in the gas phase (e.g., Tieftrunk et al. 1994; Wakelam et al. 2004; Vastel et al. 2018). Therefore, one can wonder where does the sulfur from diffuse to dense gas

go. A commonly accepted hypothesis is that most of the sulfur depletes onto icy grain mantles with decreasing temperature and increasing density which characterize the transition from diffuse to dense gas (e.g., Ruffle et al. 1999; Vidal et al. 2017; Laas and Caselli 2019). However, only $\sim 4\%$ of the solar abundance of sulfur has been detected in interstellar ices so far (Boogert et al. 2015 and reference therein). Therefore, the nature and identity of the sulfur reservoir(s) in the ISM remains an open question.

Sulfur-bearing species are ubiquitous in the solar system, especially in the diverse relics of our own planet-forming disk such as comets and meteorites but also on planets and their satellites (e.g., Calmonte et al. 2016; Lellouch et al. 2007). While nine S-bearing species were detected in cometary atmosphere from remote observations during the past two decades – namely, H₂S, CS, SO, SO₂, OCS, H₂CS, NS, atomic S, and S₂ (Meier and A'Hearn 1997; Bockelee-Morvan et al. 2004; Biver et al. 2016) – the Rosetta mission on comet 67P/Churyumov-Gerasimenko (67P/C-G hereafter) enlarged the discovery of cometary sulfur-bearing molecules. Measurements of the coma revealed the presence of S-molecules commonly detected in the gas-phase ISM and previously found in other comets, such as H₂S, atomic S, SO, SO₂, OCS, H₂CS, and tentatively CS and NS. Furthermore, multi-sulfuretted molecules, not yet found in the ISM, such as CS₂, S₃, and S₄ (Le Roy et al. 2015; Calmonte et al. 2016), were also detected as well

as complex S-molecules such as CH_3SH and $\text{C}_2\text{H}_6\text{S}$. The latter has two isomers, ethanethiol (i.e., $\text{CH}_3\text{CH}_2\text{SH}$, also known as ethyl mercaptan and only detected in Orion KL so far (Kolesnikova et al. 2014)) and dimethyl sulfide ($(\text{CH}_3)_2\text{S}$, not yet detected in any other astrophysical object). However, the 67P/C-G measurements did not allow to distinguish the proportion of these two isomers. Studying the S-chemistry in the evolutionary stages leading from the quiescent ISM to the formation of planetary system is therefore a pivotal step to giving a window into the chemical origins of our own solar system while also, and as importantly, to help us better understanding the cycle and role of sulfur in astrochemistry. This is especially important to predict what, and in which quantities, S-compounds are expected on nascent planets assembling at different disk radii around different types of stars.

Basic Methodology

Millimeter and sub-millimeter astronomy has been the principal source of S-bearing molecules discovery in space. In the twenty-first century, the unprecedented high sensitivity and spectral and spatial resolutions of the latest generation of radio-telescopes has helped to considerably enlarge this discovery. In particular, it has allowed us to start uncovering the chemistry of pivotal astrophysical objects in the evolution from molecular clouds to the formation of planetary systems, proto-planetary disks.

Providing both the volatile (gas and ice) and refractory (dust) reservoirs for planet formation, these gas- and dust-rich disks orbiting young stars are the birthplace of planetary systems. Therefore, the chemical composition of planets and by extension their hospitality to life are intimately linked to both the chemical composition and the structure of the disk in which they form. Furthermore, these pivotal astrophysical objects are vertically stratified into atmospheres, warm molecular layers, and cold mid-planes, which are analogs to PDR, luke-warm molecular clouds, and cold dense cores, respectively (Aikawa et al. 2002). Recent sulfur-bearing species observations in each of these three

types of analog astrophysical environments (e.g., Drozdovskaya et al. 2018; Vastel et al. 2018; Riviere-Marichalar et al. 2019) have revived interest in the global quest for understanding the cycle of sulfur chemistry from molecular cloud to exoplanetary systems and are timely for the exploration of the sulfur chemistry in proto-planetary disks. In this context, and for the remainder of this methodology section, we focus on these pivotal astrophysical objects that constitute perfect testbeds to study the cycle of sulfur astrochemistry.

Among the approximately 30 molecules detected in proto-planetary disks so far (http://astrochymist.org/astrochymist_disks.html), seven contain sulfur. These include CS (Dutrey et al. 1997) and SO (Fuentes et al. 2010), which were detected during the past two decades, and H_2S (Phuong et al. 2018), H_2CS , ^{13}CS , C^{34}S (Le Gal et al. 2019) and SO_2 (Booth et al. 2021), detected within the past few years, thanks to the significant sensitivity improvements made in radio-interferometry instruments. However, these six molecules remain a small fraction ($\sim 15\%$) of the collection of sulfur-bearing molecules detected in space (~ 35 ; see Table 1). CS is the most readily detected S-bearing species in proto-planetary disks (Dutrey et al. 1997; Fuentes et al. 2010; Guilloteau et al. 2016; Le Gal et al. 2019). SO, was the sole oxygenated, sulfur-bearing species detected in proto-planetary disks until the very recent detection of SO_2 in one disk (Booth et al. 2021). Remarkably, SO has only been found toward a few young disks with signs of active accretion (Fuentes et al. 2010; Guilloteau et al. 2013; Guilloteau et al. 2016; Pacheco-Vazquez et al. 2016; Booth et al. 2018). H_2S has long been thought to be a main sulfur reservoir and is a major sulfur carrier in comet 67P/C-G (Calmonte et al. 2016). However, it was only detected recently in a massive proto-planetary disk with a CS/ H_2S gas-phase column density ratio of ~ 20 (Phuong et al. 2018), after unsuccessful search in a handful of other proto-planetary disks (Dutrey et al. 2011). While additional H_2S observations in such disks are required to draw firm conclusions, this result casts doubt on the importance of H_2S in disk gas-phase S-chemistry

and has revived interest in the quest to identify the sulfur reservoir in these environments (e.g., Kama et al. 2019).

In proto-planetary disks, the abundance and spatial distributions of gas and solids is supposed to determine the chemical composition of the future planets that will eventually form within them and ultimately the architecture the emergent planetary systems, although the latter remains to be characterized. However, the observations provide only “snapshots.” Theoretical studies on the formation, excitation, and destruction of the molecules observed are therefore essential to interpret the observations. Such studies constitute the roots for the development of robust and precise chemical reaction networks, which are themselves key ingredients of astrochemical models. Such models are indeed built to compute the abundances of each of the molecular species contained in a given chemical network. Current chemical networks, combining gaseous and solid phase chemistry, globally explain the formation of the molecules observed. However, they do not always explain their abundances! This parameter is however crucial in order to interpret and develop observable molecular signatures of various astrophysical phenomena, such as planetary formation. It is therefore essential to develop the accuracy and precision of these chemical networks; however, as of today, only 5–10% of the reaction rates involved in the networks of several thousand reactions come from calculations or experimental measurements. It is thus crucial to keep developing these networks, which requires to build interdisciplinary collaborations in between theoretical chemists, experimentalists, and astrophysicists. In particular, for the case of proto-planetary disk modeling, current disk astrochemical models are still incomplete and lack accuracy about several crucial points. For instance, we still do not know the initial conditions of the chemistry, i.e., its composition, its elemental abundances, and also the initial physical conditions under which the chemistry initiates. We also do not know how stellar radiation impacts on both the disk chemistry and the chemical structure we can now capture with the latest generation of telescopes, nor do we know what the interplay is between chemistry,

disk dynamics, and planet formation. Improving these models is thus central to properly interpret the molecular gas observations we presently have access to in proto-planetary disks.

Key Research Findings

An example is the recent detection of H_2CS in a proto-planetary disk, which led to a $\text{H}_2\text{CS}/\text{CS}$ gas-phase column density ratio of $\sim 1/3$. This unexpectedly high ratio is an important new result for two reasons. Firstly, it suggests that a substantial portion of the volatile sulfur in disks may be in organic form (i.e., $\text{C}_x\text{H}_y\text{S}_z$). Secondly, it revealed some tensions between models and observations suggesting an incomplete theoretical understanding of the sulfur chemistry in disks (Le Gal et al. 2019). Pursuing studies of sulfur chemistry is therefore crucial to better constrain current astrochemical models, which in turn constitute also important tools to indirectly inform us on the potential compositions of unseen reservoirs such as the ice reservoir hosted on dust grains.

Future Directions

As of today, we still do not know what the major sulfur reservoir in proto-planetary disks is and in which form it resides. However, this is a fundamental parameter to constrain, not only to solve current modeling tensions such as the one found to interpret the high $\text{H}_2\text{CS}/\text{CS}$ ratio recently observed in proto-planetary disks but also because, more generally, many S-bearing species are observed in comets and do play an important role in the building up of prebiotic molecules and on planet habitability (Chen et al. 2015; Ranjan et al. 2018; Ruf et al. 2019).

Recently, based on the abundances of B star photospheres, Kama et al. (2019) found that ~ 81 – 97% of the S-budget should be locked in disk refractory material. Following the findings of Keller et al. (2002), the former authors proposed that most of the sulfur should be locked in the form of solid FeS in disks rather than in polymeric S_n ($n = 2$ – 8) molecules, where the

latter has been proposed for decades as a potential hidden S-reservoir in the ISM (e.g., Wakelam et al. 2004). However, the observations of solid FeS have not yet been confirmed in disks (Keller et al. 2002), whereas hints of solid S_n were recently reported on the comet 67P/C-G with the detections of S_2 , S_3 , and S_4 from the Rosetta mission (Calmonte et al. 2016), although these detections constitute only $\sim 0.2\%$ of the total detected S-content of 67 P/C-G.

OCS is another promising S-reservoir. It is the only S-bearing molecule unambiguously detected in ice mantles so far (see Boogert et al. (2015) and reference therein). Furthermore, astrochemical shock modeling benchmarked to protostellar shock observations predicted that OCS ices represent $\geq 50\%$ of the sulfur reservoir (e.g., Podio et al. 2014). The latter is therefore a promising organic S-reservoir to interpret the high H_2CS/CS ratio observed in disks. In current astrochemical models (e.g., those based on the Kinetic Database For Astrochemistry – <http://kida.astrophy.u-bordeaux.fr>), H_2CS is mainly formed from gas-phase reactions, the neutral-neutral reaction of atomic S and CH_3 , and the electronic dissociative recombination of H_3CS^+ , originating from the $S^+ + CH_4$ reaction. It is also formed, for a smaller contribution, from gas-grain chemistry where H_2CS is produced from successive hydrogenation on icy dust mantles and released for $\sim 1\%$ in the gas phase by chemical reactive desorption. However, currently, there is no consideration of OCS grain surface processing that could lead to the formation of organo-sulfur compounds such as H_2CS which, perhaps, would provide a better match with observations. To further explore this hypothesis, laboratory experiments and theoretical chemical calculation for such mechanisms are needed. The nature and identity of the reservoir of sulfur could also be changing throughout the disk, i.e., from the inner to the outer regions and/or from the atmospheric layer, where UV photons are driving the chemistry, to the mid-plane, where most of the molecules are frozen onto icy dust grain mantles. Resolved observations of the distribution of sulfur-bearing molecules in disks are thus required for further investigations, which could also allow us to test if and how any chemical

inheritance from molecular cloud stage to the planet-forming environment could be captured.

Cross-References

- [Accretion Shock](#)
- [Dense Core](#)
- [Molecular Cloud](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Protostellar Envelope](#)
- [Shock, Interstellar](#)
- [Sulphur](#)

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Sulfur Cycle

José Luis Sanz

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

The sulfur cycle, like the ► [biogeochemical cycles](#) of other elements, includes a series of oxidation and reduction stages of sulfur that are principally biotic and performed by microorganisms. Under certain pHs and redox potentials, some reactions of the sulfur cycle take place in the absence of microorganisms.

Overview

The sulfur cycle integrates and interconnects the different components of an ecosystem (soil, rock,

sediment, aquatic phase, and atmosphere). Sulfur is present as organic sulfur (in amino acids, coenzymes, etc.) and inorganic sulfur: sulfides (S^{2-}), elemental sulfur (S^0), sulfates (S^{6+}), and a series of intermediaries of minor environmental relevance. Sulfate (SO_4^{2-}) is the major bioavailable form in nature, and is particularly abundant in marine environments, because elemental sulfur and hydrogen sulfide (H_2S) are of biological or geothermic origin and metal sulfides (MeS) are insoluble.

The sulfur cycle is complex, involving aerobic and anaerobic, auto- and heterotrophic, and chemo- and photosynthetic microorganisms. In anaerobic settings, primarily in aquatic sediments and to a lesser extent in soils (generally acidic and stagnant) or the digestive tracts of warm-blooded animals, sulfur- and sulfate-reducing bacteria (SRB) reduce sulfur and sulfates, respectively, to hydrogen sulfide. Phylogenetically, these bacteria belong to the class delta-*Proteobacteria* (*Desulfovibrio*, *Desulfuromonas*) and the order *Clostridiales* (family *Peptococcaceae*: *Desulfotomaculum*, *Desulfosporosinus*). The ► [reduction](#) takes place in an ► [anaerobic respiration](#) in which oxidized forms of sulfur (dissimilative reduction) act as electron acceptors for the oxidation of simple organic compounds (acetate, lactate, etc.) or H_2 , yielding H_2S as a final product. Some ► [archaea](#) like *Archaeoglobus* also carry out this process. Some species belonging to genera such as *Clostridium* or *Alteromonas* reduce thiosulfate ($S_2O_3^{2-}$) to H_2S . Alternatively, sulfate is converted into phosphoadenosine 5'-phosphosulfate (PAPS) by many bacteria and plants. In the form of PAPS, sulfur is used in the biosynthetic processes of living organisms (assimilative reduction).

H_2S , either released by SRB or of geothermal origin, can be used by bacteria, such as purple (*Chromatium*) or green (*Chlorobium*) sulfur bacteria, that carry out anoxygenic photosynthesis typically in anaerobic conditions such as deep aquatic systems or microbial biofilms. In both cases, H_2S acts as an ► [electron donor](#), giving rise to elemental sulfur. H_2S can also be used by bacteria that carry out aerobic anoxygenic photosynthesis (*Erythromonas*, *Roseobacter*). In aerobic environments, H_2S is used by

chemolithotrophic sulfur-oxidizing bacteria, such as *Thiobacillus* or *Thiomicrospira*, that accumulate extracellular elemental sulfur granules. In *Thiovulum* or filamentous bacteria like *Beggiatoa*, elemental sulfur accumulates inside their cells. In both cases, the sulfur can be further oxidized to sulfate.

Some sulfur-dependant thermophilic archaea, belonging to the order *Sulfolobales*, also carry out the oxidation of H_2S or S^0 to sulfate in the presence of oxygen (*Sulfolobus*, *Acidianus*). In the absence of O_2 , a great number of thermophilic archaea – both *Crenarchaeota* (*Thermoproteus*, *Desulfurococcus*, *Pyrodictium*) and *Euryarchaeota* (*Thermococcus* or some methanogens) – display autotrophic, myxotrophic, or heterotrophic growth during which S^0 is reduced to H_2S (although methanogens obtain no energy in the process).

Under certain circumstances, such as in the presence of oxygen and in neutral pH, H_2S is oxidized rapidly and abiotically to elemental sulfur.

Cross-References

- [Acidophile](#)
- [Aerobic Respiration](#)
- [Anaerobic Respiration](#)
- [Archaea](#)
- [Assimilative Metabolism](#)
- [Bacteria](#)
- [Biogeochemical Cycles](#)
- [Chemolithotroph](#)
- [Crenarchaeota](#)
- [Electron Acceptor](#)
- [Electron Donor](#)
- [Euryarchaeota](#)
- [Lithotroph](#)
- [Respiration](#)
- [Sulfate Reducers](#)

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Sulfur Hydrides in the Interstellar Medium

William M. Irvine

Department of Astronomy, University of Massachusetts Amherst, Amherst, MA, USA

Synonyms

H_2S ; [Hydrogen sulfide](#); [Mercapto radical](#); S_2H ; SH ; SH^+ ; [Sulfaniumylidene](#); [Sulfanyl](#); [Sulfanylium](#)

Definition

Three neutral hydrides of sulfur, H_2S , S_2H , and SH , and also the cation SH^+ , have been detected in the interstellar medium by astronomers. Sulfur hydrides are important in many origins of life models, and two of the protein amino acids used by terrestrial life contain sulfur (cysteine and methionine).

History

Whereas H_2S was one of the first triatomic molecules detected in interstellar molecular clouds (Thaddeus et al. 1972), the identification of SH^+ (Menten et al. 2011), SH (Neufeld et al. 2012), and S_2H (Fuente et al. 2017) have been much more recent. Although H_2S , S_2H , and SH^+ were observed using ground-based radio telescopes,

radio astronomers used the SOFIA airborne observatory to detect SH (for references, see ► [“Molecules in Space”](#)).

Cross-References

- [Hydrogen Sulfide](#)
- [Interstellar Medium](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Origin of Life](#)

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Sulfur Isotopes

James Farquhar

Department of Geology, University of Maryland,
College Park, MD, USA

Keywords

Great oxygenation event · Isotopes · Isotopic ratio · Sulfates · Sulfides

Definition

Sulfur is a relatively common element in the Solar System and on Earth. It has four relatively

abundant, naturally occurring, stable isotopes with masses of approximately 32, 33, 34, and 36 atomic mass unit (amu). It has a rich chemistry, and reactions involving sulfur compounds occur in the solid, liquid, and gaseous envelopes of Earth and other planets. It occurs in a variety of valence states ranging from +6 to −2, and as a result, sulfur is used in a variety of biological capacities.

Overview

Sulfur compounds are used as an energy source for metabolic activity (catabolism) by a variety of bacteria and archaea that draw upon redox transformations, using oxidized species as electron donors and reduced species as electron acceptors. Sulfur compounds are used as important electron acceptors for anoxygenic ► [photosynthesis](#) by green and purple sulfur bacteria. Sulfur is a constituent of both essential (► [methionine](#)) and non-essential (► [cysteine](#)) amino acids. Sulfur compounds are involved in photochemical reactions in the atmosphere, and some of these reactions can be quite complex with transformations involving a variety of bound and unbound states. The variety of bonding environments, reaction pathways, and the presence of odd and even mass nuclei that have a relatively large difference in vibrational potential energy also, ultimately, contribute to a rich isotopic chemistry.

By convention, sulfur isotope compositions are described using delta notation ($\delta^{34}\text{S}$, $\delta^{33}\text{S}$, and $\delta^{36}\text{S}$). This notation describes the deviation of an isotope ratio in a sample relative to that in an international reference material (V-CDT) and is generally expressed in permil.

A second type of notation, capital delta notation ($\Delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$), is used to describe the difference between the isotopic compositions of two materials expressed in delta notation. For $^{34}\text{S}/^{32}\text{S}$, $\Delta^{34}\text{S}$ is the arithmetic difference between the $\delta^{34}\text{S}$ of two materials (e.g., $\delta^{34}\text{S}_{\text{Material} - a} - \delta^{34}\text{S}_{\text{Material} - b}$), but for $^{33}\text{S}/^{32}\text{S}$ and $^{36}\text{S}/^{32}\text{S}$, the $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$ describe the arithmetic difference between a measured $\delta^{33}\text{S}$ and $\delta^{36}\text{S}$ and a $\delta^{33}\text{S}$ and $\delta^{36}\text{S}$ that is predicted on the basis of the measured

$\delta^{34}\text{S}$. Following this convention, $\Delta^{33}\text{S} = \delta^{33}\text{S} - [(1 + \delta^{34}\text{S})^{0.515} - 1]$ and $\Delta^{36}\text{S} = \delta^{36}\text{S} - [(1 + \delta^{34}\text{S})^{1.90} - 1]$. The quantities $[(1 + \delta^{34}\text{S})^{0.515} - 1]$ and $[(1 + \delta^{34}\text{S})^{1.90} - 1]$ are approximately equal to the values of $\delta^{33}\text{S}$ and $\delta^{36}\text{S}$ that would be predicted for a single-step equilibrium isotope effect. The $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$ therefore describe deviations from an equilibrium reference frame that is anchored by the compositional reference frame, V-CDT.

The term *isotope effect* is used to describe a change in isotope ratios that is produced by a physical or a chemical process. We use the term *fractionation factor* (α) to quantify the change in isotope ratios produced by an isotope effect (e.g., $^{34}\alpha_{a-b} = (^{34}\text{S}/^{32}\text{S})_{\text{substance } a} / (^{34}\text{S}/^{32}\text{S})_{\text{substance } b}$). The term *fractionation* is used to describe an observed difference in the isotope ratio of sulfur in two reservoirs, and a *discrimination coefficient* ($\Sigma = \alpha - 1$) is used to describe the change in isotope ratios produced by one or more processes with associated isotope effects. In this context, there are a number of different types of physical and chemical processes that generate isotope effects, and some of these produce significant variations for $\delta^{34}\text{S}$ but not for $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$, while others produce significant variations for all three. Isotope effects have been grouped into several categories. These include (1) *classical or equilibrium isotope effects* (EIE) that arise principally because of differences in vibrational potential energy and that produce significant variations for $\delta^{34}\text{S}$ but not for $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$; (2) *nuclear volume effects* (NVE) that arise because differences in the size and shape of the nucleus influence the nuclear charge distribution and may have an effect on the potential energy surfaces of bonding for different isotopes and that produce other types of variations for $\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$; (3) *kinetic isotope effects* (KIE) that may in some cases produce other types of variations for $\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$ and that arise because factors other than vibrational energy, such as nuclear spin, or level matching between bound and unbound states, or molecular symmetry, control rates of reactions involving molecules containing some isotopes more than they do the rates of reactions for molecules containing other isotopes;

and (4) other *physically controlled isotope effects* that reflect the operation of physical processes such as buoyancy, gravitation, kinetic energy, and mixing processes and that produce other types of variations for $\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$.

Sulfur isotope compositional variations reflect different types of isotope effects that are relevant at different times in the history of Earth and other planets and that are relevant for astrobiology. These include, but are not limited to, (1a) an observation that the range of $\delta^{34}\text{S}$ is small in the oldest terrestrial rocks and becomes larger in samples that are younger in age; (1b) an observation that there are some ancient rocks (older than $\sim 3,000$ million years old (Ma)) that exhibit larger ranges of variability for $\delta^{34}\text{S}$; (1c) an observation that the average values for $\delta^{34}\text{S}$ of sedimentary pyrite are generally near zero or slightly positive until about 550 Ma when they became negative; (2a) an observation that the variability of $\Delta^{33}\text{S}$ is largest in the oldest terrestrial rocks and becomes significantly smaller at approximately 2,400 Ma; (2b) an observation that the $\Delta^{33}\text{S}$ of proxies for seawater sulfate have risen from slightly negative values (~ -0.5 to -0.10‰) to generally positive values (0 to $+0.5\text{‰}$) over the past 2,000 million years; and (3) an observation that samples of Martian meteorites contain sulfate and sulfide that has variable and significantly negative $\Delta^{33}\text{S}$.

The Geologic Record of $\delta^{34}\text{S}$

Monster et al. (1979) and Cameron (1982, 1983) argued that the range of $\delta^{34}\text{S}$ observed in terrestrial rocks was small in the earliest parts of Earth's history (before $\sim 2,500$ – $2,700$ Ma) and became larger after this time. They argued that this general change in the observed variability of $\delta^{34}\text{S}$ reflects a response of sulfate-reducing bacteria to rising oceanic sulfate concentrations. They cited earlier studies of Harrison and Thode (1958) that documented a similar response in laboratory culture experiments and argued that rising sulfate concentrations was a global response to generally more oxidizing conditions for mineral weathering occurring at $\sim 2,500$ – $2,700$ Ma. The presence of one locality at North Pole, Western Australia

(~3,400 Ma), which was an exception to this general rule, exhibiting sulfides with significantly negative $\delta^{34}\text{S}$, has been argued to be evidence for the presence of ► [sulfate-reducing](#) and sulfur-disproportionating bacteria (bacteria capable of splitting one compound into two different compounds, in this case an electron donor and an electron acceptor) (Shen et al. 2001; Philippot et al. 2007).

Two observations made for later points in Earth history include an observation that the average values for $\delta^{34}\text{S}$ of sedimentary pyrite are generally near zero or slightly positive until about 550 Ma and that the variability for $\delta^{34}\text{S}$ increases from ~40‰ to ~60‰ starting around 800 Ma (Canfield and Teske 1996). The first observation may be attributable to a fundamental change in the way that sulfur is cycled within seafloor sediments and may reflect the initiation of significant bioturbation (displacement and mixing of sediment particles) that recycled sedimentary sulfur to seawater and allowed for the transfer of negative $\delta^{34}\text{S}$ to sedimentary pyrite (e.g., Canfield and Farquhar 2009). The cause of the amplification in the range of observed variability of $\delta^{34}\text{S}$ at ~800 Ma is debated but includes a variety of hypotheses related to changes in the ecology of the oceans and their impacts on sulfate concentration, bioturbation, and the cycling of sulfur by a more complex biosphere.

The Geologic Record of $\Delta^{33}\text{S}$

Farquhar et al. (2000) reported significant variability in the range of $\Delta^{33}\text{S}$ (correlated with $\Delta^{36}\text{S}$) of Archean and earliest Proterozoic rocks that disappeared at ~2,400 Ma. This variability was interpreted to reflect preservation of an imprint of atmospheric reactions that produce variations with nonzero $\Delta^{33}\text{S}$. This interpretation was based on the observation of nonzero $\Delta^{33}\text{S}$ in photolysis experiments, and in today's atmosphere, and a lack of plausible alternatives to produce similar isotope signals by liquid-phase or solid-phase reactions. The preservation of the $\Delta^{33}\text{S}$ signal in the rock record was inferred to reflect limited oxidative and reductive cycling of sulfur compared to that seen in the present-day sulfur cycle,

and this was linked to atmospheric oxygen levels and therefore carried implications for ► [oxygenation of Earth's atmosphere](#) and surface environments. Subsequent studies by Pavlov and Kasting (2002) presented arguments that the opening of pathways for the transfer of atmospheric signals to the surface also depends on oxygen levels and were consistent with this interpretation. An atmospheric origin associated with self-shielding (large optical depths that limit photodissociation of the most abundant isotope) rather than a primary photochemical origin for the effect has been proposed by Lyons (2009) but would not change the implications. Given the cross sections, some amount of self-shielding is inescapable, but whether it is the sole reason for the sulfur isotope effect remains to be demonstrated. Recently, it has been shown that other pathways associated with some thermochemical (liquid-phase) reactions exist for the production of anomalous $\Delta^{33}\text{S}$ (Watanabe et al. 2009). It is unclear at present whether this chemistry provides an alternative explanation for the early Earth record.

The $\Delta^{33}\text{S}$ of oceanic sulfate younger than 2,400 Ma deviates slightly from a value of zero as a result of the way biogeochemical reactions are linked within the sulfur cycle. Johnston et al. (2005) demonstrated that the $\Delta^{33}\text{S}$ of oceanic sulfate rose from slightly negative values (~ -0.5 to -0.10‰) to generally positive values (0–0.5‰) over the past 2,000 million years. This change was attributed to a transition from a sulfur cycle dominated by sulfate reduction to a sulfur cycle where the influence of sulfide oxidation and disproportionation was expressed. Recently Wu et al. (2010) have suggested that the $^{34}\text{S}/^{32}\text{S}$ and $^{33}\text{S}/^{32}\text{S}$ fractionations between seawater sulfate and buried pyrite may have changed approximately 300 Ma ago, suggesting a change in the oceanic cycling of sulfur that also may be linked to ocean ecology, bioturbation, and reoxidation pathways for biogenic sulfide.

Sulfur Isotope Records of Martian Meteorites

In the late 1970s and early to mid-1980s, a strong case was made that the SNC (shergottite, nakhlite,

and chassingite) meteorites came from Mars (Wood and Ashwal 1981; Bogard and Johnson 1983; Mccsween 1985, 1994). While these meteorites may not themselves constitute a fully representative suite of Martian rocks, their study provides a window into aspects of Mars science that is fundamental to our understanding of Mars. Farquhar et al. (2000, 2007) reported sulfate and sulfide from these meteorites with significant and variably negative $\Delta^{33}\text{S}$ and near-zero $\Delta^{36}\text{S}$. Variations of the magnitude seen in these meteorites are larger than that seen in other types of meteorites but are smaller than those seen in ancient terrestrial samples. The origin of this signal was interpreted to reflect isotope transformations on Mars that are related to atmospheric pathways for oxidation of sulfur to sulfate. These findings point to a significant role for these atmospheric pathways in the Martian sulfur cycle. They also call for an accounting of $\Delta^{33}\text{S}$ (and $\Delta^{36}\text{S}$) in future studies that seek to use sulfur isotopes as a tracer of possible biological processing of sulfur in the search for evidence of extraterrestrial metabolic activity.

Cross-References

- [Archaean Traces of Life](#)
- [Earth, Formation, and Early Evolution](#)
- [Earth's Atmosphere, Origin and Evolution of](#)
- [Fractionation, Mass Independent and Dependent](#)
- [Great Oxidation Event](#)
- [Green Bacteria](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [SNC Meteorites](#)
- [Stable Isotopes](#)

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Sulfur Monoxide (SO)

William M. Irvine

University of Massachusetts, Amherst, MA, USA

Synonyms

SO

Definition

The diatomic molecule sulfur monoxide, SO, is normally found in the gas phase. Astronomically, it has been observed in interstellar and circumstellar ► [molecular clouds](#), in ► [comets](#), and in the atmospheres of the Jovian satellite ► [Io](#) and the planet ► [Venus](#).

Cross-References

- [Comet](#)
- [Io](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Venus](#)

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Sulphur

- [Sulfur](#)

Sun (and Young Sun)

Manuel Güdel

Department of Astrophysics, University of Vienna, Vienna, Austria

Keywords

Coronal mass ejections · Flares · High-energy particles · Internal structure · Magnetic fields · Main-sequence star · Solar atmosphere · Solar radiation · Solar wind

Definition

The Sun is the central body of our solar system and the nearest star. It is a low-mass star of spectral type G2 V located on the main sequence in the Hertzsprung-Russell diagram, with an age of about 4.6 billion years. Its mass is 1.99×10^{30} kg and its bolometric luminosity amounts to 3.84×10^{26} W. The Sun shows diverse signs of magnetic activity, in particular sunspots, a warm chromosphere, a very hot magnetic corona, flares, coronal mass ejections, and the solar wind.

Overview

The Sun is a main-sequence star in the phase of core hydrogen burning, being in the midst of the longest stable phase of ► [stellar evolution](#) before the white dwarf phase. It is a metal-rich (population I) star with an age of approximately 4.6 billion years. It will spend another ≈ 5 Gyr before evolving off the main sequence. The Sun is classified as a low-mass star of spectral type G2. It entirely dominates the solar system in terms of mass and energy. Its luminosity is such that at the distance of the Earth, a total flux of 1366 W m^{-2} is measured (the ► [“solar constant”](#)). Some of the basic properties of the Sun are summarized in Table 1. Various appearances of the Sun and its environment are illustrated in Fig. 1.

This entry reviews our knowledge of the Sun and its environment with emphasis on features relevant for astrobiology. We therefore review the internal structure of the Sun including the magnetic

dynamo and nuclear fusion in a relatively cursory way, while more emphasis is put on the escaping radiation from the solar atmosphere. We specifically focus on radiation related to solar magnetic activity, including ultraviolet and X-ray radiation. This short-wavelength radiation is crucially important for ionization, heating, and chemical reactions in planetary atmospheres and therefore for the formation and evolution of life. Important questions related to the formation of life on Earth require knowledge of the solar constitution in earlier times of solar evolution. Systematic studies of stellar samples provide this information, which we will therefore address as well.

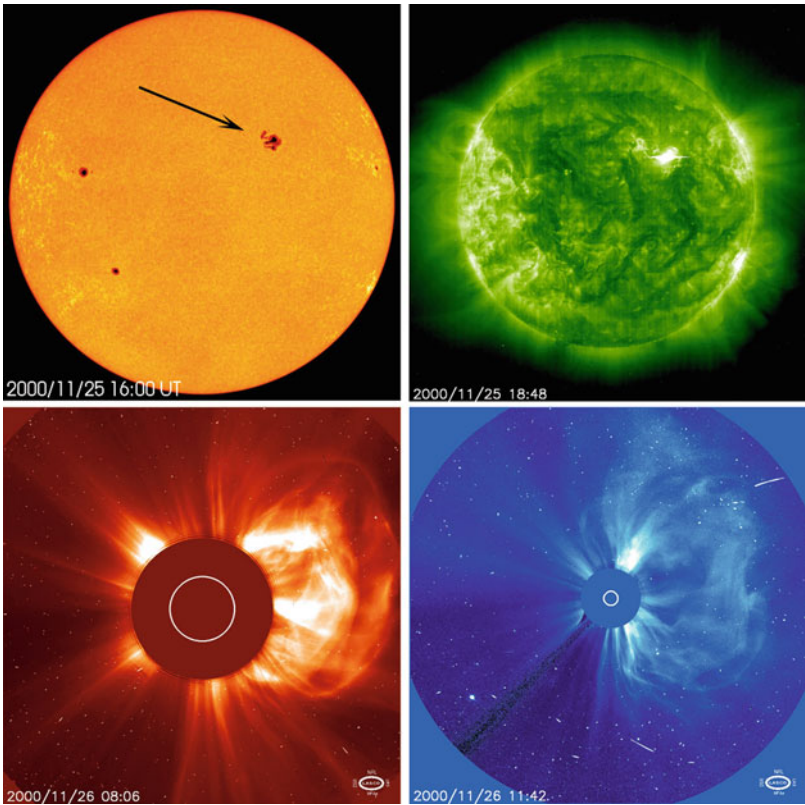
Sun (and Young Sun), Table 1 Basic parameters of the Sun

Stellar winds	Stellar winds
Mass	1.989×10^{30} kg
Radius	6.955×10^5 km
Average density	1.41×10^3 kg m ⁻³
Surface temperature	5770 K
Bolometric luminosity	3.846×10^{26} W
Spectral class	G2 V
Age	4.6×10^9 year
Sidereal rotation period	25.05 days (equator)–34.3 days (near poles)
Synodic rotation period	27.3 days at 16° latitude

Basic Methodology

The Sun is the only star that can be studied in spatial detail. This remains true even if a few stars have been marginally resolved by optical

Sun (and Young Sun), Fig. 1 Images of the Sun taken contemporaneously, showing the photosphere in the optical light (upper left), the corona in the extreme ultraviolet range (upper right), and an evolving coronal mass ejection seen in optical white light (lower images). (Credit: SOHO LASCO/EIT, ESA, and NASA)



interferometry, by speckle interferometry, or, as far as their magnetic atmospheres are concerned, by radio interferometry. But for no other star do we have similarly extensive methodology and diagnostics at hand as for the Sun.

Traditionally, radiation across the electromagnetic spectrum has been used to investigate all layers of the solar atmosphere. Specifically, the photospheric layers provide rich diagnostics in optical spectroscopy, including polarization diagnostics to infer strength and orientation of photospheric magnetic fields. The optically thin chromospheric and transition region layers with temperatures between 10^4 and 10^6 K reveal themselves best in ultraviolet emission lines. Million-degree coronal plasma emits in the extreme ultraviolet range and in X-rays, where again rich spectroscopic diagnostics are available to study temperature, density, and motion of coronal plasma. Nonthermal particles accelerated during flare episodes leave various traces at radio wavelengths and in hard X-rays and gamma rays. Although most of the electromagnetic spectrum is also studied routinely in solar-like stars (presently with the exception of nonthermal hard X-rays above 20 keV and gamma rays), the lack of spatial resolution has made solar studies indispensable for the interpretation of stellar atmospheres. In situ observations of high-energy particles (e.g., from flares), coronal mass ejections, and the solar wind are of course confined to our own solar system.

Although ground-based optical solar observatories can be used to study the solar photosphere and sunspots, investigations of higher layers in ultraviolet, EUV, and X-rays require space-borne instrumentation on satellites, such as the SOHO, Yohkoh, TRACE, STEREO, or the Solar Dynamics Observatory. The same is true for observations of high-energy particles in interplanetary space and also applies to highest-energy radiation such as hard X-rays and gamma rays during flares. In contrast, the highly diagnostic radio emission is easily observed in spectral and temporal detail with relatively modest-sized ground-based telescopes.

Our understanding of the solar interior has been revolutionized by helioseismology. Helioseismology is the analog of terrestrial

seismology although it probes sound waves in a gaseous environment. Convective motion in the outer layers of the solar interior excites acoustic waves, which develop standing waves. Sound waves traveling from the surface obliquely into the solar interior are refracted back to the surface owing to the increasing temperature toward larger depths and the temperature dependence of the sound velocity. Thousands of so-called pressure modes (p-modes) have been measured that together probe the internal structure in much detail except the central part of the Sun where nuclear reactions take place (there, sensitive measurements of g-modes would be required). Lower harmonics (p-mode waves with longer spatial scales) penetrate to deeper layers, while higher harmonics remain closer to the surface. Resulting oscillations of the photosphere can be recorded through Doppler shifts. The p-modes show a large spectrum of waves with an average period of 5 min. The observed oscillations can be inverted to derive the temperature and pressure profiles in the convection zone. Their detailed analysis provides much insight into the internal structure of the Sun.

Neutrinos define another important way to probe the solar interior, specifically the nuclear region. Detection of solar neutrinos has fundamentally confirmed the proton-proton chain reaction (p-p cycle; see below); although initially found to be deficient from the Sun, neutrinos oscillate between three flavors, the flavor produced in the Sun and initially detected in experiments being the electron neutrino. Considering this oscillation effect and measuring solar neutrinos of all flavors, there is no discrepancy between the standard solar model for the solar center and observations.

Magnetic fields play a major role in the solar atmosphere all the way from the photospheric layer to the corona and the solar wind. Photospheric magnetic fields are relatively easy to measure by making use of Zeeman splitting of spectral lines: magnetic fields split the atomic energy levels into sublevels, and the emitted radiation is polarized. Coronal magnetic fields can be deduced from approximate 3D extrapolations of photospheric fields based on some assumptions; alternatively, coherent radio emission diagnostics has been used to estimate field strengths in the emission region.

A key question relevant for the evolution of life refers to the long-term evolution of the Sun, its magnetic activity, and radiation spectrum. Although theoretical models of stellar evolution provide deep insight into the evolution of basic parameters (radius, surface effective temperature, etc.), the generation of magnetic activity and the solar wind is not sufficiently well understood to be modeled on evolutionary timescales. Here, stellar samples of solar analogs with known ages are used, with the goal of finding systematic trends with age.

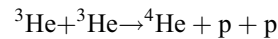
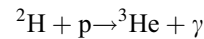
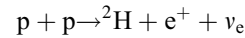
Key Research Findings

The Sun's Internal Structure, Energy Production, and Composition

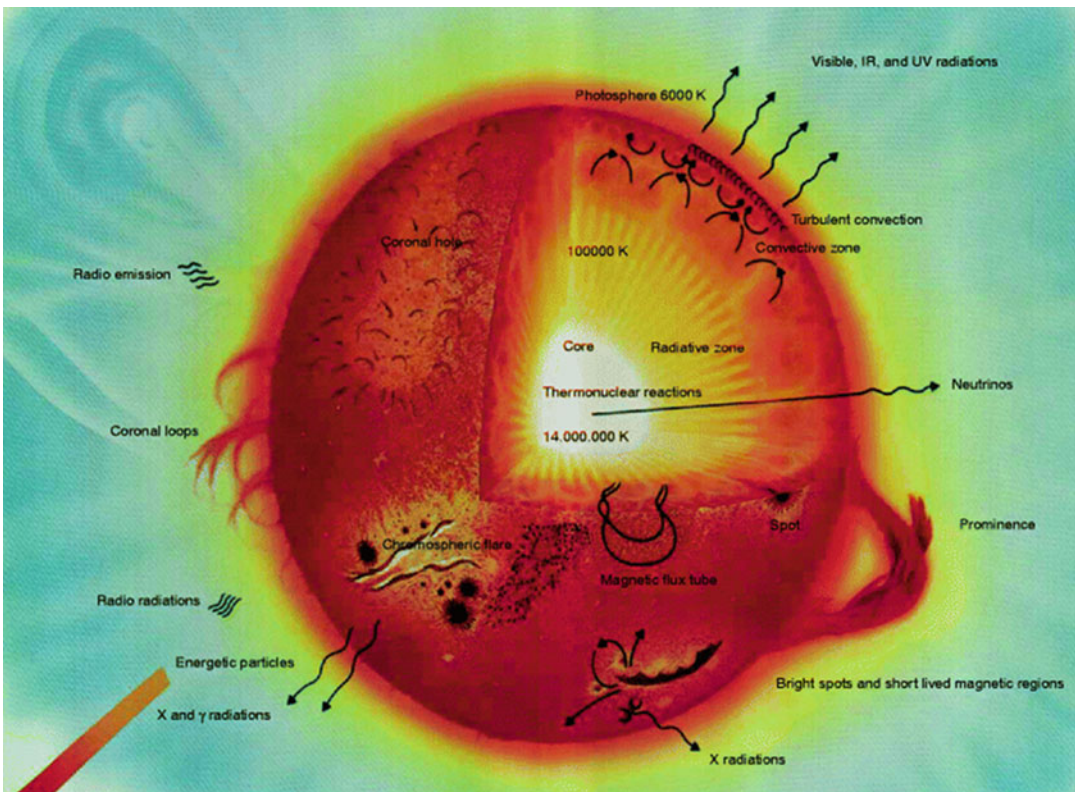
Our knowledge of the Sun's internal structure and physical state is summarized in the so-called standard model that calculates temperature, pressure,

and density as a function of radius, fulfilling the conservation equations and the boundary conditions at the solar surface.

The central region of the Sun (within a radius of approximately 10^5 km – see Fig. 2) is characterized by temperatures of about 16×10^6 K and a density of 1.5×10^5 kg m⁻³. In this core region, helium (⁴He) is synthesized from hydrogen (p) nuclei mainly in the proton-proton chain reaction:



where γ stands for energy emitted in a photon and ν_e is an electron neutrino. There is also a second path to ⁴He involving ⁷Be, ⁷Li, and ⁸Be, and a small percentage of the energy is produced in the



Sun (and Young Sun), Fig. 2 Schematic cross section of the Sun and sketch of features in the solar atmosphere. (Credit: NASA/HEASARC)

so-called CNO cycle. Within the inner $\approx 71\%$ of the solar radius, the energy liberated from the central fusion process is transported radiatively. Outside this region, convection plays a dominant role up to the solar photosphere.

The Sun is composed predominantly of hydrogen (approximately 70% by mass or 91% by number of atoms) and helium (28% by mass or 9% by atom number); heavy elements, predominantly carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron, contribute the remaining 2% of the mass. The exact composition is still a matter of debate but plays an important role for the plasma opacity and therefore the radiative transport in the solar interior and the depth where energy transport becomes dominated by convective motions.

The Solar Photosphere and Sunspots

The visible surface of the Sun defines the photosphere, that is, the layer from which photons in the visible range of the electromagnetic spectrum freely escape. This layer is only a few 100 km thick and separates the solar interior from the outer atmosphere. Its spectrum can be approximated by a blackbody spectrum corresponding to a temperature of about 5770 K. This spectrum defines most of the solar irradiance (Fig. 3), although important contributions are added at

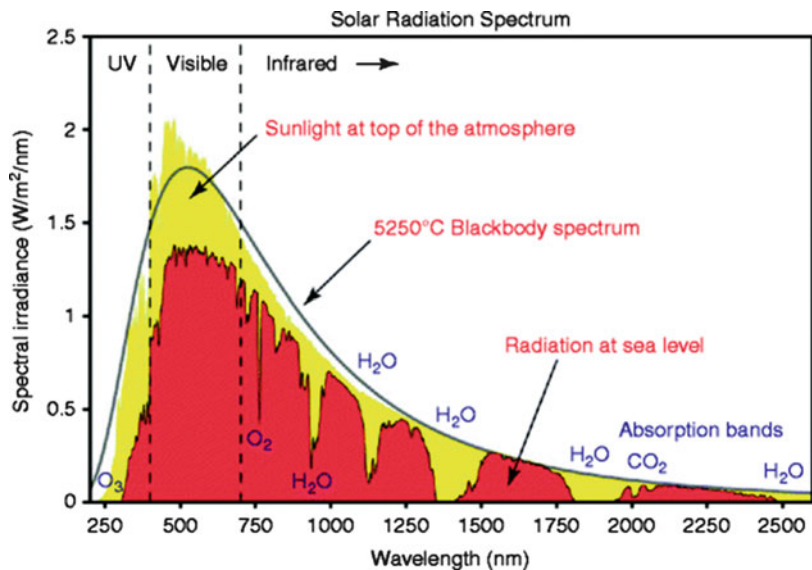
short wavelengths as a consequence of magnetic activity.

The photosphere reflects the underlying convective motions at several scales, showing granulation structure on length scales of 100–1000 km, mesogranulation on scales of 5000–10,000 km, and supergranulation on scales of about 15,000–20,000 km. In individual granules, hot, subphotospheric gas flows up in the center, radiates and cools, and then flows down in the intergranular lanes. In the latter places, bright points related to magnetic flux tubes are concentrated. Concentrations of magnetic flux tubes at the supergranulation boundary form a magnetic network visible also in the overlying chromosphere.

The photosphere hosts the remarkable sunspots. These are regions in which strongly bundled, vertical magnetic fields with a field strength of about 0.2–0.3 T suppress convection and therefore impede the energy flow from below; their temperature is therefore lower, reaching typical values of 4500 K. The sunspot core region, the umbra, is surrounded by the radially structured penumbra, which is permeated by inclined magnetic fields, and spot groups may further be surrounded by larger areas containing strong, vertical magnetic flux tubes appearing brighter than the surrounding photosphere. These latter regions,

Sun (and Young Sun),

Fig. 3 Solar irradiance spectrum for the ultraviolet, optical, and infrared part of the electromagnetic spectrum, both at the *top* of the Earth's atmosphere (yellow) and at sea level after propagation through the atmosphere (red). (Credit: Robert A. Rohde/Global Warming Art project)



the faculae, make up for the deficit of radiation from the sunspots, such that the net brightness at times of large sunspot coverage is slightly higher than at times of small coverage; the “solar constant” therefore cyclically varies by a small amount in concert with the solar spot cycle (see below), being higher by about 0.1% during the spot or activity maximum.

Spots appear in pairs with opposite magnetic polarity. The polarity of the spot leading in heliographic longitude is constant for one (north or south) hemisphere for a given 11-year sunspot cycle, which is an important observation that has helped formulate a dynamo theory for the Sun.

Magnetic flux tubes are also present in regions outside sunspots. Such magnetic flux elements are concentrated in intergranular lanes, where magnetic flux concentrations with kilogauss field strengths and sizes of less than 100 km are inferred. Despite their small size, their large number contributes significantly to the total solar magnetic flux.

The Solar Chromosphere

The chromosphere is a “layer” of tenuous gas above the photosphere, ranging in temperature from the temperature minimum at the top of the photosphere to about 20,000 K where it merges with the chromosphere-corona transition region. In modern concepts, the chromosphere is a complex mixture of cool and hot magnetically structured inhomogeneities subject to many forms of variability (flares, explosive events, flows, prominences, etc.). It is on average only about 2000 km thick, but is a source of important ultraviolet emission, in particular in prominent line transitions such as Balmer lines and lines of Ca II and He I (using the standard astronomical notation of I for neutral atom, II for once ionized, etc.). Larger heights (of order 10,000 km) are reached by the jetlike hot spicules rising into the lower corona with velocities of a few tens of kilometers per second.

The chromosphere forms a dynamic network corresponding to the photospheric supergranule cells. Nearly vertical magnetic fields emerging from the photosphere in these regions rapidly fan out, forming a canopy in the upper chromosphere that seems to overlay cool, weak-field, CO-rich

gas in the lower chromosphere. The canopy region itself is the anchorage region of the overlying coronal loops. The chromosphere is particularly well expressed in magnetic active regions. Around sunspots, the chromosphere is bright, defining the chromospheric plage (a continuation of the photospheric faculae). The heating of the chromospheric gas is not yet fully understood, but may involve dissipation of acoustic waves in shocks, magnetodynamic waves, or magnetic reconnection (e.g., in bright points).

Extensions of chromospheric material into the corona are seen in many large-scale filaments or prominences made of cool gas suspended by magnetic fields at coronal heights. They may reside there for weeks or months, but may also be activated and ejected, accompanied by flares or coronal mass ejections.

The Solar Transition Region

The temperature rises very rapidly above the chromosphere on length scales of only a few hundred kilometers, from 2×10^4 to 10^6 K. This chromosphere-corona transition region (TR) is a very inhomogeneous and dynamic layer, featuring flows (mostly downflows with velocities of up to 20 km s^{-1}), flares, and short explosive events involving velocities of 100 km s^{-1} ; many of these processes connect to the overlying, strongly variable corona. Various physical parameters change fundamentally across the TR; helium changes from the partially ionized (below) to the fully ionized state (above), dramatically reducing the radiative losses and producing a rapid jump of the temperature to the adjacent corona. Below the TR, the plasma thermal pressure dominates plasma motion, dragging magnetic fields with it, while above the TR, the magnetic pressure dominates, such that plasma is dragged by the magnetic fields. Much of the TR is structured in magnetic loops connecting footpoints of different polarity. The TR can best be observed in emission lines at wavelengths below 200 nm (e.g., He II, C IV, O VI).

The Solar Corona

The outermost and hottest region of the solar atmosphere is the magnetically structured corona.

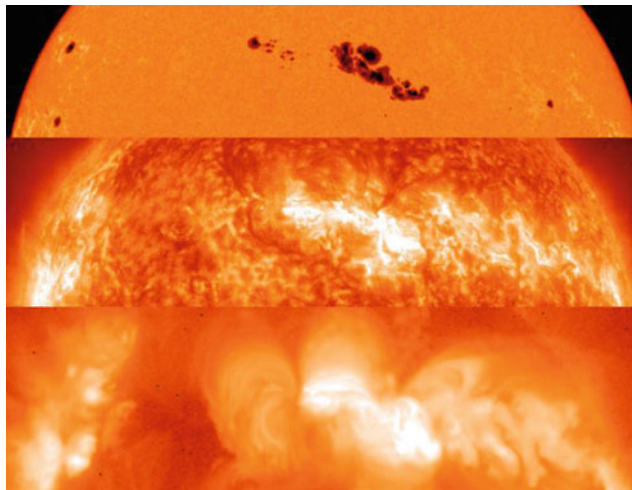
Although the corona is well known from solar eclipses when photospheric light scattered by free electrons and dust reveals its large-scale magnetic structure, it is really a phenomenon rooted in high-energy processes in the tenuous, extended magnetic fields that are anchored in the photosphere. The corona is best observed in the extreme ultraviolet (EUV) and X-ray ranges where the hot plasma confined by closed magnetic fields emits most of its radiation or in the radio range where high-energy, accelerated electrons emit various kinds of radiation such as gyrosynchrotron radiation and a plethora of coherent radiation types. The solar coronal temperature of a few million degrees has defined one of the most persistent riddles in astronomy: among the favored theoretical concepts to explain coronal heating figures magnetic reconnection in flares, in particular also in the large number of microflares or nanoflares occurring ubiquitously across the corona.

The coronal magnetic fields structure the plasma into large active regions overlying magnetic sunspot groups (Fig. 4); such volumes are filled with coronal loops with both footpoint regions anchored in the chromosphere. They

range from small bright points, probably simple magnetic loops above the chromospheric layer, to large-scale arcades connecting regions of opposite polarity on the solar surface. Coronal streamers may be attached to these structures, pointing outward into the solar wind region to distances of order one solar radius (Figs. 1 and 5).

Coronal active regions display a high level of variability, including flares, mass flows, and coronal mass ejections. Intermittent heating, changing magnetic connectivity in reconnection events, and magnetic instabilities define the corona as an extremely dynamic region. Various types of oscillations of magnetic coronal loops have been measured with periods in the range of seconds to minutes; propagating magnetohydrodynamic waves have been detected in the EUV range, including global waves expanding from strong flare sites.

Large volumes of the corona are not directly connected to the underlying photospheric and chromospheric active regions, but they reveal similar magnetically closed structures such as transequatorial loops or X-ray bright points and similar dynamic phenomena as in active regions,



Sun (and Young Sun), Fig. 4 Three images of the solar atmosphere taken at the same time but in different wavelength regions. The *top panel* shows an optical image featuring sunspots surrounded by bright faculae. The *middle panel* was recorded in the extreme ultraviolet range showing the solar transition region. The *bottom panel* records the solar corona in X-rays. (Credit: SOHO –

MDI/EIT Consortia [SOHO is a project of international cooperation between ESA and NASA], Yohkoh/SXT Project [Yohkoh was a Japanese ISAS/JAXA mission, collaborating with NASA/US and PPARC/STFC/UK; its scientific operation was conducted by the international science team organized in ISAS])

such as magnetic reconnection, mass flows, and nanoflares. These regions have traditionally been called “quiet-Sun regions” although absence of variability and dynamic phenomena are no longer implied by this term.

A physically distinct type of coronal feature emerges in regions dominated by nearly radial, “open” magnetic fields; these “coronal holes” contribute importantly to the fast solar wind but appear as very dim regions in X-ray or EUV images, as a consequence of their low densities. Prominent coronal holes are often seen in the polar regions of the Sun.

Solar Rotation, the Solar Magnetic Dynamo, and Magnetic Cycles

The Sun’s rotation period, P , is a function of depth and latitude. The surface rotation period varies between about 25 days at the equator and about 36 days near the poles, characterizing solar differential rotation. Throughout the convective zone, the rotation period determined using helioseismology methods depends on latitude in a similar way as on the surface. In contrast, the core shows approximately solid-body rotation.

The interaction between differential rotation and convection generates an internal dynamo at the base of the convection zone, in the so-called tachocline where the rapid change in rotation together with convection is held responsible for the amplification of magnetic fields. The shearing differential rotation generates toroidal fields from poloidal fields. These fields eventually rise buoyantly to the surface in the form of magnetic flux tubes; there, they become evident in a plethora of features related to magnetic activity such as bipolar sunspots and coronal magnetic loops.

There is as of yet no complete theory that explains all features of the solar magnetic dynamo. At the beginning of a magnetic cycle, spots appear at relatively high heliographic latitudes (about 35° on both hemispheres), but the regions of spot emergence slowly migrate toward the equator in the course of the 11-year sunspot cycle. A new spot cycle starts when new field concentrations appear at high latitudes. Their polarity (leading vs. trailing spot) is reversed for a given hemisphere during the new cycle, thus

defining the 22-year magnetic (or Hale) cycle of the Sun.

Spot and magnetic cycles are not only evident in sunspots but can be monitored in essentially all tracers of magnetic activity, including coronal X-ray emission, the rate of flares, prominences, mass ejections, or the structure of the solar wind. The same features are used as diagnostics of solar magnetic activity, that is, the complex interplay between magnetic fields that leads to time-variable energy release, heating, acceleration, and mass motions.

Active Regions, Flares, and Coronal Mass Ejections

Active regions on the Sun are areas of enhanced magnetic flux, that is, regions where magnetic flux tubes break through the photosphere from the interior, in pairs of opposite polarity. Active regions can therefore be traced throughout all layers of the solar atmosphere, showing up, in larger examples, as sunspot groups and faculae in the photosphere, spots and chromospheric plages at chromospheric levels, and large magnetic loop systems at transition region and coronal heights. These regions are particularly prone to instabilities leading to large-scale magnetic energy release and reconnection in flares and coronal mass ejections.

Observationally, solar flares express themselves as sudden increases in electromagnetic radiation, localized in solar active regions or coronal loops in which obviously a large amount of energy is liberated following some instability. Flares may last from minutes to several hours. Flares are currently considered to be a consequence of magnetic reconnection in non-potential (mostly coronal) magnetic fields. Non-potential fields emerge in the corona as a result of convective motions of the photospheric/chromospheric footpoints of magnetic loops. Increasingly stressed fields occasionally adjust by changing their topology, settling in a lower-energy state by liberating energy from the non-potential field. This large-scale reconnection process is induced by field annihilation once antiparallel field components (e.g., from different coronal loops) are pushed together in the corona. In the course of

this process, particles are accelerated to high energies, plasma can be heated locally, and plasma jets can be ejected. Initially “open” magnetic fields may reconnect in such a way as to produce systems of closed magnetic loops, while overlying magnetic regions may “detach” and be ejected from the corona, escaping into the interplanetary space as “coronal mass ejections” (CMEs; Fig. 5), accompanied by an erupting prominence.

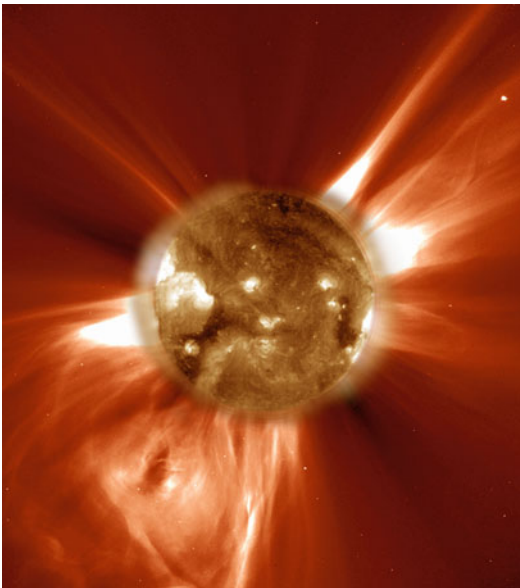
The size of CMEs may rapidly evolve to the order of a solar radius while they escape with a speed of 10^2 – 10^3 km s⁻¹. At 1 AU, a CME evolves to a typical size of 0.2 AU. It may carry of order 10^{15} – 10^{16} g of material into the solar wind.

The relation between CMEs and classical flares is still a matter of debate as there is no one-to-one correlation between these expressions of magnetic energy release. Flares and coronal mass ejections may simply be two observational manifestations

of large-scale coronal magnetic energy release by the reconnection process.

A large fraction of the released flare energy appears in the form of kinetic energy of highly accelerated electrons and ions. As they propagate along magnetic fields, they eventually encounter denser TR and chromospheric gas layers where they collide. The collisions result in nonthermal hard X-ray and gamma-ray radiation during the first minutes of a flare event, also known as the impulsive phase. The bulk part of the particle energy is, however, deposited as thermal energy in the chromospheric plasma, signatures of which are strong ultraviolet and optical enhancements in the magnetic footpoint regions. Electron temperatures up to about 20 million degrees are reached in the collision zone, which, as a consequence of the corresponding pressure increase, expands upward along the closed magnetic-field lines to fill coronal loops (chromospheric evaporation). This is the gradual phase of the flare when strong X-ray emission from coronal loops dominates the radiative losses. Various kinds of radio emission from the accelerated electrons (e.g., gyrosynchrotron emission from electrons spiraling around magnetic fields) or electron populations with non-Maxwellian velocity distributions can be monitored during large portions of a solar flare. Radio emission is, together with hard X-rays and gamma rays, an ideal tracer of the energy release and particle acceleration processes. Similarly, radiation in Balmer lines from chromospheric heights is prominent during extended periods of a flare. Flares are also the source of high-energy particles (protons, electrons, ions) ejected from the Sun and traveling in interplanetary space. Chromospheric filaments or prominences can be activated and ejected in the course of a flare or a coronal mass ejection.

Flares may be important contributors to the coronal heating process because they occur stochastically and in large numbers at many places in the solar corona. The distribution of their occurrence rate as a function of released energy shows a dramatic increase toward low-energy (small) events. The cumulative energy of such “micro-” or “nano-” flares could be sufficient to heat the



Sun (and Young Sun), Fig. 5 A coronal mass ejection (*lower left*) seen by the LASCO (Large Angle and Spectrometric Coronagraph Experiment) instrument on the SOHO satellite. Several coronal streamers (e.g., *upper right*) can also be seen. The solar disk was recorded by the EIT (Extreme ultraviolet Imaging Telescope) instrument and shows hot coronal structures. (Credit: SOHO/EIT and LASCO Consortia; SOHO is a mission of international cooperation between ESA and NASA).

entire coronal gas, although current debate has not converged to a clear answer.

Flares and mass ejections lead to significant interactions with planetary environments. Flare X-ray radiation increases the ionization of upper planetary atmospheres dramatically. When CMEs reach the Earth, they may interact globally with the magnetosphere and induce geomagnetic storms. Together with the solar wind, they interact with the higher atmosphere, carrying away ions and neutrals and thus contributing to atmospheric erosion.

Solar Wind

The Sun continuously loses mass in an approximately radially expanding solar wind. It consists of hot ($\approx 10^5 - 10^6$ K) plasma. The wind is permeated and structured by magnetic fields originating in the solar photosphere and also by shocks, waves, and turbulence. It is therefore a highly variable structure filling the interplanetary space and interacting with planetary magnetospheres and atmospheres, leading to the removal of atoms and ions in the higher atmospheres and therefore to planetary erosion. High-energy particles (from the Sun, planetary bow shocks, and cosmic rays) and coronal mass ejections are also occasionally immersed in the solar wind.

The solar wind is a consequence of the high coronal temperatures close to the Sun, leading to coronal expansion rather than a hydrostatic structure. The processes of wind heating and acceleration are, however, still poorly understood and may involve wave dissipation and magnetic reconnection. The present-day average mass loss of the Sun in the magnetized wind is approximately $2 \times 10^{-14} M_{\odot} \text{ year}^{-1}$. The wind flow varies locally depending on whether it originates in magnetic streamer regions above the magnetically closed coronal active regions, leading to the slow wind with velocities of $300\text{--}500 \text{ km s}^{-1}$, or in open-field coronal holes, leading to the fast wind with velocities of approximately $600\text{--}800 \text{ km s}^{-1}$. This structure is further modulated by the solar activity cycle.

The volume filled by the solar wind defines the heliosphere. At distances beyond 90 AU, the solar wind collides with the interstellar medium,

forming a termination shock, a heliopause, and the bow shock beyond which the undisturbed interstellar gas is encountered. Because the Sun moves relative to the interstellar plasma, the heliosphere is compressed in the direction of solar motion and elongated in the opposite direction.

The Sun in Time

The past magnetic evolution of the Sun is studied using solar analogs with different ages and therefore activity levels. For stars with masses $\leq 1.5 M_{\odot}$ and ages of at least a few hundred million years, angular momentum loss by a stellar wind brakes rotation in such a way that rotation becomes nearly uniquely determined by the stellar age. Age thus becomes the only independent variable on which the rotation period and, through the internal magnetic dynamo, magnetic activity at all levels of the stellar atmosphere depend, probably also including characteristics of the stellar wind. Studying a sample of near-solar-mass stars with known ages back to stages close to the zero-age main sequence (ZAMS), age is, therefore, sufficient to approximately reconstruct the history of our Sun and the interaction of its magnetic activity with its environment.

The Evolution of the Solar Wind

Stellar equivalents of the solar wind have not yet been detected; judged from the presence of coronae in all main-sequence solar analogs, coronal winds are undoubtedly present in these stars as well. The evolutionary spin down of cool stars like the Sun is in fact the best – albeit indirect – proof of the presence of ionized, magnetized winds because such winds carry away angular momentum from the star.

Ionized [stellar winds](#) are, in principle, sources of thermal bremsstrahlung in the radio regime, but the emission is too weak to be detected even in the nearest stars with current technology. A presently more promising approach makes use of Lyman-alpha ($\text{Ly}\alpha$) absorption in the so-called astrospheres, stellar analogs to the solar heliosphere. The astrospheres are permeated by neutral hydrogen with $T \approx (2\text{--}4) \times 10^4$ K. Much of this gas is piled up between the “heliopause” and the bow shock, forming a “hydrogen wall”

that can be detected through excess absorption of the Ly α line. The measured absorption depths are then compared with results from hydrodynamic model calculations. It is found that the astrospheric absorption should scale with the wind ram pressure, which itself scales with the mass-loss rate assuming that the wind velocity is constant. A systematic observational study shows that dM_w/dt correlates with the stellar X-ray luminosity (L_X) and with stellar age (t),

$$dM_w/dt \propto L_X^{1.34 \pm 0.18}$$

and equivalently,

$$dM_w/dt \propto t^{-2.33 \pm 0.55}$$

The stellar-wind mass loss can therefore – in principle – be used as a genuine activity indicator. The mass loss is thus expected to be higher in young, magnetically active stars. Extrapolating the above law up to stars at the saturation limit (with an average surface magnetic flux of $2 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$) suggests dM_w/dt of the youngest solar analogs to be about a thousand times higher than the present-day solar mass loss ($dM_w/dt \approx 2 \times 10^{-14} M_\odot \text{ year}^{-1}$). The above power-law relations appear to break down for the most active stars, however. While intermediately active stars may reach mass-loss rates two orders of magnitude higher than the Sun, the most active, youngest main-sequence stars suggest loss rates no more than about ten times the present solar value. The cause for this breakdown has not been identified but could be related to the appearance of high-latitude active regions (spots) in the most active stars; if the magnetic field becomes more akin to a global dipole, then wind escape may be inhibited in such stars.

The Rotation Rate of the Young Sun

Because the magnetized stellar winds transport angular momentum away from the star, a solar analog spins down with age. The rate of change of angular momentum is related to the mass-loss rate, the rotation rate, and the Alfvén radius. For solar analogs, the rotation period is

$$P = 0.21 t_6^{0.57} [\text{d}]$$

where t_6 is the age in Myr after arrival on the ZAMS and d means day. This equation implies an increase in rotation period from ZAMS age to the end of the main-sequence life by a factor of about 20.

For solar analog stars with ages of less than a few hundred million years, the [stellar rotation](#) period is not a function of age but of the pre-main-sequence history, especially the history of circumstellar-disk dispersal. Once the inner disk disappears, the lack of magnetic locking via star-disk magnetic fields and the contraction of the star toward the main sequence will spin up the star and thus determine the initial rotation period on the ZAMS. After arrival on the main sequence, the angular momentum loss in a wind will decrease the magnetic activity and presumably also the wind mass loss itself; therefore, the rotation period will eventually converge to a value that is only a function of age, as specified above.

The Evolution of the Solar Magnetic Field

Polarization measurements of the integral light from solar analog stars have provided important information on the average field strength of magnetic areas on the star, including corresponding surface filling factors. Doppler imaging methods have further deepened our understanding of the size, distribution, location, and evolution of stellar magnetic fields.

Whereas maximum magnetic-field strengths in younger solar analogs are similar to the present-day Sun, the filling factors of magnetic active regions are much higher; spot coverage of order 10% is common and testifies to much increased magnetic activity in the young Sun. This obviously relates to an enhanced dynamo as a result of the increased rotation rate of young solar analogs.

Although surface spot distributions vary significantly between young solar analogs, most stars show evidence of high-latitude magnetic activity and the presence of polar spots. The origin of polar magnetic activity has been related to strong Coriolis forces acting on magnetic flux bundles

that rise from the dynamo region of the star. This force would deflect rising flux to higher altitudes. Alternative models use magnetic bipoles (structures with two footpoints of opposite polarities) injected at various heliocentric latitudes and migrating along meridional flows. A high injection rate of interacting bipoles leads to the formation of nested polar rings of opposite polarity.

The Evolution of Solar Activity and High-Energy Radiation

Stellar evolution calculations indicate that the young, zero-age main-sequence Sun was bolometrically about 30% *fainter* than at present. This trend is related to the fact that hydrogen is slowly being converted into helium in its core, raising the density and causing corresponding increases in temperature and the rate of nuclear fusion.

This slow, evolutionary increase in optical luminosity of the Sun contrasts sharply with all radiation that is related to magnetic activity. Meteoritic evidence indicates that the Sun was magnetically much more active in its youth than at present. This direct evidence is fundamentally supported by observations of young solar analogs that show systematically higher levels of magnetic activity and related electromagnetic radiation.

The cause of this steady decline of magnetic activity during the main-sequence evolution is, as already mentioned above, the declining dynamo as a star spins down by losing angular momentum through its magnetized wind. Because magnetic activity is particularly important for the generation of short-wavelength radiation (ultraviolet emission from the chromosphere and the TR; EUV and X-rays from the TR and the corona), this part of the spectrum shows particularly strong evolutionary trends; the short-wavelength input into planetary atmospheres thus diminished significantly with time.

The young Sun showed stronger rotationally induced modulation in the optical light due to surface magnetic spots but also due to magnetic activity cycles that induced light variations up to 0.3 magnitudes in the course of spot cycles; such cycles have been found in solar-like stars, with cycle periods ranging from 2 to 13 years. The presence of excess emission from photospheric

faculae outweighs the darkening by the spot area in old solar analogs, making these stars slightly brighter in optical light during activity maxima, while in young stars, spots dominate and make them fainter. Cycles are not present in all solar-like stars, however, and irregular variations abound among very active examples.

The increased magnetic activity in younger solar analogs enhances ultraviolet emission from transition regions by factors of a few, in particular in emission lines forming at temperatures around 10^5 K. Much more dramatic changes must have occurred in the evolution of the shorter-wavelength radiation from the solar corona (Fig. 6). Studies of solar analogs with ages of tens to about hundred million years in young stellar clusters and in the field indicate X-ray and EUV luminosities exceeding the present-day solar output by several hundred to approximately thousand times. The same is true for stars in the younger, pre-main-sequence T-Tauri phase.

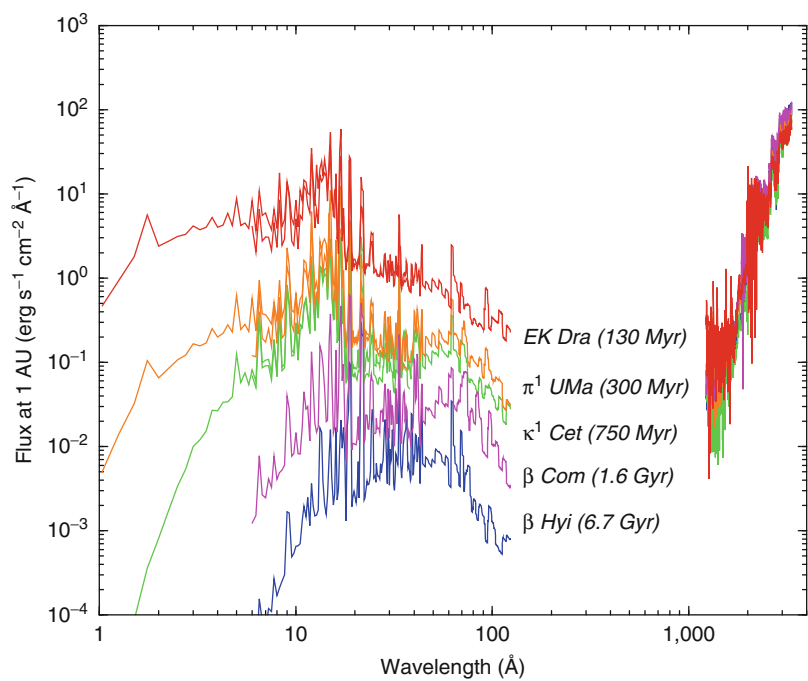
This enhanced radiation is a consequence of higher-density coronal plasma combined with a much larger filling factor of magnetic active regions. Also, the characteristic temperature of young coronae is higher, reaching average levels of 10–20 million K (Sun: two million K), and therefore the X-ray emission is much harder than X-rays from the present-day solar corona. How the corona can be kept three orders of magnitude more energetic and ten times hotter than the present-day solar corona is unclear; an interesting possibility is excess heating by a high rate of flares. Such “continuously flaring coronae” may be important as they also produce appreciable levels of gamma rays and high-energy particles that interact with planetary atmospheres.

The decaying trends of the short-wavelength radiation are well fitted by power laws that become *steeper toward shorter wavelengths*, as summarized in Table 2. A power-law decay law has been assumed for the rotation rate with age t , $\Omega \propto t^{-0.6 \pm 0.1}$. Table 3 provides numerical estimates for the solar spectral irradiance at various ages.

X-ray radiation thus suffered by far the strongest reduction (by three orders of magnitude) in the course of the Sun’s history, initially achieving

Sun (and Young Sun),

Fig. 6 Solar irradiance in the ultraviolet, extreme ultraviolet, and X-ray ranges for various ages of the Sun as derived from observations of solar analogs. The irradiance refers to a distance of 1 AU from the Sun in the absence of a planetary atmosphere. Stellar names and ages are given in the middle of the figure (where radiation is absorbed by the interstellar gas). (Reproduced by permission of ASP)



Sun (and Young Sun), Table 2 Long-term trends of short-wavelength solar radiation

Radiation type	Symbol	Relation with rotation	Relation with age
UV line radiation from chromosphere	L(chrom)	$\propto P^{-1.25 \pm 0.15}$	$\propto t^{-0.75 \pm 0.1}$
UV line radiation from transition region	L(TR,UV)	$\propto P^{-1.6 \pm 0.15}$	$\propto t^{-1.0 \pm 0.1}$
FUV from transition region (920–1180 Å)	L(TR,FUV)	$\propto P^{-1.4}$	$\propto t^{-0.85}$
EUV/X-rays from corona (20–360 Å)	L(EUV)	$\propto P^{-2.0}$	$\propto t^{-1.2}$
X-rays from corona (1–20 Å)	L _X	$\propto P^{-3.2}$	$\propto t^{-1.9}$

Sun (and Young Sun), Table 3 Enhancement factors of solar irradiance in solar history^a

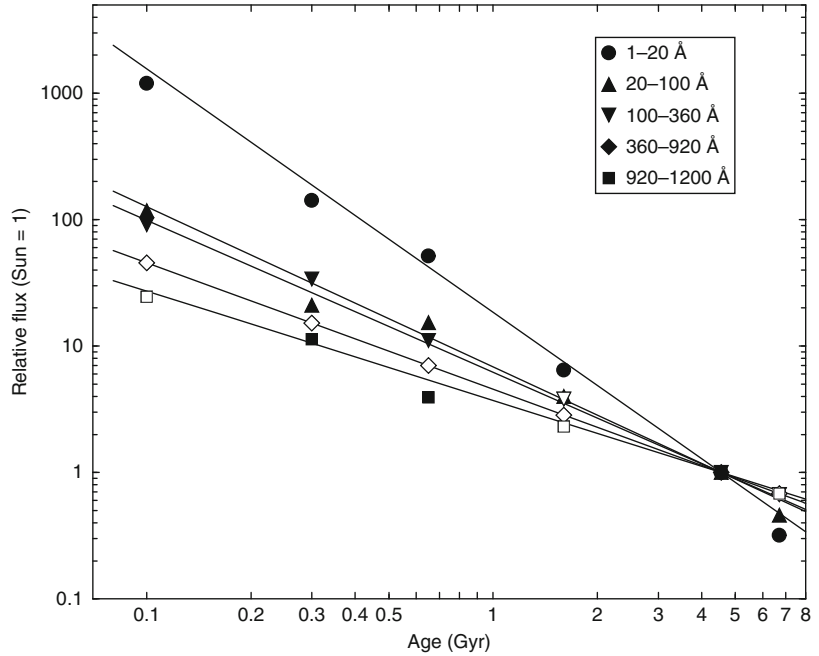
Solar age (Gyr)	Time before present (Gyr)	X-rays (1–20 Å)	Enhancement in soft X-rays (20–100 Å)	FUV (920–1180 Å)	UV lines, transition region	UV lines, chromosphere
			EUV (100–360 Å) XUV (1–1180 Å)			
0.1	4.5	1,600 ^b	100	25	50	18
0.2	4.4	400	50	14	20	10
0.7	3.9	40	10	5	7	4
1.1	3.5	15	6	3	4	3
1.9	2.7	5	3	2	2.4	2
2.6	2.0	3	2	1.6	1.8	1.5
3.2	1.4	2	1.5	1.4	1.4	1.3
4.6	0	1	1	1	1	1

^aNormalized to zero-age main-sequence age of 4.6 Gyr before present. (Table adapted from Güdel 2007)

^bLarge scatter possible due to unknown initial rotation period of the Sun

Sun (and Young Sun),

Fig. 7 Decay of the irradiance in time for a solar analog for different spectral bands, normalized to the present-day levels. The decay is steepest for the shortest wavelengths. (Reproduced by permission of the AAS)



as much as 0.1% of the bolometric output or $(2-4) \times 10^{30} \text{ erg s}^{-1}$. The trends are graphically illustrated in Fig. 7.

Applications

At its ZAMS stage, the Sun's luminosity was only 70% of its present-day level. In the absence of an atmosphere, the Earth's surface equilibrium temperature would then have amounted to 255 K. Assuming an albedo and an atmospheric composition equal to values of the present-day Earth, the mean surface temperature would have been below the freezing point of seawater until ≈ 2 Gyr ago. The increase of the surface temperature in the presence of an atmosphere is due to the greenhouse effect. The present-day atmosphere of the Earth raises the surface temperature by only 33 K compared to the atmosphere-free equilibrium value. Evidence for a mild early climate both on the Earth and Mars (the [Faint Young Sun Paradox](#), FYSP) either requires substantially more effective greenhouse mechanisms from the presence of larger amounts of, for example, CO_2 or methane or a lower albedo (see [Faint Young Sun Paradox](#)).

Increased wind mass-loss rates may solve the FYSP as well. The Sun itself may have been more luminous in its past, which would imply that it had a higher mass by a few percent, having lost the extra mass by the solar wind and CMEs. However, estimates of the total wind mass loss seem to be insufficient to support this model (see [Faint Young Sun Paradox](#)).

The ionized and magnetized solar wind interacts strongly with planetary magnetospheres and atmospheres. Wind-planet interactions have played an important role in the formation and evolution of planetary atmospheres and consequently the formation of life on Earth. Irradiation of upper atmospheric layers by high-energy (EUV, X-ray) photons leads to atmospheric heating in the thermosphere and eventually to thermal escape from the exosphere above the thermosphere. In the exosphere, the mean free path of the particles is large; particles, in particular hydrogen atoms, with thermal energies exceeding the gravitational binding energy escape into space (Jeans escape). If in the upper atmosphere the mean particle energy exceeds the gravitational binding energy ($kT > mv_{\text{esc}}^2/2$, where v_{esc} is the escape velocity), then the exosphere becomes unstable and escapes ("blows off") into space.

Evaporation played an important role in early Venus. If surface water was initially present in large quantities, it would have evaporated due to a more efficient greenhouse (Ingersoll 1969; Kasting 1988) and subsequently dissociated in the high atmosphere due to strong solar EUV irradiation (Kasting and Pollack 1983) after which hydrogen atoms escaped to space. Hydrodynamic escape conditions for hydrogen applied as long as 250 Myr after the Sun's arrival on the main sequence; a terrestrial water ocean could have escaped in as little as 50 Myr from Venus (Kulikov et al. 2007).

For the young Mars, there is clear evidence for a warmer climate and liquid surface water. Evidently, a strong greenhouse would be required, but its origin is debated (Chassefière and Leblanc 2004). Hydrodynamic escape conditions may have applied to Mars during the first few hundred million years for hydrogen (Kulikov et al. 2007) and possibly for heavier gases such as C, N, and O as well (Tian et al. 2009).

Atmospheric escape is also driven by the interaction of high-energy (nonthermal) particles and the solar wind; here, the escape process is related to microscopic, nonthermal mechanisms, in particular dissociative recombination or photochemical escape (in which the forming neutrals are energetic), ion pickup (in which ions produced by photons or particle irradiations are dragged along by magnetic fields), ionospheric outflow, and ion sputtering (in which newly produced atmospheric ions re-impact and eject neutral particles; see, e.g., Chassefière and Leblanc 2004; Kulikov et al. 2007; Lundin et al. 2007). These processes are thought to have fundamentally altered the atmospheres of Venus, Earth, and Mars, leading to strong loss of oxygen (Lammer et al. 2006) and therefore water after its photodissociation in the upper atmosphere. The amount of shielding depends on the strength of the wind and its ability to compress the magnetosphere. A strong magnetosphere around the Earth, shielding the lower atmospheric layers, may have been instrumental in retaining much of its water and making it habitable.

In the case of the young Venus, oxygen could have been lost from the atmosphere as a consequence of ion pickup by the solar wind in a matter

of tens of million years (Lammer et al. 2006; Chassefière 1997), but a very strong solar wind – perhaps stronger than inferred indirectly for the young Sun – would have been required. A similar process as well as sputtering may have applied to the young atmosphere of Mars. But for Mars, the lack of a magnetic shield already early on in its evolution further strengthened interactions between the strong solar wind and the upper atmosphere, and escape processes were additionally enhanced by the weak gravitational potential of Mars. Some calculations indicate that a global Martian ocean of 12–15-m depth may have been lost as a consequence of such processes (Lammer et al. 2003; Chassefière and Leblanc 2004).

Coronal mass ejections (CME) add significantly to atmospheric erosion. An ejection rate of several CMEs per day acts like an enhanced solar wind and will therefore further compress planetary magnetospheres and erode the upper atmospheres (Khodachenko et al. 2007), especially in combination with enhanced exospheric heating by EUV irradiation and its consequent exospheric expansion (Lammer et al. 2007).

The future Sun will continue to affect planetary atmospheres and therefore habitability significantly, albeit in a progressively different way. As the solar bolometric output will gradually increase during the next 5 Gyr, the surface temperatures of the planets will increase. For the Earth, an increase by 60–70 K was predicted (Sagan and Mullen 1972). Beyond that phase, Sun-planet interactions will start changing fundamentally as the Sun will develop toward its giant phase. Then, it will expand considerably although its surface temperature will drop; at the same time, a strong solar wind mass loss will set in, but at that time the habitable phase of the Earth will be long gone. Eventually, a planetary nebula will be ejected from the Sun, expanding across the solar system and beyond.

Future Directions

Solar physics is an extremely rich field, involving the study of the solar interior, magnetic-field generation in a dynamo, plasma physical processes in the outer atmosphere, and various processes of particle acceleration and heating. Some of the

most pressing issues in solar physics and related stellar astronomy are listed below:

- The precise solar composition in terms of chemical elements, which is of fundamental importance to test the standard model of the solar interior.
- A comprehensive theory of solar magnetic-field generation in the internal dynamo.
- The problem(s) of chromospheric and coronal heating by waves and/or magnetic processes, possibly involving microflares and nanoflares.
- The acceleration and heating of the solar wind.
- Direct detection of ionized stellar winds based on radio emission.
- Improved modeling of interactions between the solar wind or solar radiation and young planetary atmospheres.

Cross-References

- [Astero-seismology](#)
- [Chronological History of Life on Earth](#)
- [Faint Young Sun Paradox](#)
- [Mass-Luminosity Relation](#)
- [Solar Constant](#)
- [Solar Luminosity](#)
- [Solar Particle Events](#)
- [Solar UV Radiation, Biological Effects](#)
- [Space Environment](#)
- [Stellar Evolution](#)
- [Stellar Rotation](#)
- [Stellar Winds](#)
- [Zero Age Main Sequence](#)

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Super-Earths

Nader Haghighipour

Institute for Astronomy, University of Hawaii-
Manoa, Honolulu, HI, USA

Keywords

Exoplanets · Mini-Neptunes · Transit · Kepler
space telescope

Definition

Super-Earth is the suggested term for a diverse class of planets with masses ranging from two to ten Earth masses. Prior to the operation of the *Kepler* space telescope, the value of the minimum mass of a planet was used to define the term “super-Earth.” After the detection of many small planets by the *Kepler* telescope, in the interest of identifying small, rocky planets that could be habitable, in addition to mass, a radius criterion was also added to the definition. A “super-Earth” is, therefore, a planet with a mass of two to ten Earth masses and radius of 1–1.8 Earth radii.

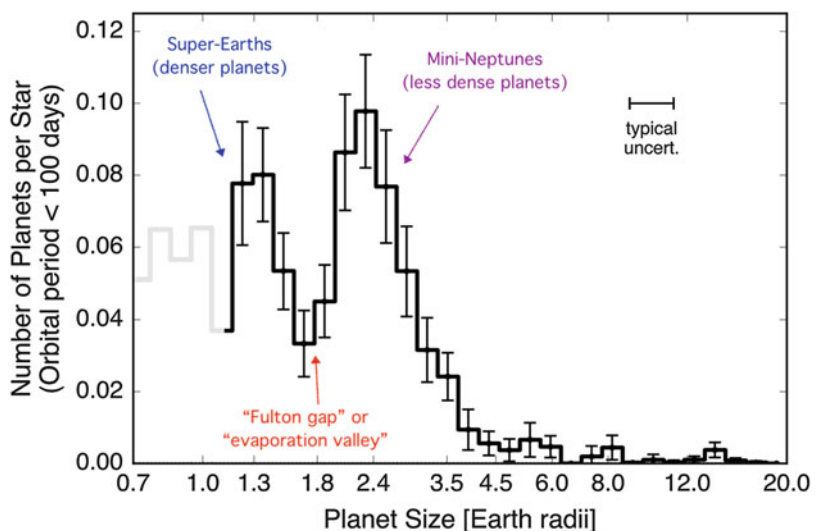
Overview

The first super-Earth around a main sequence star was discovered by Rivera et al. (2005) using the radial velocity technique. (Note that in 1992, Wolszczan and Frail (1992) discovered at least two terrestrial-sized planets around the pulsar PSR 1257+12. See the entry on “► [Pulsar Planets](#).”) Thanks to several ground- and space-based observational projects, to date, the number of these objects has exceeded 900. One major outcome of the *Kepler* satellite survey has been to show that super-Earths are very common and its population is now better characterized. In particular, Fulton et al. (2017) showed that using high-resolution spectroscopy to obtain more precise stellar properties, the population of super-Earth could be differentiated from the population of mini-Neptunes (see Fig. 1). Later, improving the stellar parameters using the precise astrometry allowed by the satellite *Gaia* allowed to constrain the two populations even better (Fulton et al. 2018). More details can be found in the entry “► [Transiting Planets](#).”

For the past few years, the formation and characteristics of super-Earths have been the subject of extensive research. This is primarily because being slightly larger than a typical terrestrial planet, these

Super-Earths,

Fig. 1 Radius distribution of the super-Earths and mini-Neptune planets. (Figure adapted from Fulton et al. (2017)). The peak on the right corresponds to the mini-Neptune family: planets which are thought to be dominated by a thick hydrogen and helium atmosphere, the left peak corresponds to the population of super-Earths, that is, planets with a higher density, which could be predominantly rocky



objects can have a solid surface with a solid-to-gas or liquid-to-gas phase transition at their upper boundary, similar to Earth. Super-Earths have the capability of developing moderate atmospheres and may have dynamic interiors with plate tectonics – two conditions that would render a super-Earth potentially habitable if its orbit were in the habitable zone of its host star.

Unlike Earth-sized planets, super-Earths are relatively easy to detect. Current observations of super-Earths have indicated that these objects seem to be more common around cool and low-mass stars (e.g., Dressing and Charbonneau 2013; Swift et al. 2013), where the habitable zone is in closer orbit. Two prime examples of such systems are Gliese 581, an M3V star with one or two potentially habitable super-Earths, and the M1.5 star GJ 667C, with up to three super-Earths in its habitable zone including the 4.5 Earth-mass planet GJ 667Cc. A recent example, which has stirred the community, is K2-18, an eight Earth-mass planet in the Habitable Zone of its M2.5 dwarf star. Using the Hubble Space Telescope, several teams managed to detect water vapor and clouds in its atmosphere (Benneke et al. 2019; Tsiaras et al. 2019). However, K2-18 with a radius of about 2.6 Earth radius is more likely to be a mini-Neptune than a super-Earth. Nonetheless, this observation shows that atmospheric characterization is improving toward the detection of important atmospheric species around smaller and smaller planets, which is a necessary step to 1 day detect life.

Cross-References

- Atmosphere, Structure
- Biomarkers, Spectral
- Habitability of the Solar System
- Habitable Planet, Characterization
- Habitable Zone
- Mini-Neptunes
- Modelling Terrestrial Planetary Atmospheres

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Supercontinent

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

A supercontinent is a landmass comprising a large fraction of the entire continental crust. It is the product of the assembly of many smaller

continents into one single continent. Supercontinents form in cycles (e.g., Mitchell et al. 2021), coming together and breaking apart about every 300–500 million years as a result of the plate-tectonic movements (Wilson's cycle). Pangea is the last supercontinent, which broke out 300 to 200 Ma ago to form the present-day continents. The assemblage and break out of supercontinents seem to affect the entire Earth system, by controlling sea level and chemistry, oceanic circulation, and climate, and possibly provoking mass extinctions or life explosions.

Cross-References

- [Mass Extinctions](#)
- [Pangea](#)
- [Plate Tectonics](#)

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Supercritical Fluid

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

A supercritical fluid is a substance at a temperature and pressure above its critical point. It can effuse through solids like a gas and dissolve materials like a liquid. Supercritical fluids thus have properties between those of a gas and a liquid.

Supercritical fluids have no surface tension, as there is no liquid/gas phase boundary. By changing the pressure and temperature of the fluid, the properties can become more liquid-like or more gas-like. The solubility of dissolved substances in a supercritical fluid tends to increase with the density of the fluid at a constant temperature. Since density increases with pressure, solubility tends to increase with pressure. The relationship with temperature is more complex. At constant density, solubility increases with increasing temperature. Close to the critical point, however, the density can drop drastically with slight increases in temperature. Thus, close to the critical temperature, solubility may drop with increasing temperature and then rise again.

Submarine hydrothermal vents are widely distributed on the ocean floor. Many lie at great depth where the tremendous pressure from the overlying seawater prevents the explosive release of steam and gas. In some cases, seawater can be heated to over 400–465 °C, where it becomes a supercritical fluid depending on the ambient pressure.

The atmosphere of Venus is composed of 96.5% CO₂ and 3.5% N₂. The surface pressure is 9.3 MPa, and the surface temperature is 735 K, well above the critical points of both gases; thus, the atmosphere near the surface is a supercritical fluid.

Superkingdom

- [Domain \(Taxonomy\)](#)

Supernova

Robert Mochkovitch
Institut d'Astrophysique de Paris, Paris, France

Keywords

Chandrasekhar mass · Collapse · Cosmology · Dense matter · Massive stars ·

Nucleosynthesis · Stellar evolution · Shock wave · Thermonuclear reactions · White dwarfs

Definition

Supernovae are cataclysmic explosions of stars at the end of their evolution. Two categories of stars are known to explode: massive ones ($M > 8\text{--}10 M_{\odot}$; $M_{\odot}$ is the solar mass) and white dwarfs (the remnants of low mass stars) if they can grow by accretion in a binary system. When they explode, supernovae inject energy into the ► [interstellar medium](#) and eject ► [heavy elements](#) such as carbon, oxygen, or ► [iron](#). Supernovae are one of the main contributors to the chemical evolution of galaxies.

History

Five times in the last millennium, a new star suddenly appeared in the sky. Initially very bright, it progressively declined to finally disappear after a few months or a few years. The first star, in 1006, was the brightest one, even visible during daytime. It was followed in 1054 by a new event described as a “guest star” by the Chinese astronomers. The remnant of this object is the famous Crab nebula in the Taurus constellation. A third, less bright supernova was seen in 1181. Then, nothing was noticed until 1572 when the Danish astronomer Tycho Brahe observed another new star in Cassiopeia and recorded his observations in Latin in his work, “De nova stella.” Only 32 years later, in 1604, Kepler studied the last one of these extraordinary events. We now know that they all were supernovae having exploded in our own galaxy, the ► [Milky Way](#). The modern study of supernovae started during the thirties with F. Zwicky (who coined the word supernova). He launched a search for supernovae in external galaxies which was very successful with more than 100 discoveries in about 30 years. In 1987, a supernova was found in the Large Magellanic Cloud, a small irregular satellite galaxy of

the Milky Way, 150,000 light years from us. Reaching magnitude 4.5 at its maximum, it was barely visible with the naked eye but still the brightest supernova since 1604.

Overview

Supernovae represent the end point of evolution of two main categories of stars: (1) the most massive ones ($M > 10 M_{\odot}$) which successively fuse hydrogen, helium, carbon, oxygen, neon, and silicon in their cores, eventually leading to the formation of a central core made of iron (Stars between 8 and $10 M_{\odot}$ do not burn oxygen but probably also produce a supernova by a different mechanism, resulting from the captures of electrons by the oxygen, neon, and magnesium nuclei present in their core). When this core approaches $1.4 M_{\odot}$, it becomes unstable and collapses. However, when the central density reaches a few times 10^{14} g/cm^3 (the density of nuclear matter), the core bounces and launches a strong shock wave outward which ejects the envelope at velocities exceeding 10,000 km/s. (2) The second category is white dwarfs (the remnants of stars with $M < 8 M_{\odot}$), which can explode if they accrete material from a companion star in a binary system. The accretion process can occur by progressive mass transfer from the companion or by true coalescence, if the binary is made of two white dwarfs. The ► [white dwarf](#) material (a mixture of carbon and oxygen) ignites ► [nuclear reactions](#) in an explosive way and the combustion propagates to the whole star, which is entirely destroyed. The first group represents the so-called core-collapse supernovae, while the second corresponds to “thermonuclear supernovae.” Besides their own interest, supernovae play a key role in the chemical and dynamical evolution of galaxies: they synthesize heavy elements and inject energy into the interstellar medium which triggers the formation of new stars. Cosmic rays are also accelerated in the shock waves present in their remnants. Due to their extreme luminosity (over 1 billion solar luminosities), they can be detected at very large distances and used for cosmological studies.

Basic Methodology

The nature of the stars ending their evolution as supernovae and the physical mechanisms responsible for the explosion are studied through a close interplay between observational and theoretical research. Spectroscopy provides clues on the progenitor stars (composition of the envelope) and energetics of the explosion (expansion velocity obtained through the Doppler effect). The light curve (i.e., the luminosity as a function of time) offers additional information on the sources of energy and constraints the mass and radius of the envelope.

The classification of supernovae was originally (and largely remains) based on spectroscopy. Hydrogen lines are absent from type I supernova spectra and present in type II. Moreover, type I supernovae have been divided into three subclasses: at maximum light (the peak of the light curve), type Ia (SN Ia) exhibit lines of intermediate mass elements (especially a bright silicon line) while they show mainly iron and cobalt lines at late times. Helium lines dominate SN Ib spectra at maximum light and are absent in SN Ic. Conversely, SN II have conspicuous hydrogen lines both at maximum light and at late times.

Population studies, which relate supernovae to their environment, show that SN Ib/c should be clearly distinguished from SN Ia. Like SN II, they are only observed in regions of ongoing star formation, contrary to SN Ia which are present in all kinds of environments, including elliptical galaxies which have not formed stars for several billion years. SN Ib/c and SN II progenitors should then be massive stars which only live a few million years and are therefore expected to explode close to their birthplace. The absence of hydrogen in SN Ib/c can be explained by mass loss due to stellar winds prior to the explosion. In SN Ib the helium layer lying below the lost hydrogen envelope remains, while in SN Ic it is also lost, leaving the “stripped” carbon and oxygen-rich core of the star.

The progenitors of SN Ia are low mass stars – the only ones remaining in an old stellar population – which should also be highly evolved to have lost all their hydrogen. This suggests an explosion scenario involving a white dwarf.

White dwarfs are the remnants of low mass stars ($M < 8 M_{\odot}$). They are perfectly stable when isolated but can become explosive if their mass is brought by accretion close to the Chandrasekhar limit ($1.4 M_{\odot}$; see ► [Chandrasekhar’s Limit](#)).

Theoretical models of SN Ib/c and SN II supernovae invoke the collapse of the central core of the star, which becomes a ► [neutron star](#) or even possibly a ► [black hole](#) (these supernovae are now globally called “core-collapse supernovae”). Most of the gravitational energy released in the collapse is carried away by neutrinos, but less than 1% of the total is sufficient to power the explosion. For SN Ia, a thermonuclear runaway which incinerates and destroys the whole star appears able to account for the major observational facts.

These various explosion mechanisms are studied by numerical simulations involving both a complex hydrodynamics (multidimensional treatment of the fluid motion) and input physics (equation of state of dense matter, neutrino transport). The general explosion scenarios outlined above are probably correct, but many questions are still unsolved and the study of supernovae remains an active research field.

Key Research Findings

Core-collapse and thermonuclear supernovae have very different explosion mechanisms, but the concept of Chandrasekhar mass plays a key role in both. It represents the maximum possible mass for an object “supported by electron pressure,” the interior of which is “degenerate.” In degenerate matter, the usual thermal pressure is replaced by a pressure of quantum origin, resulting from the impossibility for two electrons to be in the same quantum state (Pauli’s exclusion principle).

After successive episodes of nuclear burning (fusion), massive stars terminate their evolution having an “onion-shell structure” with a central degenerate iron core surrounded by non-degenerate layers of lighter elements from silicon (next to the core) to the outer hydrogen envelope, if it is present. Iron is the most stable nucleus and cannot undergo further burning. As a result of

silicon burning, the core mass grows – iron nuclei being the nuclear ashes of silicon – and eventually reaches the Chandrasekhar limit where it becomes unstable. It collapses in less than 1 s until the central density reaches a few times 10^{14} g/cm^3 (i.e., 100 million tons per cm^3 !). This corresponds to the density of nuclear matter, where nuclei are brought into contact with each other. Nuclear matter is strongly incompressible and provides an additional pressure which stops the collapse of the inner $0.6\text{--}0.8 M_{\odot}$ of the core. The outer core violently bounces on it and acts as a piston moving outward. A strong shock wave forms and it was initially believed that it carried enough energy to power the explosion. However, it was subsequently shown that, due to energy losses behind the shock (mainly the breakup of iron nuclei into free nucleons), the bounce alone was not able to produce an outburst. Additional energy coming from the neutrinos escaping from the cooling inner core was then invoked. Neutrino interaction with normal matter is very weak, but the extreme densities encountered in the shock region may allow the transfer of a small fraction of the neutrino energy to heat the core and restart the shock propagation. Unfortunately, numerical simulations of this process are so complex that no clear consensus has been reached among the different groups of experts: some get a successful explosion, while for others the material falls back.

White dwarfs are also made of degenerate material (a carbon-oxygen core surrounded by a helium layer in SN Ia progenitors), so that they become potentially explosive if their mass increases. This may happen if they receive material from a companion star by mass transfer in a binary system. Two evolutionary channels are a priori possible: slow accretion of matter outflowing from the companion or direct coalescence in a system of two white dwarfs. In the first case, carbon is ignited at the star center when the white dwarf approaches the Chandrasekhar limit. Nuclear burning in degenerate material is explosive and rapidly extends outward, the whole star being eventually destroyed. In the second case, coalescence results from the decrease of orbital separation caused by the emission of gravitational

radiation from the system. At some point, the less massive of the two white dwarfs (which has the largest radius) is disrupted and coalescence ensues in about 1 min. Nuclear fuel (first helium and then carbon and oxygen) ignites in the collision region and the combustion now proceeds inward. Again, the white dwarf is entirely destroyed.

A major uncertainty comes from the difficulty of estimating the velocity of propagation of the burning front. It can be supersonic (and then called a “detonation”) or subsonic (“deflagration”). Some models adopt a mixture of the two, starting with a deflagration which evolves into a detonation. Complete burning of the inner $0.6\text{--}0.8 M_{\odot}$ leads to ^{56}Ni , a radioactive isotope of nickel which decays into cobalt and iron, releasing energy which powers the light curve. The outer region undergoes incomplete burning leading to elements such as silicon or sulfur. This distribution of nucleosynthetic products agrees well with the results from spectroscopy.

Applications

- If stars did not explode, all the elements formed by nucleosynthesis during their lifetime (and during the explosion itself) would stay trapped in stellar interiors. Supernovae allow most of them to be ejected into the interstellar medium, which then gets progressively enriched in heavy elements (just after the Big Bang, the universe contained only hydrogen, helium, and very small fractions of deuterium, lithium, and beryllium). Carbon (the elementary brick of all organic molecules), oxygen, and silicon, for example, come from core-collapse supernovae, while SN Ia are the main providers of iron. It is remarkable to realize that all the atoms from which human beings are made (except hydrogen) were formed in stars which have disappeared before the solar system formed, 4.5 billion years ago. Supernovae also inject energy into the interstellar medium. They drive strong shock waves which create bubbles filled by hot gas. At the boundaries of these bubbles, the formation of new stars is triggered.

- Supernovae are so bright that they can be detected to cosmological distances. This is especially important in the case of SN Ia which are also considered to be reasonably good “standard candles,” that is, objects which all have the same luminosity. A plot of their apparent magnitude (at maximum light) as a function of redshift, called the Hubble diagram, can then be used to constrain cosmological models. This has shown that the expansion of our universe is accelerating (and not decelerating as was previously believed), which implies that space is pervaded by some form of “dark energy,” the nature of which remains unknown.

Future Directions

The details of the mechanism responsible for the explosion of core-collapse supernovae are still highly debated. Numerical simulations of the whole process are very difficult and only a few groups in the world are performing them. It has been recently realized that supernova explosions might be asymmetric due to a new kind of instability developing shortly after core bounce. It is also believed that this instability may greatly help obtain successful explosions as recently suggested by simulations in three dimensions. A related question concerns the separation between models giving a neutron star remnant and those collapsing to a black hole. What are the key factors controlling the fate of the star? Is the initial mass the only important parameter? How critical is the amount of rotation present in the core?

In the case of SN Ia, the respective roles of detonation and deflagration in the burning mechanism are still unclear, but the main issue remains the nature of the progenitors: standard accretion from a normal star and coalescence of a system of two white dwarfs represent two possible channels. We don't know how they contribute to the rate of SN Ia in different ► [stellar populations](#) and even if they always both contribute.

Cross-References

- [Black Holes](#)
- [Chandrasekhar's Limit](#)
- [Explosive Nucleosynthesis](#)
- [Heavy Element](#)
- [High-Mass Star](#)
- [Neutron Star](#)
- [Nova](#)
- [Nuclear Reaction](#)
- [Nucleosynthesis, Stellar](#)
- [Pulsar](#)
- [R-Process](#)
- [Stars](#)
- [Stellar Evolution](#)
- [Stellar Yield](#)
- [Supernova Remnant](#)
- [Supernova Types](#)
- [White Dwarf](#)

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Supernova Remnant

Thierry Montmerle

Institut d'Astrophysique de Paris, Paris, France

Definition

In the optical domain, supernova remnants (SNR) appear as spectacular, bright filamentary nebulae, testifying to the past explosion of a star. There are two main types of SNRs, depending on the type of the explosion: (1) In “shell-type” SNRs, the nebula is hollow and filaments are arranged more or less in the form of concentric circular shells, and are interpreted as shock waves triggered by the explosion, propagating into the interstellar medium at velocities of up to a few 1000 km/s. Famous representatives of this class are the “Cygnus Loop” and the “Medusa” in the constellation Gemini. (2) In “filled-type” SNRs, also known as “plerions” (from a Greek word

meaning “full”), the nebula looks like a web of filaments of stellar origin, emanating from a bright center. Plerions contain a ► [pulsar](#) (a rotating, very condensed star called a “neutron star”). The most famous representative of the class is the “Crab nebula,” illustrated in Fig. 1. Supernova remnants are also conspicuous in the radio centimetric range and in X-rays. Since these wavelengths are much less sensitive to interstellar extinction than the optical, supernova remnants are known at large distances throughout the Galaxy. Many are also known in the galaxies nearest our own, the Magellanic Clouds.

History

Today nearly 300 SNRs are known, the majority having estimated ages from several thousand to several hundred thousand years. Six supernova explosions have been witnessed with a naked eye in historical times, many being recorded by Chinese astronomers, like the Crab nebula in AD

Supernova Remnant,

Fig. 1 The “Crab Nebula,” in the Taurus constellation is the remnant of a supernova that exploded in 1054 AD. The filaments are the remains of the parent star, and the diffuse light is due to energetic electrons accelerated by the central pulsar. (Photograph ESO Very Large Telescope)



1054. The first one was recorded in AD 185, and the last appeared in 1987 in the Large Magellanic Cloud. Two more are known to have exploded in the Milky Way during historic times (around 1671 and 1870), but were not seen because of the high interstellar dust obscuration.

Cross-References

- [Pulsar](#)
- [Supernova](#)

Supernova Types

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

Supernovae are classified according to their early spectra as Type I (SNI) or Type II (SNII), depending on the absence or presence of hydrogen, respectively. SNI are further divided into SNIa (Si present), SNIb (Si absent, He present), and SNIc (Si and He absent, C present). It turns out that SNIa correspond to thermonuclear explosions of ► [white dwarfs](#) in binary systems, while all other types result from the gravitational collapse of the core of a massive star that has lost various amounts of its envelope (little H in SNII, all of H in SNIb, and all of H and He in SNIc). It is expected that in a galaxy like the Milky Way, 2 SN per century explode, SNIa are five times less frequent than gravitational supernovae and (SNIb+SNIc) are three times less frequent than SNII.

Cross-References

- [Supernova](#)
- [Supernova Remnant](#)
- [White Dwarf](#)

Superrotation

Agustín Sánchez-Lavega
Escuela de Ingeniería de Bilbao, Universidad del País Vasco UPV/EHU, Bilbao, Spain

Keywords

Planetary Atmospheres · Planetary rotation · Atmospheric dynamics · Meteorology

Synonyms

[High speed jetstream](#)

Definition

Superrotation refers to the state in which the atmosphere of a planet or a satellite has an angular velocity much higher than that of the body or a much shorter period of rotation than that of the body.

Overview

All planets and satellites rotate around an axis with very different periods, the longest is that of Venus with 243 days and the shortest is that of Jupiter with 9.92 h. An atmosphere that does not move with respect to the direction of rotation is in solid body rotation (i.e., is in corotation with the underlying planet surface or the planet itself). If the atmosphere moves with respect to the rotation of the body, it is in a super- or sub-rotating state depending on the rotation direction. If the motion takes place in the same direction as the rotation of the planet, it is prograde (retrograde if it is in the opposite sense). To characterize the magnitude of this phenomenon on each planet, one can use different types of indexes (Read and Lebonnois 2018). A simple way to characterize the state of rotation of an atmosphere is to consider the mean

Superrotation, Table 1 Planetary parameters and superrotation index

Planet or satellite	R (km)	Rotation period τ_p	Equatorial zonal velocity U – rotational period τ_{ATM}	Index s
Venus	6052	−243.01 days	−110 m/s – 4 days	61.8
Earth	6371	23.93 h	−20 m/s – 25 h	0.96
Mars	3396	24.62 h	30 m/s – 21.9 h	1.1
Jupiter	71,400	9.84 h	100 m/s – 9.76 h	1.01
Saturn	60,330	10.65 h	450 m/s – 10.19 h	1.05
Uranus	25,562	17.23 h	−50 m/s – 17.57 h	0.98
Neptune	24,622	17.24	−400 m/s – 20.54 h	0.8
Titan (Saturn satellite)	2576	15.95 days	100 m/s – 350 m/s 1.68 – 0.52 days	9.5–30.7
HD 209458b	94,380	3.52 days	2000 m/s – 1.74 days	2.03

motion velocity in its equatorial region at a given altitude level. For example, through the ratio of the rotational period of the body τ_p to the rotation period of the atmosphere τ_{ATM} . The atmospheric rotation period is given by $\tau_{ATM} = 1/((U/2\pi R) + (1/\tau_p))$ where U is the zonal velocity relative to the body (zonal means in the direction of the parallels). Table 1 shows the value of the rotation index $s = \text{period planet } (\tau_p)/\text{period atmosphere } (\tau_{ATM})$ for solar system planets, one satellite, and one exoplanets of the “hot Jupiters” type.

According to this scheme, Venus atmosphere is at the upper cloud level (altitudes about 60–70 km above surface) under an extreme superrotation. Its motion state has been measured remotely tracking clouds and using the Doppler effect and in situ by descending probes (Sánchez-Lavega et al. 2017). Titan is the major satellite of Saturn and is covered by a thick haze layer. Atmospheric velocities are measured in the altitude range from 200 to 1000 km by a variety of techniques that use the Doppler effect (Lellouch et al. 2019). They show the presence of high wind speeds along this large altitude range. The Huygens entry probe also measured high wind speeds at 145 km altitude level (Folkner et al. 2006), confirming the high superrotating state of this atmosphere. Earth and Mars equatorial lower atmospheres have moderate mean zonal winds (Schneider 2006; Mitchell et al. 2019; Barnes et al. 2017) showing low sub- and superrotation states, respectively. However,

intense eastward jets occur on both planets at mid-latitudes that are seasonally dependent on Mars. The giant planets Jupiter and Saturn exhibit a pattern of zonal jets alternating in their direction with latitude (Sánchez-Lavega et al. 2019). Cloud tracking is the standard method to measure winds in the giant and icy planets. Jupiter and Saturn have broad and high-speed equatorial jets. Their atmospheres are in a low superrotation state according to the definition above since these planets are rapidly rotating bodies. The situation is different for the giant “hot Jupiter” exoplanet HD209458b that, being close to its star should have its spin synchronized to the orbital period (Showman et al. 2010). Intense winds should blow from the hottest to the colder side of the planet implying a superrotation state. The icy planets Uranus and Neptune show retrograde equatorial jets, then they are subrotating relative to their bodies (Sánchez-Lavega et al. 2019; Hueso and Sánchez-Lavega 2019).

Different mechanisms have been proposed to explain the extreme superrotating states of Venus, a planet close to the Sun and subjected to high insolation, and the satellite Titan that is far and cold. They involve global meridional overturning circulations and nonaxisymmetric eddies to transport momentum upward and equatorward in these atmospheres but the details are not known and may differ between them (Read and Lebonnois 2018).

Cross-References

- [Atmospheric Circulation](#)
- [Climates, Diversity in the Solar System](#)
- [Climates, Exoplanets](#)
- [Climates, Terrestrial Planets](#)
- [GCM](#)
- [Hadley Cells](#)

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Supersonic Beams, Supersonic Flow

- [Supersonic Jet Expansions](#)

Supersonic Jet Expansions

Astrid Bergeat and Christian Naulin
Univ. Bordeaux, CNRS, Bordeaux INP, ISM,
Talence, France

Keywords

Supersonic expansion · Supersonic beams ·
Molecular beams · CRESU · Crossed beams ·
Merged beams

Synonyms

[Supersonic beams](#), [Supersonic flow](#)

Acronyms

CRESU (French acronym for uniform supersonic flow reactor for chemical kinetics studies)

Definition

A **jet** is generated when expanding a gas through a nozzle, from a high-pressure reservoir into a low-pressure medium. The flow is called **supersonic** when the **Mach number** (the ratio of final velocity after expansion to **the sound velocity** at the final temperature) is higher than 1. This condition is fulfilled when the pressure in the reservoir is sufficiently high so that many collisions occur within the nozzle, resulting in an efficient conversion of the initial energy content of the gas into kinetic energy along the nozzle axis. In the context of laboratory astrophysics, supersonic beams are used to measure chemical kinetics at low temperature (CRESU technique), to facilitate spectroscopic data determination (as the rotational temperature is low), to study photodissociation or ionization processes, and to explore the dynamics of reactions or inelastic processes with crossed supersonic molecular beams: The collisional processes are studied under physical conditions

(pressure and temperature) relevant for many interstellar media, thus providing a stringent test for input data of astrophysical models, calculated with quantum methods.

History

The history of (*atomic or molecular*) jets is nicely introduced by Otto Stern (1943 Nobel Prize in Physics) and also by Dudley R. Herschbach (1986 Nobel Prize in Chemistry) who gives a nice historical background in his Nobel Lecture.

Cross-References

► [Molecular Beams](#)

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Suprathermal

► [Suprathermal](#)

Suprathermal

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

[Suprathermal](#)

Definition

Motion of particles (atoms, molecules, ions) with velocities much larger than the characteristic local thermal (Maxwellian) velocity is called suprathermal or superthermal. Processes involving magnetic fields, such as solar flares, can produce suprathermal particle motions. In the case of ► [interstellar dust](#) grains, suprathermal rotation has been invoked as a process involved in the grain alignment that is responsible for polarizing transmitted radiation.

Although the term suprathermal could also in principle be applied to situations like astrophysical masers, where a group of atoms or molecules exists in a condition with more members in an excited energy state than in a linked lower energy state (thus providing a negative thermodynamic temperature and the possibility of stimulated emission of radiation), this use of the term has not been in common use.

Cross-References

► [Alignment of Dust Grains](#)
► [Interstellar Dust](#)

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Surface Gravity

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Surface gravity is defined as the acceleration of a test mass in free fall at the surface of a massive

body under the gravitational force produced by the body. Noted g , the surface gravity for a spherical body is derived from Newton's formula $g = G M/R^2$, where G is the gravitational constant and M and R are the mass and radius of the massive body. Unit: m s^{-2} . The surface gravity on Earth is equal to 9.81 m s^{-2} .

Surface Plasmon Resonance

Nita Sahai

Department of Polymer Science, University of Akron, Akron, OH, USA

Synonyms

[SPR](#)

Definition

Surface Plasmon Resonance (SPR) spectroscopy is based on excitation of electronic oscillations by light at a planar interface between two materials for which the real part of the dielectric constants has opposite signs (e.g., metal/vacuum or metal/air). The electromagnetic waves that travel parallel to the interface are reflected by total internal reflection, and the evanescent wave probes the interface. The reflected intensity decays exponentially as a function of distance away from the interface. SPR is, therefore, a very sensitive probe of changes in the interfacial roughness due to adsorption of large molecules, such as polymers and proteins, on the metal surface. This technique is the basis of many lab-on-a-chip and biosensor applications.

Cross-References

► [Biosensor](#)

Surfactant

► [Amphiphile](#)

Survival

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Dormant state · Growth · Microbial survival · Survival curves

Synonyms

[Viability](#)

Definition

The term “survival” describes a capability of individuals, communities, or whole populations of staying alive over a certain period of time. In astrobiology “survival” is mainly applied to microorganisms – individuals or communities – that withstand hostile environmental conditions. Several microorganisms are capable of forming dormant states, e.g., bacterial spores, of high resistance to temporarily unfavorable conditions.

Overview

During the about 3.5 billion years history of life on Earth, microorganisms have developed a variety of adaptive strategies to survive in environments that are toxic to most other life-forms. There are two ways of responses of microorganisms to extreme conditions: (1) capability of growth, i.e., the maintenance of an active population, which finds its optimum or near optimum conditions in those environments, and (2) capability of survival for short or even extended periods of time in a dormant state (Table 1). Examples for the latter one are spores produced by fungi and bacteria, cysts produced by various eukaryotes, and seeds produced by plants. Most of these forms are usually unicellular bodies – exceptions

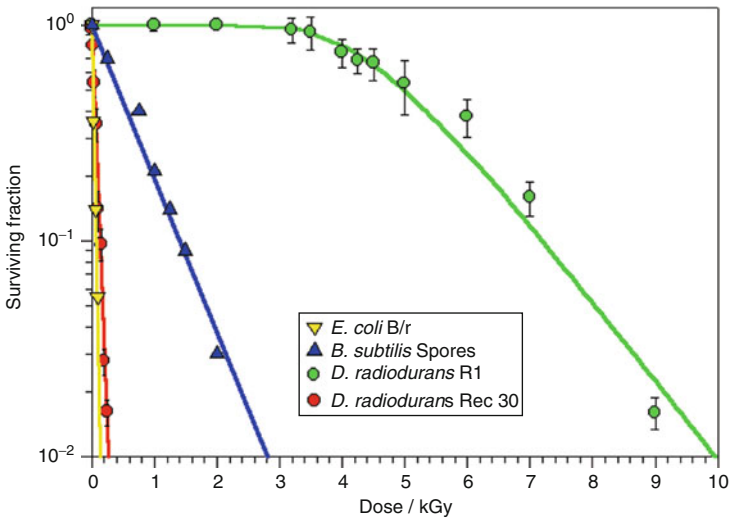
Survival, Table 1 Environmental range allowing growth or survival of at least some species of microorganisms

Parameter	Growth	Survival
Temperature (°C)	−20 to +113	−262 to +113
Pressure (Pa)	10 ⁵ –10 ⁸	10 ^{−7} to ≥10 ⁸
Ionizing radiation (Gy)	≈50	≤5000
UV radiation (nm)	Depending on wavelength	Depending on wavelength
Water stress (a _w)	≥0.7	0–1.0
Salinity	≤30‰	Salt crystals
pH	1–11	0–12.5
Nutrients	High metabolic versatility, high starvation tolerance	Not required, better without
Gas composition	Different requirements (oxic or anoxic)	Better without oxygen
Time (a)	≤0.5 ^a	≤(25–250) × 10 ^{6b}

^aLongest generation time of microorganisms recorded so far

^bLongest survival time of microorganisms recorded so far

Survival, Fig. 1 Survival curves for *Deinococcus radiodurans* R1 and its recombination-deficient mutant Rec 30 compared to survival curves for spores of *Bacillus subtilis* and cells of *Escherichia coli* B/r following exposure to X-rays. (From Horneck and Baumstark-Khan 2002)



are seeds – which are encased by a thick protective coat. They are very resistant to environmental extremes, such as heat, ► [desiccation](#), radiation, and other stresses. Bacterial ► [spore](#) formation represents a strategy by which a bacterium escapes temporally and/or spatially from unfavorable conditions, resulting in incredible longevity – survival times of 25–250 Ma have been reported (Cano and Borucki 1995; Nicholson et al. 2000; Vreeland et al. 2000).

The survival capacity of microorganisms in response to stressors is quantified in survival curves, which give the survival rate as a function of the dose of the applied agent (Fig. 1). The bacterium *Deinococcus radiodurans* has been

known as the most resistant organism in response to ionizing radiation, tolerating doses up to 4 kGy without a decrease in survival.

The exceptionally high resistance against environmental extremes over long periods of time makes bacterial spores suitable candidates for astrobiology studies, such as the likelihood of transport of life between the planets of our solar system, i.e., the hypothesis of ► [lithopanspermia](#), and ► [planetary protection](#) considerations. Experiments in space and at ground simulation facilities as well as model calculations have shown that spores would survive a hypothetical interplanetary transfer, including shock waves and high temperatures during the ejection process

(Horneck et al. 2008), extreme vacuum, intense radiation, and varying temperatures during the journey in space (Mileikowsky et al. 2000), and finally accelerations and high temperatures during entry and landing on another planet (Westall and de la Torre Noetzel 2008; Horneck et al. 2010). Desiccation-resistant organisms, such as bacterial spores and ► [lichens](#), survive especially well in the hostile space environment because of their low water content and the protection by outer thick layers.

Cross-References

- [Desiccation](#)
- [Endospore](#)
- [Ionizing Radiation, Biological Effects](#)
- [Lichens](#)
- [Lithopanspermia](#)
- [Microorganism](#)
- [Panspermia](#)
- [Planetary Protection](#)
- [Spore](#)
- [Sterilization](#)

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Svedberg Unit

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A Svedberg unit (represented as S or sometimes Sv) is a non-Système Internationale unit for sedimentation rate. The unit is named after Swedish chemist Theodor Svedberg (1884–1971), who won the 1926 Nobel Prize in chemistry for his work on colloids and the invention of the ultracentrifuge. The sedimentation rate is a measure of how quickly a particle sediments from a solution or suspension under the induced gravitational field of a centrifuge.

The sedimentation coefficient is the ratio of the speed of a substance in a centrifugal field to its acceleration in comparable units. A substance with a sedimentation coefficient of 1S (10^{-13} s) will travel at 1 mm per second (10^{-6} m s $^{-1}$) under the influence of an acceleration of 10^6 G (10^7 m s $^{-2}$). Centrifugal acceleration is given as ωr^2 , where r is the radial distance from the rotation axis and ω is the angular velocity in radians s $^{-1}$.

Though the Svedberg unit is technically a measure of time (10^{-13} s), it also offers a measure of particle size, density, and shape, as these aspects

of a particle contribute to sedimentation behavior. All other things being equal, larger particles tend to sediment faster and thus have higher Svedberg values.

The Svedberg has commonly been used to distinguish among the ribosomes found in the different domains of life, as well as the relative sizes of their subunits.

Cross-References

► [Ribosome](#)

Swamp Gas

► [Hydrogen Sulfide](#)

SWAS

► [Submillimeter Wave Astronomy Satellite](#)

Swaziland Supergroup (outdated)

► [Barberton Supergroup](#)

Symbiosis

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Synonyms

[Mutualism](#)

Definition

Symbiosis is the association of two or more species, resulting in a new entity. The relationship can be metabolic or genetical and may lead to a continued association, from generation to generation. In a more restricted sense, it refers to cases in which all the associated partners obtain benefits (mutualism). But the nature of the association can be detrimental to some of the partners (parasitism) or neutral (commensalism). The association can also be optional (facultative) or obligate. Symbiosis is widespread in nature and plays a central role in the origin of evolutionary innovations. The case of intracellular symbionts (► [endosymbiosis](#)) represents a mechanism for the origin of the eukaryotic complexity.

Cross-References

► [Endosymbiosis](#)
► [Evolution, Biological](#)

Synchronous Rotation

Emeline Bolmont
Observatoire de Genève, Université de Genève, Sauverny, Switzerland

Synonyms

[Tidal locking](#)

Definition

Synchronous rotation or tidal locking occurs when the rotation period of a body (planet or satellite) is equal to its orbital period. When a planet is synchronously rotating, it is always showing the same side to the star so that the region facing the star is in a permanent dayside and the opposite region is in a permanent night side.

The rotation of a planet reaches synchronization as a result of tidal interaction with the host star (e.g., Hut 1981). The timescale of synchronization is relatively short compared to the circularization timescale. Note that synchronization occurs for planets/satellites with a low eccentricity (e.g., Makarov and Efroimsky 2013). If the eccentricity of the planet is significantly nonzero, other types of rotations are to be expected, in particular spin-orbit resonances (like Mercury, which rotates three times on itself while it orbits twice the Sun). But then we do not speak of tidal locking, but use rather the more generic term of spin-orbit resonances. The major satellites of the solar system are all synchronously rotating (like the Moon) and all close-in exoplanets are usually thought to have reached this rotation.

This has important implications for the climate of close-in planets and particularly in the context of planets in the Habitable Zone (HZ) of low mass stars like Proxima and TRAPPIST-1. Due to the low luminosity of low-mass stars, the HZ is located close-in, so that the temperate planets are thought to be tidally locked. In particular, the planets of TRAPPIST-1 have a low eccentricity and they are thought to have reached a synchronous rotation in less than a million year after the formation of the planets (while the system is thought to be several gigayears old). Due to the very specific insolation pattern (permanent day and night sides), tidally locked planets have different climates from what we know in the solar system.

In particular, it has been proposed by Yang et al. (2013) that considering a tidally locked planet changes the distance of the inner edge of the classical HZ: it moves closer to the star. In other words, a synchronous planet could sustain surface liquid water even if it receives more energy than the runaway greenhouse limit. This is due to the presence of clouds above the substellar point, which act to increase the reflective power of the planet and thus lower the surface temperature.

The climate of a tidally locked planet in the HZ of its star strongly depends on the amount of carbon dioxide and the total amount of water present on the planet. Depending on these amounts, there are several outcomes regarding

the presence of surface liquid water (see Turbet et al. 2016 for a visual representation of these states):

- For a very small amount of water (around 10^{-5} times the Earth ocean content), no liquid water can exist on the surface of the planet whatever the amount of carbon dioxide. For low CO_2 content, the dayside is completely dry and there are glaciers on the night side (cold trap on the nightside, see also Leconte et al. 2013). For very low CO_2 content and without background gas (like N_2), CO_2 can also condense on the night side. For high CO_2 content, all water is in vapor state.
- Increasing the amount of water, a new possibility appears for intermediate CO_2 content: the dayside remains dry but the night side can sustain surface liquid water. This situation would mean that the planet is habitable in the astronomical sense, but the repercussions for the origin of life are not clear. This liquid water would never be submitted to stellar radiation.
- Increasing the amount of water (few percent of Earth ocean content), liquid water can be found on the dayside for intermediate CO_2 content.
- For high content of water ($>10\%$ of Earth ocean content), liquid water can be found on the planet unless the CO_2 amount is very high, for which case the water is in vapor state. For lower amount of CO_2 , the planet is either an ice-free ocean or partially covered with ice.

If there is a background gas (like nitrogen), the cases with low CO_2 content would be slightly different: the background gas would favor heat redistribution and it would impede the extent of the water ice and could also prevent the condensation of the CO_2 reservoir on the night side.

Cross-References

- [Habitable Zone](#)
- [Proxima-b](#)
- [Rotation Planet](#)
- [Tides, planetary](#)
- [TRAPPIST-1 System](#)

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Synchrotron Accelerator

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

A synchrotron accelerator is a particular type of cyclic particle accelerator in which the magnetic field and the electric field are carefully synchronized with the traveling particle beam. While a cyclotron uses a constant magnetic field and a constant-frequency applied electric field, both of these fields are varied in the synchrotron. By increasing these parameters appropriately as particle energy increases, the path of the particles can be held constant as they are accelerated. This allows the vacuum chamber for the particles to be a torus. A path of large effective radius can then be constructed using simple straight and curved pipe segments, unlike the disk-shaped chamber of cyclotrons.

Cross-References

► [Synchrotron Radiation](#)

Synchrotron Radiation

Daniel Rouan
 LESIA, Observatoire Paris-Site de Meudon,
 Meudon, France

Definition

Synchrotron radiation is the continuous electromagnetic radiation produced by a highly relativistic plasma in a magnetic field. It can cover a very broad range of wavelengths, from gamma rays to radio wavelengths. In a magnetized ► [plasma](#), an electron gyrates around the direction of the magnetic field because of the Lorentz force and thus radiates as does any accelerated charge. When electrons reach highly relativistic speeds, the emission comes from a narrow beam in the direction of motion, so that the observer sees extremely narrow pulses whose resulting spectrum is a continuum spread over a very broad range of frequencies. The slope of the spectrum is characteristic of the electrons' energy distribution. Synchrotron emission is seen in extreme energy environments such as the accretion disks around ► [black holes](#), ► [neutron stars](#), and some ultra-massive black holes at the centers of galaxies. This type of radiation is called *nonthermal*, as opposed to *thermal* radiation such as ► [blackbody](#) or free-free emission.

Cross-References

- [Black Holes](#)
 ► [Continuum](#)
 ► [Electromagnetic Radiation](#)
 ► [Neutron Star](#)
 ► [Radiative Processes](#)

Syngenicity

Nicola McLoughlin

Department for Geology, Rhodes University,
Makhanda (Grahamstown), South Africa

Keywords

Antiquity · Biosignatures

Definition

Syngenicity means a feature that may be textural, chemical, mineral, or biological and that formed at the same time as the encapsulating material. In other words, a primary component that is preserved contemporaneously with the deposition of the host-sedimentary rock, or crystallization of the host igneous melt, or precipitation of the encapsulating mineral or ice phase(s). The demonstration of syngenicity is equivalent to the demonstration of antiquity, and this is essential to establish the history of life in our universe.

History

In economic geology, the term syngenetic has traditionally been used to refer to ore deposits formed at the same time as the enclosing rock as opposed to epigenetic that describes mineral deposits formed later. Here, a definition is provided that is more generally applicable to the investigation of astrobiological materials including not just terrestrial rocks and minerals but also meteorites, interplanetary dust, and ice particles.

Overview

A syngenetic textural, chemical, mineralogical, and/or biological component is formed at the same time as the host material. Syngenetic components of low-temperature deposits are those that were stable at the ambient pressure, temperature, redox, and salinity conditions prevailing at or near

the planetary surface at the time of formation. In the case of high-temperature volcanic rocks and precipitates, syngenetic components formed in equilibrium with the solidifying magma or fluid, for example, primary melt or fluid inclusions, and mineral phases. Syngenicity concerns the source of a component in time. This differs from ► [endogenicity](#) that concerns the source of a component with regard to space. Components that are syngenetic are nearly always also endogenetic, that is, derived from within the system. There are a few exceptions, however, for example, windblown ash particles preserved in ice cores, or pollen grains entombed within desert varnish crusts.

The demonstration of syngenicity is equivalent to the demonstration of antiquity, and this is especially important to establish the history of life on planetary bodies (e.g., Wacey 2009). Syngenetic components are found within early phases in the host material and do not occur in late-stage alteration products or crosscutting veins, and this can be tested by microscopic examination of thin section. Thus, for example, microbial remains found in superficial cracks, late-stage veins, or metastable minerals are unlikely to be syngenetic and rather, more likely, to be derived from subrecent organisms (e.g., Westall and Folk 2003). Syngenetic components should also have experienced the same degree of deformation and alteration as the host rock. Thus, for example, spherical structures should be flattened parallel to the regional deformation fabrics if these exist (e.g., Appel et al. 2003). Moreover, the distribution and abundance of syngenetic components in a system should reflect primary environmental gradients such as light levels or redox gradients. This can be investigated by meter- to micron-scale mapping to establish if there is a correlation between primary depositional or magmatic variables and the distribution of the candidate biosignatures. Sometimes it is possible to measure an absolute radiometric age for the feature of interest (e.g., Grosch and McLoughlin 2014) who used U-Pb dating to establish the age of microtextures comprising the mineral titanite CaTiSiO_4 , or more commonly the phase of interest can be relatively dated to mineral cements or veins of known age and placed within the chronology of processes that have affected the whole system.

Cross-References

- [Archaeal Traces of Life](#)
- [Biogenicity](#)
- [Biomarkers](#)
- [Biomarkers, Morphological](#)
- [Endogenicity](#)
- [Geochronology](#)

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Synthetic and Hybrid Tissues

Hagan Bayley and Linna Zhou
Department of Chemistry, University of Oxford,
Oxford, UK

Keywords

Genome editing · Manufacturing · Microbiome · Microgravity · Nutrition · Origin of life · Space medicine · Stem cells · Synthetic tissue · 3D printing · Tissue engineering

Definition

Synthetic tissues are relatively simple materials that carry out one or more of the functions of natural tissues. Synthetic tissues could provide a medical or surgical lifeline during space travel or on a distant colony. Functional synthetic tissues

might also provide clues about the origins of multicellular life. Hybrid tissues formed between synthetic tissues and natural or edited living cells will create materials with higher functions or form the basis of personalized implants. The manufacture of such materials for use on Earth might be improved in microgravity.

Overview

Synthetic Tissues

While a significant body of work now describes synthetic cells, relatively little work has been done on synthetic tissues. By “tissue,” we mean a multi-compartment system in which the compartments can communicate with each other and with the external environment, thus constituting a material with emergent properties, the sum being greater than the parts. We have devised a simple approach to such systems in which networks of 3D-printed picoliter droplets are formed in oil (Villar et al. 2013). The droplets are separated from one other by single lipid bilayers, which provide interfaces through which the compartments can communicate assisted by membrane proteins (Bayley et al. 2019). While other approaches are possible, our system illustrates the requirements and qualities of synthetic tissues.

Synthetic tissues are required to carry out one or more of the functions of natural tissues. 3D-printed droplet networks have been produced that can transmit electrical signals and change shape, thereby mimicking nerves and muscles (Villar et al. 2013). Recent work has shown that such structures can receive and process external signals, presaging the genesis of sophisticated functionality (Booth et al. 2016; Downs et al. 2020). Droplet networks can be transferred from oil into a purely aqueous environment by a variety of means (Alcinesio et al. 2021), allowing applications in biology and medicine.

Printed Cells

The construction of tissues by the 3D printing of living cells has been investigated for at least 20 years (Murphy and Atala 2014; Heinrich et al. 2019; Zhang et al. 2021). Most work has

been done with printers in which a “bioink” is extruded like toothpaste from a tube. We are using a droplet-printing approach similar to that used for synthetic tissues (Graham et al. 2017; Zhou et al. 2020). While the process is slow, and improvements in this regard are forthcoming, it has the ability to perform high-resolution patterning, and it is compatible with the construction of soft tissues, such as that of the brain. Further, cells can be printed at high density and with high viability in naturally derived extracellular matrix, and after printing they remain able to divide, differentiate, and migrate (Zhou et al. 2020). The approach is amenable to a wide variety of cells and, given advances in stem cell technology and genome editing, we find ourselves at an especially exciting juncture for 3D tissue fabrication.

Hybrid Tissues

The formation of hybrids between synthetic tissues and natural or edited living cells and tissues has the potential to create materials with higher functions or that form the basis of personalized implants. Communication between the components of the hybrid tissues might be direct: for example, through proteins that resemble gap junctions (Mantri et al. 2013), or between compartments and cells that are not in contact through a paracrine system. The structures and functional properties of such materials are limited only by imagination.

The Origins of Multicellular Life

The origins of life are a primary concern of astrobiology. Despite the considerable experimental work on synthetic cells, “protocells” in the origins field, there has been little effort on the discovery of the origins of multicellular organisms. Many researchers consider that “prototissues” would have been generated by the aggregation of protocells. Nonetheless, the formation of droplet networks in oil should be considered as a precursor of multicellular organisms, especially since the oil can be readily removed to yield multi-compartment structures in an aqueous environment (Deng et al. 2016; Alcinesio et al. 2021). Cooperative functions may have emerged in these structures in which the compartments are

separated by individual lipid bilayers, before double-bilayer compartmentalization appeared, further down the evolutionary pathway.

Manufacture in Microgravity

The manufacture of synthetic tissues, printed cells, and hybrid tissues might be improved in microgravity. Indeed, there is a long list of companies engaged in the manufacture of a variety of materials in space, supporting this conviction [www.factoriesinspace.com/manufacturing-companies]. For example, soft tissues generated by printing cells might be stabilized in a microgravity environment until the extracellular matrix enveloping the cells has gelled (Zhou et al. 2020), strengthening the materials sufficiently for return to earth. The production of larger structures might be less problematic, because of the decreased tendency to deform under microgravity. Improvements in the precision of 3D printing of synthetic tissues are also required (Alcinesio et al. 2020), which might also be aided by microgravity.

Materials for use in space or extraterrestrial colonies that might be produced by synthetic tissues or printed cells include fuels, gases, biopolymers, and pharmaceuticals (Menezes et al. 2015). The production of food in space, including meat from cultured cells [e.g., www.meatable.com], is also an attractive proposition that could exploit printing technologies.

Experimental Science in Microgravity

Printed cells might contribute to investigations of fundamental space biology. After printing, eukaryotic cells can divide, differentiate, and migrate (Zhou et al. 2020). Further, stem cells and genome-edited cells can be used to form 3D tissue constructs, which can be printed in natural or unnatural arrangements, suggesting a plethora of experiments that might be performed to test the effects of low gravity or radiation on developing and mature mammalian tissues. Printed tissues might also be used to test therapies that could be affected by the space environment, such as treatments for wound healing.

Recently, we examined “warfare” between strains of bacteria patterned by printing (Krishna Kumar et al. 2021). Similar approaches will allow

various aspects of the properties of microbiomes to be explored under microgravity and in extreme space environments. Indeed, the effects of the space environment on all manner of cells patterned in two- or three-dimensions could be examined.

Synthetic and Hybrid Tissues for Space Medicine

Synthetic tissues could provide a medical or surgical lifeline during space travel or on a distant colony. Modern medical treatments include cell-based therapies (e.g., immunotherapies) and tissue and organ transplantation, and all but the most mundane treatments will have to be manufactured on demand during space travel or in distant colonies (Snyder et al. 2019). Complex treatments will most likely be mediated by robotic telemedicine procedures. It will be necessary for spacecraft to carry a minimal “larder” of chemical and biological reagents that can in turn be used to service a full range of medical and surgical needs (Menenez et al. 2015). For example, hybrid tissues formed from synthetic tissues and natural or edited living cells might form the basis of personalized implants requiring the growth and differentiation of stem cells derived from the space travelers themselves. Small molecules required for such endeavors might be generated by programmable synthetic devices (Steiner et al. 2019) and growth factors, and other biologicals would be produced from cells (Menenez et al. 2015) including 3D cultures. Besides droplet printing, other approaches might be advanced or amalgamated for bringing cells together under microgravity, including versions of magnetic bioassembly (Parfenov et al. 2020) with improved resolution and patterning capacity.

Additional medical requisites that might be produced by printing and related technologies include tailored microbiomes as therapeutics and personalized microtumors for the evaluation of treatment regimens with available agents.

Cross-References

- ▶ [Artificial Life](#)
- ▶ [Artificial Organelles](#)

- ▶ [Biopolymer](#)
- ▶ [Biosensor](#)
- ▶ [Cell](#)
- ▶ [Cell Membrane](#)
- ▶ [Cell Models](#)
- ▶ [Cell, Minimal](#)
- ▶ [Evolution, Biological](#)
- ▶ [Evolution, Molecular](#)
- ▶ [Life Support Systems](#)
- ▶ [Lipid Bilayer](#)
- ▶ [Membrane](#)
- ▶ [Microbiome of the International Space Station](#)
- ▶ [Microgravity](#)
- ▶ [Multicellular Organisms](#)
- ▶ [Organelle](#)
- ▶ [Origin of Life](#)
- ▶ [Radiation Biology](#)
- ▶ [Self-Assembly](#)
- ▶ [Self-Assembly, Biological](#)
- ▶ [Space Biology](#)
- ▶ [Space Environment](#)
- ▶ [Synthetic Biology](#)
- ▶ [Systems Biology](#)

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Synthetic Biology

Daisuke Kiga

Tokyo Institute of Technology, Tokyo, Japan

Keywords

What life could be · Realization of biosystems

Synonyms

Constructive biology

Definition

Synthetic biology is a biological study, in scientific and engineering fields, depending on the construction of biological systems. A living organism is a system containing multilayers such as cells, biomacromolecules (proteins, RNAs, and DNAs), and monomers (amino acids and nucleotides). Because the numbers of combinations are huge, few combinations have been tried throughout the history of the Earth. Through realization of synthetic biological systems which represent what life could be, synthetic biology allows evaluation of models and hypotheses formulated from observations. Synthetic biology thus uses the complementary approach to the analytical approach which has been used in traditional biology.

Overview

Synthetic biology relies on accumulated biological information from comprehensive analyses such as genomics and on the development of technologies for the preparation of biomolecules. One example is the creation of a bacterial cell controlled by a genome derived from chemically synthesized DNA (Gibson et al. 2010). Although the genome sequence of this “artificial cell” is only slightly modified from the natural one, researchers can now obtain genome DNA with any sequence. In another field of artificial cell study, synthetic micro-containments consisting of lipid molecules encapsulate proteins and/or nucleic acids which confer a part of cellular function (Szostak et al. 2001; Chen et al. 2005; Sunami et al. 2010).

Due to the tremendously huge combination of bio-components, synthetic biology allows realization of biosystems with different properties from the one universally shared by the present life. Although natural ribozymes show a limited range of catalytic diversity, artificial evolution of RNA has uncovered a wide range of activity of aptamers or ribozymes (Ellington and Szostak 1990). Creations of genetic codes containing 21 amino acids (Wang et al. 2001; Kiga et al.

2002) or less than 20 amino acids (Amikura and Kiga 2013) assist the discussion for possible codes on exoplanets or evolution toward the universal genetic code. Such a huge combination, however, invokes two potential problems.

One problem is the rarity of combinations with a proper function. Not only the ratio of amino acids sequences with biological function to that without function, but the ratio of functional biosystems containing multiple macromolecules to nonfunctional biosystems is so small that realization of the functional ones requires evolution through a long time or a rational design process. Mathematical modeling for biological systems leads to fundamental understanding in systems biology and predicts behavior of a designed system in synthetic biology. Designed genetic circuits thus have given living cells programmed bistability (Gardner et al. 2000) or population control via cell-cell communication (Sekine et al. 2011). Through modeling in synthetic biology, furthermore, researchers can estimate the difficulty in construction of a designed system.

The other problem is that systems without correlation to the systems in exoplanet environments or in the past Earth can be created. Thus research on the environmental conditions of exoplanets or the past Earth is crucial for applications of synthetic biology to astrobiology, in order to provide appropriate constraints.

Cross-References

- ▶ [Aptamer](#)
- ▶ [Cell, Minimal](#)
- ▶ [Chemical Bistability](#)
- ▶ [Genetic Code](#)
- ▶ [Genome, Minimal](#)
- ▶ [Quorum Sensing](#)
- ▶ [Ribozyme](#)
- ▶ [RNA World](#)

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Synthetic Cell Division

- ▶ [Artificial Cell Division](#)

Synthetic Cells

- ▶ [Cell Models](#)
- ▶ [Protocell](#)

Synthetic Organelles

- ▶ [Artificial Organelles](#)

System Solar Formation, Chronology of

François Robert
Laboratoire de Minéralogie et Cosmochimie du
Muséum (LMCM), Muséum National d'Histoire
Naturelle, UMR 7202 CNRS, Paris, France

Keywords

CAI · Chondrules · Chronology · Iron
meteorites · Meteorites · Radioisotope · Solar
system

Overview

Historical

The knowledge of the age of the Earth and of the Solar System has always been a fundamental

question not only for scientists but also in most human cultures. The possibility of finding a solution to this question emerged in the beginning of the twentieth century with the discovery of radioactivity. The probability of transformation (the decay) of a radioactive nuclide (the parent) into a stable nuclide (the daughter) is constant, so that the ratio between a quantity of the parent and that of the daughter is only a function of time. Temperatures or pressures that are reached during geological or planetary processes (including formation processes) can alter this natural clock. Since all rocks contain traces of natural radioactive elements, the age of a rock can be obtained by measuring the present-day quantity of parent and daughter isotopes, provided daughter isotopes accumulated in mineralogical sites via the decay of their parent were never transported away.

Although in principle a simple task, the determination of the age of a rock relies on a precise measurement of the isotopic ratios of the element that contains the daughter nuclide. Since radioisotopes are present only in trace amounts in most natural samples, the routine determination of the age of a rock was not possible before the early 1960s. The age of the Earth cannot be measured directly because tectonics, erosion, and weathering have eliminated any primordial sample. The age of the Solar System, in contrast, was determined in 1956 by Claire Patterson as the uranium-lead age of chondrites (undifferentiated meteorites) and iron meteorites (Patterson 1956). It is remarkable that this age is still valid within its error bars (4.54 ± 0.07 Ga; $1 \text{ Ga} = 10^9$ years). What we know of the age of the Earth comes from extinct radioactivities: the age of the Earth cannot be different by more than a few Ma from the age of the other planetary objects of the Solar System, such as chondritic meteorites. The Apollo missions returned some samples from the lunar mantle which turned out to be hardly younger than the age of the Solar System, 4.43 Ga. It is therefore accepted that this age of 4.55 Ga characterizes the formation of the Solar System. The age of the Sun calculated from nuclear physics is compatible with this value but is known only to within ± 0.15 Ga. A consequence of all these observations is that the formation of the Solar System took

place within a time span of 0.1 Ga, i.e., faster than what can be defined by the analytical precision achievable 25 years ago.

The short duration of the formation of the planets prompted a massive technological effort in geochemical laboratories, beginning in the late 1980s. The motivation was to reach a precision on isotope ratios allowing us to distinguish events differing in time by a period of the order of 0.001 Ga but 4.5 Ga old! This is now achieved. New problems have nevertheless emerged simply because understanding the significance of an age measured with such a relative precision ($\pm 0.2\%$) is an unprecedented challenge in cosmochemistry.

Before addressing these problems, we review the analytical methods commonly used to date events that took place during the condensation of the first solids, their accretion to form small *planetoids* (sometimes referred to in the literature as planetary embryos or also as ► [planetesimals](#)), and the assembly of these small planetoids to form the present-day planets. Each of these stages has an age that can be deciphered in minerals.

The Concept of Radiometric Ages

The general law of radioactivity (see the detailed treatment of this problem by Albarède 2003) is written as $P = P_0 \exp(-\lambda t)$. P and P_0 are the number of parent atoms at time t and at time 0, respectively, and λ is the decay constant, which is equal to $\ln 2$ divided by the half-life $T_{1/2}$ (see ► [Decay Constant](#), ► [Half-Life](#)). In cosmochemistry, long-lived ($T_{1/2} > 200$ Ma) and short-lived ($T_{1/2} < 200$ Ma) radioactivities are distinguished because most radioactive isotopes formed with the solar nebula have now disappeared. Short-lived isotopes are therefore “extinct,” although minute amounts may be created by interaction of galactic cosmic rays with planetary atmospheres. The surviving long-lived nuclides may be used to obtain *absolute ages* – i.e., ages expressed relative to today – while short-lived systems are used to obtain *relative ages* between different objects. Because of their fast decay, the resolution in time offered by extinct radioactivities is usually much finer with short than with long-lived systems. In other words, the absolute ages of events dated by extinct isotopes are not known, but their

time difference is accurately known. ^{235}U has an intermediate status because its half-life of 704 Ma gives the ^{235}U - ^{207}Pb absolute ages a particularly high precision.

An absolute age is derived by combining the law of radioactivity and the rules of mass balance, and because thermal equilibration homogenizes isotopic abundances and not elemental concentrations, the chronometer is formulated in terms of isotope ratios (see Chronology) where the normalizing denominator isotope is stable: $P_0 - P = D - D_0$. D stands for daughter isotope – the stable element resulting from the decay of P . In this equality, the initial quantities P_0 and D_0 are unknown since we have only access to the present-day concentrations. Using the radioactive law defined above, we derive $D = D_0 + P \exp(\lambda t - 1)$. Taking the example of the long-lived radioactive nuclide ^{87}Rb , which decays to ^{87}Sr , we have, using ^{86}Sr to normalize the concentrations, the equation

$$(^{87}\text{Sr}/^{86}\text{Sr})_t = (^{87}\text{Sr}/^{86}\text{Sr})_0 + (^{87}\text{Rb}/^{86}\text{Sr})_t [\exp(\lambda t) - 1]$$

In this equation there are two unknowns: the age t and the isotopic composition $(^{87}\text{Sr}/^{86}\text{Sr})_0$ at initial time. Using several minerals from the same rock or several rocks having the same age t , the two unknowns can be determined. This equation is often displayed graphically as a linear relation referred to as an “isochron” and expressed as $y = ax + b$, with the slope a giving the age of the rock ($a = e^{\lambda t} - 1$) and b the isotopic composition of the melt at the time of its isotopic homogenization or $b = (^{87}\text{Sr}/^{86}\text{Sr})_0$.

It should be stressed that the two fundamental “assumptions” of radiochronology – i.e., that the samples dated have the same age and that the system was isotopically homogeneous at some time in the past – are tested through an isochron diagram; if they fail, the linear relation $y = ax + b$ does not hold.

Relative ages are based on the same principles but the parent isotope has long disappeared. Similarly an isochron can be written using the stable isotopes to normalize the concentration. An important example is ^{26}Al ($T_{1/2} = 0.7$ Ma) which decays into stable ^{26}Mg . Normalizing to the other

stable isotopes of magnesium (^{24}Mg), the isochron equation follows:

$$^{26}\text{Mg}/^{24}\text{Mg} = (^{26}\text{Mg}/^{24}\text{Mg})_0 + (^{26}\text{Al}/^{24}\text{Mg})_0$$

Using the stable isotope of aluminum (^{27}Al), the isochron equation can be rewritten as

$$\begin{aligned} ^{26}\text{Mg}/^{24}\text{Mg} &= (^{26}\text{Mg}/^{24}\text{Mg})_0 + (^{26}\text{Al}/^{27}\text{Al})_0 \\ &\quad \times (^{27}\text{Al}/^{24}\text{Mg}) \end{aligned}$$

For systems formed at the same time with homogeneous Mg isotope compositions, i.e., same $(^{26}\text{Mg}/^{24}\text{Mg})_0$, this equation represents a straight line in a plot of $^{26}\text{Mg}/^{24}\text{Mg}$ vs $^{27}\text{Al}/^{24}\text{Mg}$ (all values measured today). In a continuously homogenized gas that condensed Al-bearing phases, the $^{26}\text{Al}/^{27}\text{Al}$ ratio depends on time and decays by a factor of 2 every 0.7 Ma. Thus, two samples formed at two different times will have a different $(^{26}\text{Al}/^{27}\text{Al})_0$, i.e., a different slope in the isochron diagram. The time Δt elapsed between these two samples is given by $(^{26}\text{Al}/^{27}\text{Al})_{0,1} / (^{26}\text{Al}/^{27}\text{Al})_{0,2} = \exp(-\lambda \Delta t)$. Theoretically a relative chronology can be established for several samples, provided they originated from the same reservoir with homogeneous $^{26}\text{Al}/^{27}\text{Al}$. This point can be tested by plotting Δt vs $(^{26}\text{Mg}/^{24}\text{Mg})_0$: in an infinite reservoir of homogeneous gas, such as the solar nebula, $(^{26}\text{Mg}/^{24}\text{Mg})_0$ should increase with Δt (see equation above) and its rate of change should reflect the $^{26}\text{Al}/^{27}\text{Al}$ of the reservoir. Recent observations on meteorites attest that the Solar System $^{26}\text{Al}/^{27}\text{Al}$ was indeed homogeneous.

In the last 40 years, evidence for the presence of many extinct radioisotopes has been found in meteorites (parent/daughter nuclides): $^7\text{Be}/^9\text{Be}$ ($T_{1/2} = 53$ days), $^{41}\text{Ca}/^{40}\text{Ca}$ ($T_{1/2} = 0.1$ Ma), $^{26}\text{Al}/^{27}\text{Al}$ ($T_{1/2} = 0.7$ Ma), $^{60}\text{Fe}/^{56}\text{Fe}$ ($T_{1/2} = 2.6$ Ma), $^{10}\text{Be}/^9\text{Be}$ ($T_{1/2} = 1.5$ Ma), $^{53}\text{Mn}/^{55}\text{Mn}$ ($T_{1/2} = 3.7$ Ma), $^{107}\text{Pd}/^{108}\text{Pd}$ ($T_{1/2} = 6.5$ Ma), $^{182}\text{Hf}/^{180}\text{Hf}$ ($T_{1/2} = 9$ Ma), and $^{129}\text{I}/^{127}\text{I}$ ($T_{1/2} = 15.9$ Ma). Multiple chronometric systems have been studied in meteorites with the hope of establishing a coherent relative chronology, and substantial progress has been achieved. Isotopic

homogeneities of these radioactive systems in the Solar System are still in debate (Chaussidon and Gounelle 2007).

There are several sources of uncertainties on these ages (see ► [geochronology](#)). When minerals are formed at high temperature in a gas of solar composition, the gas is rapidly mixed by turbulence and isotopic compositions are kept constant. As long as the gas, or the liquid in the case of molten material, is homogenized, the radioactive clock is constantly reset and does not keep the time. When the gas condenses or the liquid freezes, exchange is only achieved by molecular diffusion, a process which is extremely temperature dependent. When isotopic homogenization by diffusion stops and the parent and daughter isotopes remain in the same crystallographic location, the system is closed to exchange, the clock starts ticking, and this is the moment in time which will be dated.

The timescales of closure are also determined by the cooling rate, and for terrestrial magmas, figures of 0.01–1 Ma are not uncommon. For slow cooling, different minerals that originated from the same parent melt may exhibit substantial differences in age. Chondrules (cf. ► [Chondrule](#); Zanda 2004), which are spherules constituting the main mass of chondrites, have a radius in the mm range. They probably remained molten only for minutes, and complete isotopic homogenization of the melt may not have been achieved.

In addition to analytical precision on the determination of isotopic ratios, which depends on each particular chronometer, the most often quoted sources of errors in age are (1) the difference of the closure temperature for different isotope systems and (2) the accuracy of experimentally determined decay constants, which is a serious, neutrino-related issue for β -decay schemes.

A textbook example of (1) is the absolute age of phosphates in H ordinary chondrites determined by the uranium-lead chronometer and for which the mineralogy attests to a progressive metamorphism. The phosphates located in meteorites that experienced the higher metamorphic temperature are 60 Ma younger than their low-grade metamorphic counterpart (Göpel et al.

1994). This duration reflects the time elapsed in the planetoid that originally hosted the H chondrites to reach the closure temperature of the U-Pb chronometer: in the deepest regions of the H planetoid, the temperature reached during metamorphism was the highest, the corresponding cooling rate was the slowest, and the closure temperature for apatite was reached latest. The span in ages of H meteorites has thus no significance as far as their accretion time is concerned, but offers important clues about the thermal history of the parent body.

A second source (2) of errors is the difficulty of measuring decay constants for β -radius activity. This problem is usually solved by cross calibration with U-Pb ages.

The Planetary Significance of Radiometric Ages

In order to obtain an isochron, the process of rock and mineral formation must efficiently redistribute the parent and daughter nuclides and induce variations in the parent/daughter ratios. Such a redistribution is controlled by the chemical properties of the minerals hosting the parent and the daughter nuclides. If the accretion of grains takes place at low temperature (typically <400 °C), the slow diffusivity of most chemical elements prevents such a parent/daughter fractionation from taking place in solids, and these solids cannot be easily dated.

Four processes have been identified that cause chemical fractionation. Some of them are related to phase changes: condensation from a gas, melting, and crystallization of minerals from a cooling silicate melt. Others are slow solid-state processes (metamorphism) and mechanical sorting. These four processes characterize four steps of planetary formation; some of them being still active today on Earth (magmatic activity and metamorphism).

Condensation fractionates parent and daughter nuclides between the solid and the gas, and its efficiency depends on the condensation temperature of each element. Refractory elements, such as Al and Ti, tend to form oxides at high temperatures (1400–1800 K), whereas volatile elements such as K, Na, Pb, and S condense into solids at lower temperature (700–1000 °C).

- Crystallization or recrystallization during magmatic activity and metamorphism fractionates parent and daughter nuclides between minerals as a function of temperature, crystallization rate, and geochemical affinity of the parent and daughter for particular minerals. Some elements tend to enter the liquid during melting, while others partition into some minerals at the early stages of the crystallization.
- Mechanical sorting also fractionates parent and daughter isotopes among silicates, sulfide, and metallic phases. Some elements are preferentially fractionated into silicates while others stay in the metallic melt. The formation of a planetary core is an example of this mechanism.

Ascribing an age to a particular process is essentially based on petrographic observations. For example, several carbonaceous meteorites contain calcium-aluminum-rich inclusions (cf. ► **CAIs**) that exhibit geochemical evidence of condensation at high temperature and – for some of them – of reactions with the surrounding volatile-rich matrix. The oldest ages of CAIs are therefore ascribed to their condensation and their younger ages to secondary heating events. Similarly, iron meteorites or basaltic meteorites result obviously from melts, and thus their ages reflect the time of solidification of these melts.

In summary, the significance of isotopic ages relies on hypotheses that may turn be difficult to test rigorously and independently.

The Age of the Solar System

It is generally accepted that the age of the oldest meteorites is a good approximation of the age of the whole Solar System. Two lines of evidence show that this statement is sound: (1) the Earth, the Moon, and most meteorites have approximately the same absolute age, and (2) this age corresponds to the astrophysical age of the Sun. The recent discovery of ^{10}Be in CAIs from carbonaceous meteorites has improved the precision on the genetic relation between the planets and the Sun (McKeegan et al. 2000). The ^{10}Be is a radioisotope produced by nuclear reactions (*spallation* reactions) between energetic solar particles (*solar*

flares) and the circumsolar gas. These particles are emitted from the young Sun in its *T-Tauri phase*, which lasts no more than a few million years after its birth. The half-life of ^{10}Be being 1.5 Ma, the Sun cannot predate the CAIs by more than a few half-lives of ^{10}Be that is a few Ma.

By the same token, since CAIs contain ^{10}Be produced by solar flares, they cannot predate the Sun. Thus, it is firmly established that the minerals later incorporated into the present-day planets were contemporaneous with the Sun within approximately ± 5 Ma.

This argument can be extended to ^7Be , whose half-life is 53 days. Although the occurrence of ^7Li , the decay product of ^7Be , in the reservoir from which CAIs formed is now confidently established (Chaussidon et al. 2006), it is not possible to ascertain if the ^7Be was still alive during the formation of CAIs. This analytical issue is crucial to establish a strict concordance in ages between the planetary material and the Sun.

The existence of CAIs and their mineralogical compositions were predicted thermodynamically before they were actually found. According to these calculations, they represent the first condensates appearing in the solar gas when it cooled. Their absolute ages of crystallization are indeed the oldest of all the Solar System objects. This age is known with a great precision using the combination of the two chronometers $^{235}\text{U}/^{207}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ which provide ages known as lead-lead ages. At the current level of the analytical precision, the CAIs range from 4567.2 ± 0.6 Ma (Amelin et al. 2002) to 4568.5 ± 0.5 Ma (Bouvier et al. 2007) and 4568.2 ± 0.3 Ma (Bouvier and Wadhwa 2010). Scaling this age with the relative age of eucrites suggests that, to a first approximation, the formation of solids and protoplanets took place between 4568 and 4559 Ma ago.

Because of their short half-lives, extinct radionuclides have concentrations decreasing rapidly as a function of time and thus offer a way to establish a more precise chronology of the processes that have taken place during this short period of time, i.e., between 4567 and 4559 Ga.

The Chronology of Accretion

A major discovery in the field of short-lived radioactive nuclides was the finding of ^{26}Mg excesses in Allende CAIs that were positively correlated with the $^{27}\text{Al}/^{24}\text{Mg}$ ratio (isochron), demonstrating that the source of the ^{26}Mg excess was the in situ decay of short-lived ^{26}Al nuclide (Lee et al. 1976). Because the abundance of ^{26}Al found in most CAIs ($^{26}\text{Al}/^{27}\text{Al} = 4.5 \times 10^{-5}$) is higher by at least one order of magnitude than that predicted by models of continuous galactic nucleosynthesis, the presence of ^{26}Al in the protosolar disk requires the presence of a “last-minute input.” The debated question of the origin of the ^{26}Al is not discussed here: either it originated from nucleosynthesis in a massive star dying in the vicinity of the nascent Solar System or may have been produced by local irradiation of part of the protosolar disk by high-energy solar cosmic rays.

Recently, in situ analyses at micrometer scale using secondary-ion mass spectrometers (ion probes) and high-precision magnesium isotopic analyses have shown that the Earth, CAIs, and chondrules (the major high-temperature constituent of chondrites) formed from a reservoir in which the Al/Mg (parent/daughter) ratio and the $^{26}\text{Mg}/^{24}\text{Mg}$ isotopic ratio were homogeneously distributed across the solar nebula. At the current level of analytical precision, this homogeneity allows ^{26}Al to be used as a quite precise chronometer. In this context, high-precision ^{26}Al isochrons for chondrules reveal distinct chondrule melting events taking place between ~ 1.2 and ~ 4 Ma after CAIs, with formation peaks at around ~ 1.5 and ~ 3 Ma.

The mineralogical, textural, and chemical characteristics of chondrules indicate that these objects formed during brief and incomplete melting events of solid precursors (Hewins et al. 2005) and that they subsequently went through strong gas-melt interactions. It is not clear whether this gas was the background [protosolar nebula](#) medium or resulted from the continuous evaporation of solids at high temperature. Lead isotopes show that chondrule formation occurred over a few million years ago. For example, chondrules in the CR-chondrite Acfer have an age of 4564.7 ± 0.6 Ma and therefore postdate CAIs by

about 3.8 Ma. Chondrules in two CB chondrites have younger ages of 4562.7 ± 0.9 Ma and are 5.8 Ma younger than CAIs. In general, the time-scales given by lead isotopes are in quite good agreement with those inferred from the ^{26}Al systematics. Many chondrules, however, show no measurable record of ^{26}Al and no sign of metamorphic perturbations: they are therefore probably younger by at least ten half-lives of ^{26}Al , i.e., ≈ 7 Ma.

The problem of the significance of the chondrule ages is further complicated by the presence in Mg-rich chondrules of unequilibrated, likely relict olivines. This is clearly visible with oxygen isotopes. One of the geochemical requirements for obtaining a radiometric age is therefore not fulfilled since, upon its formation, the melt contained isotopically heterogeneous material. So far, however, no ^{26}Al isochron is known that would support a contemporaneous formation of chondrule and CAIs.

The in situ decay of ^{10}Be into ^{10}B was detected in all CAIs in which the distribution of B was not perturbed by metamorphism, alteration, or contamination, all processes that may have strong isotope effects for a trace element like boron present at the sub-ppm level. However, such a variation cannot be a priori interpreted as a chronological signature because a particularly refractory multiple oxide of Ca, Al, Ti, and Mg known as hibonite present in some rare CAIs appears to have formed with a $^{10}\text{Be}/^9\text{Be}$ ratio which is half the ratio of normal CAIs. In a condensation sequence, a refractory mineral such as hibonite should form early with respect to the other minerals from the same CAI. Therefore the $^{10}\text{Be}/^9\text{Be}$ ratio did not record the condensation time of CAIs but some other process. Because of the small number of documented cases, this conclusion should only be considered as a provisional, but it reaffirms the importance of these observations.

Lithium is very depleted in the Sun. The prevalence of irradiation processes forming ^6Li excesses in the protosolar disk, most likely during the T-Tauri phase of the Sun, is supported by the $^7\text{Li}/^6\text{Li}$ ratio of CAIs, which is lower than in chondrites. Values of $^7\text{Li}/^6\text{Li} = 9.20 \pm 0.22$

were observed in one Allende CAI and of 9.9 ± 1.1 in one Axtell CAI and should be compared with the chondritic value of 12.0 ± 0.3 .

The ^{53}Mn - ^{53}Cr extinct radioactivity is particularly useful for the early history of the Solar System. Numerous isochrons $^{53}\text{Cr}/^{52}\text{Cr}$ vs $^{55}\text{Mn}/^{52}\text{Cr}$ have been produced in meteorites. In CAIs, the parent/daughter fractionation (Mn/Cr) is a magmatic process: Mn and Cr are redistributed among various silicates and metal during melting. Therefore a $^{53}\text{Mn}/^{55}\text{Mn}$ age stands for the age of condensation provided that the post-formation heating events were short. As for ^{26}Al , this last point can be supported by petrological observations. On average, the $^{53}\text{Mn}/^{55}\text{Mn}$ ratio is $2.8 \pm 0.3 \times 10^{-5}$ in CAIs, while chondrules and whole-rock chondrites give a $^{53}\text{Mn}/^{55}\text{Mn}$ ratio of $9.5 \pm 3.0 \times 10^{-6}$. The estimated age difference between CAIs and chondrites ranges between 3.7 and 10.8 Ma. This result is consistent with those obtained from ^{26}Al , although noticeable discrepancies of about ± 2 Ma still exist.

Among the various short-lived radioactive nuclides, ^{60}Fe ($T_{1/2} = 2.62$ Ma decaying in ^{60}Ni) is the only isotope that cannot be produced in the Solar System and must result from explosive nucleosynthesis in distant stars. Evidence of ^{60}Fe occurrence has been found in FeS (troilite) and in magnetite from several ordinary chondrites (Mostéfaoui et al. 2004). The highest $^{60}\text{Fe}/^{56}\text{Fe}$ ratio measured so far is $0.92 \pm 0.24 \times 10^{-6}$. Somewhat lower $^{60}\text{Fe}/^{56}\text{Fe}$ ratios (2.2 and 3.7×10^{-7}) have been found in chondrules. Again, the issue of ^{60}Fe initial abundance and distribution are the subject of ongoing research.

The Chronology of Planet-Forming Processes

Mounting evidence shows that small planetoids accreted and differentiated very early around the Sun, more or less contemporaneously with the formation of CAIs, and thus earlier than chondrites. Recent models of runaway growth show that asteroids can form in a few times 10^4 to less than 10^6 years, but, until very recently, very little isotopic data from meteorites would allow us to constrain such short timescales.

Among the first evidence for an early differentiation of a meteoritic parent body was the finding

of ^{26}Mg excesses in plagioclase crystals from a magmatic (melted) meteorite (the eucrite Piplia Kalan; Srinivasan et al. 1999). A $^{26}\text{Al}/^{27}\text{Al}$ ratio of $7.5 \pm 0.9 \times 10^{-7}$ was inferred from these data at the time of the crystallization of these plagioclases from melts produced during the melting and differentiation of the eucrite parent body, possibly the asteroid $\blacktriangleright$ Vesta. This result implies that differentiation took place very early, some 4.6 Ma after the crystallization of CAIs. Several other similar results were found showing that the differentiation of the planetoids starts as early as ≈ 2.5 Ma after the condensation of the CAIs. The time required for the radioactive elements ^{26}Al and ^{60}Fe to produce enough heat to melt a thousand-kilometer-size asteroid has been estimated 1.8 Ma. This time represents the minimum duration taken by the planetoid to melt after its formation. Accordingly, the accretion age of these differentiated meteorites should postdate the CAI by only $2.5 - 1.8 = 0.7$ Ma.

The extinct radioactivity of ^{53}Mn has also been used to establish a detailed chronology of the differentiation. Igneous meteorites (eucrites) define a single isochron with a slope indicative of a $^{53}\text{Mn}/^{55}\text{Mn}$ ratio of $4.7 \pm 0.5 \times 10^{-6}$. This whole-rock isochron dates fractionation of Mn from Cr, which is thought to represent the isolation of the material that formed the eucrites prior to their melting. The corresponding time elapsed between the formation of the CAIs and the formation of the eucrite parent body before its differentiation is ≈ 11 Ma. Alternatively, if different minerals from a same sample are analyzed separately, the isochrons of each meteorite, the duration of the differentiation process increases to 18 Ma.

Among meteorites, iron meteorites are pure metallic bodies. They likely result from melting of asteroids followed by a gravitational segregation of the metallic and silicate melts. The metal segregates and eventually crystallizes to form the planetary cores. Debris of such cores produced by collisions among asteroids or by tidal effects in the asteroid belt are now sampled as iron meteorites. Because reducing conditions are prevalent at high temperatures, early melting of asteroids must have resulted in metal-silicate differentiation. ^{182}Hf decays to ^{182}W with a half-life of 8.9 Ma,

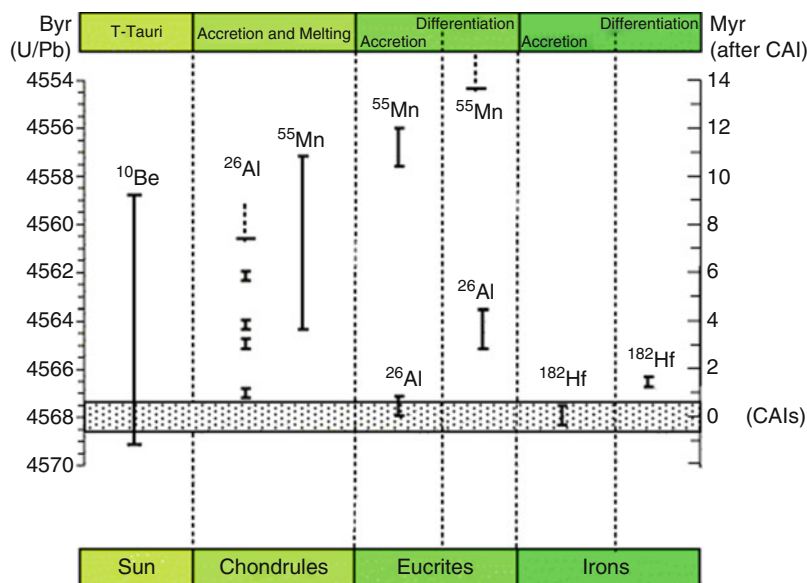
and the ^{182}Hf - ^{182}W system is a suitable chronometer to date core segregation: W fractionates into the metal and Hf into the silicate mantle. The radiogenic ^{182}W excesses measured in CAIs are used to determine that, at the time of formation of CAIs, the $^{182}\text{Hf}/^{180}\text{Hf}$ ratio in the protosolar nebula was $1.07 \pm 0.10 \times 10^{-4}$ and tungsten was depleted in ^{182}W by $\approx 0.35\%$ with respect to the Earth. Surprisingly, the ^{182}Hf - ^{182}W ages of the iron meteorites are indistinguishable from those of CAIs (Kleine et al. 2005), which, taking uncertainties into account, requires that the metal-silicate differentiation took place on the parent body of magmatic irons no later than ≈ 1 Ma after CAIs. Again a picture in which small planetoids accrete very early in the protosolar disk emerges from this chronometer.

If asteroids indeed formed early – say between 0.1 and 1 Ma – most of them experienced high collision rates during the runaway growth period. Because chondrules seem, on average, to be younger than CAIs by up to a few Ma, their precursors might have incorporated fragments of the early

accreted and differentiated asteroids. Such fragments were isolated recently in chondrules from the CV carbonaceous chondrite Vigarano. Oxygen isotopes show that these chondrules contain relict textures that are most likely accounted for by small fragments of olivine-rich differentiated planetoids. The different aspects of the chronology of the Solar System formation discussed in this text are summarized (Fig. 1).

Future Directions

The age of the oldest known solids of the Solar System is now known to be within ± 0.3 Ma at 4.5682. Condensation and accretion of all solid material in the Solar System took place within a few million years of this age. The presence of the in situ decay products of short-lived radioactive nuclides in both undifferentiated and differentiated meteorites demonstrates that, within a few million years or less, grains were condensed and the first planetoids were accreted and then



System Solar Formation, Chronology of, Fig. 1 Ages are reported for chondrules and for differentiated meteorites (eucrites and irons). The absolute age of CAIs is expressed in billions of years (Ga); all other ages are relative to CAIs and expressed in millions of years (Ma). The extinct nuclides used for these relative determinations

are indicated (*dashed error bars* stand for lower limits). Contrary to chondrules that cooled rapidly, for eucrites and irons, it is possible to define an accretion age that predates their complete melting (differentiation). The age of the Sun is indirectly deduced from the presence of live ^{10}Be in CAIs, which is produced by solar flares at its birth

differentiated. Various chronometers provide an overall consistent chronology but show some discrepancies in detail. Several assumptions underlying isotopic chronometry still need validation and should be regarded as pending issues, namely: (1) Was the distribution of the various short-lived radioactive nuclides across the disk homogeneous in time and space? (2) To what extent were the observed short-lived radioactive nuclides' abundances modified by secondary processes either in the solar nebula or on the parent bodies?

Cross-References

- Activity, Magnetic
- CAIs
- Chondrule
- Chronological History of Life on Earth
- Cratering Chronology
- Geochronology
- Planetary Evolution
- Planetesimals
- Protosolar Nebula, Minimum Mass
- T Tauri Star
- Vesta

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Systems Biology

- Kepa Ruiz-Mirazo¹ and Andrés de la Escosura²
- ¹Department of Logic and Philosophy of Science, FICE, UPV-EHU, Biophysics Research Unit (CSIC – UPV/EHU), San Sebastián, Spain
- ²Nanoscience and Molecular Materials Research Group, Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Biochemical networks · Cellular metabolism · Biological complexity · Self-organization · Emergent dynamic behavior · Computational modeling

Definition

Systems biology is a young scientific discipline within the broader field of cell biology, or biology at large, whose major goal is the study of complex dynamic behaviors in biochemical and interactive networks, through the acquisition of quantitative experimental data and the complementary aid of theoretical modeling and computational tools. It is considered a more comprehensive or holistic approach than those traditionally taken in biological and biomedical research to deal with metabolic processes, regulatory networks, and adaptive cellular responses. For general references on this topic, see (Kitano 2002; Westerhoff and Palsson 2004; Boogerd et al. 2007; Camacho and Collins 2009; Klipp et al. 2009; Hübner et al. 2011).

History

Over the last century, a number of scientists and philosophers pointed out the necessity of adopting a *systems* perspective in order to make significant scientific progress, especially with regard to the challenge of biological complexity (de la Escosura et al. 2015). Von Bertalanffy was one of those pioneers, putting forward a “theory of systems” already in the 1950s and 1960s (von Bertalanffy 1950). However, he did not provide a concrete methodological framework to develop such a research program in practice, probably because the required technological advances were not available at that time yet. In addition to those early insights, various disciplines seeded the scientific soil with ideas that contributed to the later foundation of systems biology, like cybernetics and control theory, nonequilibrium thermodynamics, or the mathematical modeling of enzyme kinetics and population growth, among others. The actual term “systems biology” was coined in this context by Mesarovic (1968), followed by other relevant theoretical developments for the field, such as metabolic control analysis, biochemical systems theory, and the first stochastic simulations of complex reaction dynamics. However, the golden age of systems biology came with

the advent of genomics, proteomics, and metabolomics (i.e., the “omics” revolution) in the late 1990s, which allowed gathering massive amounts of biochemical data. With the main objective of providing an adequate interpretation of those data and contributing to integrate knowledge from different levels of description of the living phenomena (in particular, from the biomolecular and cellular levels), the field of systems biology has been growing exponentially since 2000 (Hübner et al. 2011).

Overview

Systems biology, rather than a full change of paradigm, represents an important move to find a new balance in the natural sciences, a redistribution of weights in the production of biological knowledge. Oversimplifying history, during the second part of the twentieth century, the focus of biology was on the discovery of the molecular bases that could account for the complex properties and behavior of living organisms. Then, with the increased power of molecular biology’s data extraction techniques (the “omics” era), the need to find criteria to interpret that huge amount of information, together with new explanatory tools to link molecular specificities with global cellular responses, became more manifest. Systems biology was the main response from the community (hand in hand with other emerging research areas, like bioinformatics, synthetic biology, or computational biology) to those new challenges. Essentially, it proposes the combination of experimental and theoretical modeling methodologies to work out possible mappings or connection routes (both “upward” and “downward”) between molecular details and collective dynamic behaviors, with special emphasis on the cellular level – but also below and, potentially, beyond that level.

Some of the topics currently faced by systems biologists include the study of information processing in signaling networks, the inference of mechanistic models for intricate phenotype development, the modeling of metabolic interactions and complex microbiomes, or the understanding of cellular dynamics and regulation. More

recently, systems biology is starting to contribute significantly to the field of biomedicine, as well (e.g., in drug design and development – see Brown and Okuno 2012). It keeps a special relationship with synthetic biology, a field that was founded approximately in the same historical period and may also be instrumental to reveal basic principles of biological organization – in this case, by synthesizing and trying to assemble standardized bio-modules into more complex circuits or networks. Finally, systems biology has served as a source of inspiration for the onset of its sister discipline in chemistry, “systems chemistry,” whose aim is to understand the emergence of biological phenomena from their chemical bases, namely, through the spontaneous self-organization of biomolecular components into protocells and, ultimately, living cells (de la Escosura et al. 2015).

Cross-References

- Genomics
- Metabolic Networks
- Proteome, Proteomics
- Protocell
- Synthetic Cells
- Systems Chemistry

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Systems Chemistry

Jan W. Sadownik and Sijbren Otto
Stratingh Institute for Chemistry, University of Groningen, Groningen, The Netherlands

Keywords

Molecular networks · Far-from-equilibrium systems · Dynamic combinatorial chemistry · Supramolecular chemistry · Autocatalysis · Self-replicating molecules · Oscillating reactions · Chiral symmetry breaking · Prebiotic chemistry · De novo life

Definition

Systems chemistry is an area of chemistry that seeks insight into complex networks of interacting molecules and their system-level properties. These properties emerge through the collective behavior of the system’s components and cannot be attributed to the individual components acting in isolation. The way in which specific interactions between the components propagate through the system dictates these emergent properties.

History

The term “systems chemistry” was first used in 2005 by von Kiedrowski in a publication (Kindermann et al. 2005) describing the kinetic and computational analysis of a nearly exponential organic replicator. In this paper, von Kiedrowski claims new research “could open a door to a field that may be termed systems chemistry, namely, the design of prespecified dynamic

behaviour.” In the same year, a systems chemistry workshop (Stankiewicz and Eckardt 2006) was held in Venice, Italy where a more detailed definition was given describing systems chemistry as “a new field of chemistry seen as the offspring of prebiotic and supramolecular chemistry on the one hand and theoretical biology and complex systems research on the other.” In 2007, a new EU research network on systems chemistry (COST CM0703; European Cooperation in Science and Technology) was established, which followed a similar line of reasoning. In the context of this COST Action systems chemistry is seen as the bottom-up chemical pendant of systems biology toward synthetic biology. This approach would be made feasible by a joint effort of prebiotic and supramolecular chemistry assisted by computer science from theoretical biology, theoretical chemistry, and complex systems research to tackle dynamic supersystem integration including at least one autocatalytic subsystem. In 2009, the Centre for Systems Chemistry was established at the University of Groningen, Netherlands, and an open access *Journal of Systems Chemistry* (von Kiedrowski et al. 2010) was launched through the Chemistry Central platform now part of the Springer publishing house. The 2007 COST action was followed by Action CM1304 that started in 2013.

Overview

Most chemists have traditionally focused on devising chemical transformations that produce a single, desired compound with given properties selectively. In such approaches, mixtures of compounds are undesired and eliminated with various purification techniques. This situation is no longer the case, since more complex mixtures have become tractable by the development of advanced analytical methods. Today, it is possible to move away from the reductionist approach that inspired most research in chemistry previously and develop methods to study multiple variables simultaneously paving the way for systems chemistry (Ludlow and Otto 2008; Peyralans and Otto 2009; Nitschke 2009; Stoddart 2012). Systems

chemistry defines a new area of chemistry in which a few already well-established branches of chemistry come together. Many systems featured in the area incorporate phenomena under thermodynamic control such as dynamic combinatorial libraries (Li et al. 2013), molecular recognition, and self-assembly. In many cases, it is the combination and fine interplay between these elements that give rise to specific emergent properties sought for in systems chemistry research. While thermodynamically controlled molecular networks are probably easier to study and understand, kinetically controlled networks have greater relevance to biology, as life operates far from equilibrium. Some examples of studied kinetic processes in the scope of systems chemistry include autocatalytic reactions and self-replicating molecules, kinetic self-assembly, self-sorting processes, and oscillating reactions. One of the major questions that systems chemistry sets out to answer (Szostak 2009; Ruiz-Mirazo et al. 2014) is what made the transformation of a complex mixture of molecules on the prebiotic Earth into a living chemical system possible. What most researchers agree upon is that a combination of thermodynamic and kinetic processes as well as an array of auto- and cross-catalytic cycles played a major role in this development. Another aspect of this research is finding out why the particular biochemical building blocks of life that we know today were selected and how some of these biomolecules developed to have specific chirality. Systems chemistry addresses these issues by devising model synthetic systems with properties that could reflect aspects of prebiotic biogenesis. Another topic at the core of systems chemistry is the quest for de novo life. However, life is just one incredibly complex functional molecular system, and many others are conceivable, and what may be achieved with systems chemistry is ultimately only limited by the creativity of the chemist.

Cross-References

- [Artificial Life](#)
- [Autocatalysis](#)

- [Chemical Reaction Network](#)
- [Chirality](#)
- [Complexity](#)
- [Origin of Life](#)
- [Prebiotic Chemistry](#)
- [Self-Assembly](#)
- [Self-Replication, Chemical](#)
- [Systems Biology](#)
- [Thermodynamical Chemical Equilibrium](#)

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T

T Association

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Definition

Solar-type stars that are still in the pre-main-sequence phase of evolution are known observationally as ► [T Tauri stars](#). These objects are not seen in isolation but in coherent groups, known as T associations. One example is Taurus-Auriga, about 140 parsecs away. Along with the eponymous T Tauri stars, which are optically visible, the associations also contain more embedded, infrared objects. Indeed, the entire group is contained within a ► [molecular cloud](#). The density of stars is too low for significant mutual gravitational attraction. Rather, the group is maintained by the gravity of the parent cloud.

Cross-References

- [Birthline](#)
- [Molecular Cloud](#)
- [OB Association](#)
- [Pre-main-sequence Star](#)
- [Protostars](#)

- [Stellar Cluster](#)
- [T Tauri Star](#)

T Tauri Star

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Star formation

Definition

T Tauri stars are solar-type objects in the pre-main-sequence phase. They are found in loose groups, located in or near molecular clouds. All T Tauri stars exhibit variability in their light and have strong surface magnetic fields. Some, the classical T Tauri stars, have strong spectral emission lines in their spectra, as well as an infrared and ultraviolet excess. The weak-lined T Tauri stars are lacking in these properties. These differences plausibly reflect the presence or absence of circumstellar accretion disks. In any case, both types are located above the main sequence in the ► [Hertzsprung-Russell \(HR\) diagram](#), confirming their pre-main-sequence status.

Overview

Stars that are too young to fuse hydrogen into helium are said to be in the pre-main-sequence phase of evolution. Lacking a nuclear energy source, these objects contract gravitationally. Contraction drives up the central temperature. Eventually, the temperature is high enough for fusion to begin. The star has now joined the main sequence, the evolutionary phase of our Sun and most other stars we see.

T Tauri stars are pre-main-sequence objects similar to the Sun in mass. They can easily be distinguished from main-sequence stars by their irregular variability and their strong spectral emission lines, particularly the H alpha line at 6563 angstroms (656.3 nm), as well as by the presence of ► [lithium absorption](#). They are found within groups called T associations, which are in or near regions of visual obscuration. Such patchy obscuration is caused by molecular clouds, confirming the youthful status of this class of stars.

We may also gauge their evolutionary status in a more quantitative manner. Once the surface temperature and total luminosity of a star are measured, the object may be plotted in the HR diagram. When this exercise is done for any T association, the representative points fall below the stellar ► [birthline](#) but above the main sequence. Moreover, their positions within the diagram allow one to assess the stars' ages. This technique gives T Tauri stars ages of a few million years.

There are two broad classes of T Tauri stars – classical and weak lined. Both are located above the main sequence in the HR diagram. Only classical stars, however, exhibit strong emission lines. They also have infrared and ultraviolet excesses, as gauged from their spectral energy distributions. Weak-lined stars, as the name implies, lack the strong emission lines, as well as infrared and ultraviolet excess. Both types of stars are variables, and both have strong magnetic fields.

These differences in part reflect the presence or absence of circumstellar disks. Such disks are present in classical T Tauri stars. The infrared excess arises from heated dust in the disk, while the ultraviolet may originate from disk matter crashing onto the stellar surface. Apparently, the

disks are absent in weak-lined stars, although these objects have similar ages. As pre-main-sequence stars further evolve, their infrared and ultraviolet excess and temporal variability fade away. There should be large numbers of relatively nearby post-T Tauri stars, although only relatively few have so far been observed.

Cross-References

- [Birthline](#)
- [Convection, Stellar](#)
- [Hertzsprung-Russell Diagram](#)
- [Lithium Absorption](#)
- [Pre-main-sequence Star](#)
- [Protoplanetary Disk](#)
- [Spectral Veiling of Young Stars](#)

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Table Mountain

- [Mensa/Mensae](#)

TACK, Archaea

Ricardo Amils
Departamento de Biología Molecular, Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Definition

TACK is the acronym for a group of archaea originated from the names of the first identified

phyla (Thaumarchaeota, Aigarchaeota, Crenarchaeota, and Korarchaeota). They have been identified in diverse extreme environments like those at high temperature (thermophiles), low temperature (psychrophiles), and low pH (acidophiles). Most members of this group are anaerobic. Crenarchaeota are the best known members of this group; together with the Euryarchaeota, these were the first two phyla described for the archaeal domain. Due to their metabolic relationship with sulfur compounds, they were also known as “sulfo-bacteria.” The best characterized hyperthermophilic archaea belong to the Crenarchaeota phylum (*Sulfolobus acidocaldarius*, *Pyrodictium occultum*, *Pyrolobus fumarii*, *Ignicoccus islandicus*). Korarchaeota was the third historical phylum described for Archaea and most of its members were detected in hydrothermal environments.

Cross-References

- [Archaea](#)
- [Acidophile](#)
- [Euryarchaeota](#)
- [Thermophile](#)

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Taconite

- [Banded Iron Formation](#)

Taq Polymerase

Ricardo Amils

Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Heat-stable DNA polymerase](#)

Definition

Taq polymerase denotes the heat-stable DNA polymerase extracted from the thermophilic bacterium *Thermus aquaticus*. It is used to automate the repetitive steps in the ► [polymerase chain reaction](#) (PCR) technique, an extremely important method of amplifying specific DNA sequences. The polymerase chain reaction can multiply DNA molecules up to a billion-fold in the test tube, yielding large amounts of specific genes for their use in multiple applications. The steps in PCR amplification are the following: DNA incubation with an excess of specific primers of the selected gene, the DNA polymerase extends the primers using the target strands as templates, after incubation the mixture is heated to separate the DNA strands and cooled to allow primers to hybridize with complementary regions of the newly synthesized DNA and, finally, the operation is repeated several times. The introduction of a thermophilic DNA polymerase avoids the denaturation of the enzyme during the heating step required to separate the newly synthesized strands, thus simplifying the methodology while increasing its efficiency.

Cross-References

- [Amplification \(Genetics\)](#)
- [Cloning](#)
- [Genomics](#)
- [Hybridization](#)
- [Hyperthermophile](#)

- [Polymerase Chain Reaction](#)
- [Replication \(Genetics\)](#)

Taurus Molecular Cloud 1

- [TMC-1 Molecular Cloud](#)

Tautomer

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A tautomer is a constitutional isomer of a compound, most usually an organic compound, that has a low energetic barrier to interconversion to another isomeric state (which is another tautomer of the same molecule), a process termed tautomerization. Tautomerization may result in the migration of a proton, accompanied by the change of location of a single bond and an adjacent double bond. Due to the low energetic barrier to interconversion and consequent rapid interconversion of tautomeric forms, tautomers are generally considered to be the same chemical compound, though they have different formal bonding geometries.

Tautomerization produces an equilibrium mixture of possible tautomers. The final ratio depends on factors including temperature, solvent, and pH, as well as the intrinsic stability of the tautomers. Prototropy is a special form of tautomerism caused by the relocation of a proton in a molecule. Prototropy is a form of acid-base behavior.

Keto-enol and imine-enamine tautomers are especially important in the process of mutation

in nucleic acid copying. For example, the nitrogen heterocyclic moieties of nucleotides can exist in various tautomeric equilibria, some of which are able to form mismatched base pairs with non-canonical complements.

Cross-References

- [Base Pair](#)
- [Isomer](#)
- [Nucleic Acids](#)

Taxonomy

Ramon Rosselló-Móra
IMEDEA (CSIC-UIB), Mallorca, Spain

Keywords

Classification · Hierarchy · Systematics

Synonyms

[Classification](#)

Definition

Taxonomy (from Greek *taxis* [order or arrangement] and *nomos* [law or science]) is the scientific discipline that deals with the classification of the living organisms.

Overview

Taxonomy pursues the generation of a classification system that is operative and predictive with the ultimate goal of identifying the patterns of recurrence (► [species](#)) that can be observed in nature. However, the word “taxonomy” is often used as a synonym for “classification,” and both terms indicate the hierarchical system that organizes biological diversity. Taxonomy is an

essential discipline of the biological sciences because it provides a framework that facilitates the scientific community's understanding and knowledge exchange. The main basis of taxonomic classification is the category of "species" that is considered as the unique entity. Different taxonomies tailor their species circumscriptions with different criteria depending on their ability to reveal genetic, phenotypic, and ecologic particularities. Thus, such units are not always comparable. However, higher-rank categories (from genus to phylum) are considered abstract entities and thus comparable among the different taxonomies. The main success of taxonomy will be to achieve a classification that reflects the natural genealogical and evolutionary relationships among living (and fossil) organisms.

It is perhaps one of the oldest biological sciences, having been in existence for at least 2400 years, since Aristotle devised the first hierarchy based on creationist and essentialist tenets. Linnaeus established the first serious taxonomy in the eighteenth century when he created the binomial system of nomenclature (genus and specific epithets) for plants, as well as the first hierarchical system based on five taxonomic ranks (kingdom, class, order, genus, and species). Later, in the middle of the twentieth century, Mayr and Simpson enlarged the hierarchical system in about 19 different taxonomic ranks as a result of an enormous increase of classifications and the difficulties in fitting them into the five-rank system. One of the major drawbacks of the current view on taxonomy is that scientists take for granted that the whole of biological diversity, including prokaryotes and eukaryotes from any source, can be organized by following a single hierarchical model of categories, equally ranked for any kind of organism, which is a tendency called "monism" by philosophers. However, some scientists advocate for the allowance as many parallel taxonomies as possible, following a tendency called "pluralism" by philosophers, as the only solution to the so-called species problem.

The success of taxonomy as a science will be the achievement of a classification system that is operative and predictive (i.e., the identification of an individual belonging to a given taxon will be

accompanied by the prediction of genetic, phenotypic, or ecologic traits) and reflects the natural relationships among the classified organisms.

Cross-References

- [Evolution, Biological](#)
- [Phylogeny](#)
- [Species](#)

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Tectonic Plate

- [Plate, Lithospheric](#)

Tektite

Philippe Claeys
Earth System Science, Vrije Universiteit Brussel,
Brussels, Belgium

Definition

Tektites (and microtektites) are centimeter (or millimeter)-sized rounded or elongated natural glass particles of homogeneous composition and commonly SiO₂ rich. They are an ► [ejecta](#)

material produced during hypervelocity impact by the fusion (high temperature $>2000\text{ }^{\circ}\text{C}$) of the uppermost part of the target rock. Their chemical composition thus reflects that of the fused impacted rocks. The molten material is ejected from the crater and quenched in flight, which explains their aerodynamically shaped morphologies, and deposited over a vast geographic area called a “strewn field” extending up to $>1000\text{ km}$ from the source. Four strewn fields are known: the North American, European, Australasian, and Ivory Coast.

Cross-References

- [Crater, Impact](#)
- [Ejecta](#)
- [Impactite](#)

Telescope

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Image formation · Mirror · Optics · Radio telescope

Definition

A telescope is an instrument used to study remote objects in the universe. It is able to collect on a large surface the ► [electromagnetic radiation](#) (light) emitted by those objects when it reaches Earth. Originally designed for visible light, telescopes have now been developed for all other types of electromagnetic waves, from gamma rays to radio waves.

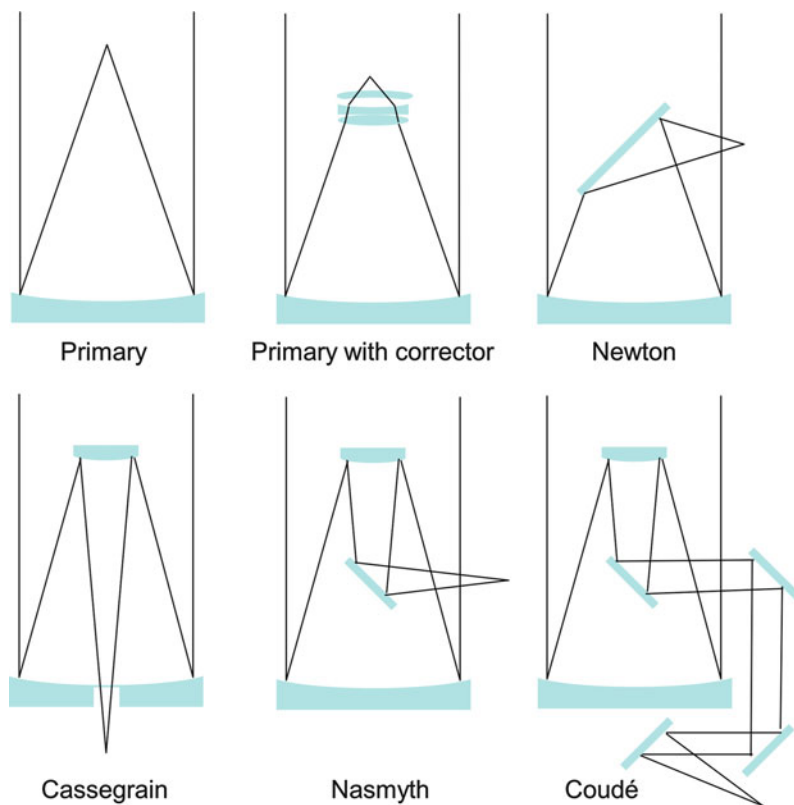
Overview

Geometrical optics provides the first approximation in designing a telescope. Whatever the total number of mirrors or lenses used, the telescope has a first optical element of large dimension which defines the capacity of energy collection and forms a first image. This first element (lens or primary mirror) is generally followed by other optical elements (secondary, tertiary) whose purpose is to change the magnification and improve the image quality. At the end of the chain, the focal plane of the telescope is found, where the light is concentrated and the image is formed to be used by dedicated systems for analysis (camera, spectrometers, polarimeters, etc.).

The main parameters for characterizing a telescope are:

- (a) The focal configuration. Figure 1 depicts the most usual ones. The Cassegrain configuration where the beam crosses the primary mirror through a central hole is one of the most current. Note that a single telescope may have several foci, the transition from one to another being done by simply switching a secondary or tertiary mirror. The advantage is to have different instrumentations available and to switch from one to another with no loss of time.
- (b) The scale of the image at each focal plane, usually given in mm per arcsec. This scale should be adapted to the pixel size of the analysis systems.
- (c) The numerical aperture of the beam, given by the ratio f/D , i.e., the equivalent focal length to the diameter of the primary mirror.
- (d) The field, which is the region of the focal plane in which both the image quality and the uniformity of illumination remain acceptable.
- (e) The quality of the image. It is measured by the angular diameter of the circle in which a significant fraction (e.g., 50% or 80%) of the energy of a point object is focused.

Telescope, Fig. 1 The different possible focal configurations found in a telescope



Telescopes operating in the visible are the oldest imaging instruments used in astronomy. The increase in diameter was made in stages, depending on advances in materials and technologies: after refractors, whose role was virtually extinct in the twentieth century, the first half of that century saw the appearance of instruments with mirror diameters of 5–6 m, followed by mirrors up to 10 m in the second half. By the years 2020–2030, there is little doubt that instruments from 30 to 50 m in diameter will come into operation. Their extension to the near and medium infrared was made in the 1970s, with the availability of sensitive detectors and of sites of excellent quality that allowed good atmospheric transmission in a few spectral windows. Some recent developments have allowed astronomers to go beyond the apparent limits set by the difficulty of access to space and by image degradation due to atmospheric turbulence. During the late

1970s, it was thought unlikely to continue construction of telescopes on Earth with a diameter larger than 5–6 m. This view quickly evolved for a set of reasons:

- The technological limitations in the construction of very large mirrors have been overcome, thanks to the emergence of new materials (ceramics), the advent of active control of thin mirrors leading to substantial reductions of weight, and by making segmented mirror surfaces.
- Methods of correction of atmospheric turbulence have emerged in the late 1980s and (► [Adaptive Optics](#)) preceded by numerical methods for post-correction of images (speckle interferometry) in the 1970s; breaking the limit previously imposed by turbulence (atmospheric “seeing”), they allowed astronomers to actually benefit from the

theoretical gain of angular resolution proportional to the diameter D of the telescope (see ► [Diffraction](#)).

Telescopes were traditionally installed on an equatorial mount with one axis parallel to Earth's rotation axis, which allowed a simple motion about that axis to compensate for the diurnal motion. These are now discontinued, for reasons of space and lightness and therefore of cost, in favor of so-called altazimuth mounts, where the diurnal motion compensation operating on two axes is driven by a computer.

Telescopes for reception in the radio domain are called radio telescopes or antennas. These telescopes are usually made of a very large primary mirror (tens or hundreds of meters), generally parabolic, whose precision of surface is fixed by the wavelength of use. The surface may even be made of metallic mesh or panels. The growing importance of the submillimeter domain leads to the building of quality mirrors, at the borderline of optical instrumentation. The receiver, either based on heterodyne principles for spectroscopy or a bolometer for measuring continuum emission, is either placed directly at the primary focus or at a secondary Cassegrain focus. Multi-pixel array receivers are now becoming common. On Earth, the telescope is usually carried by an altazimuth mount and follows the source in its diurnal motion. At these wavelengths, the sky is practically the same between day and night so that these instruments can operate continuously. The robustness of their mirror allows them to be built in the open air, without a dome, which reduces the cost.

At high energy the term telescope is still used, but the instruments are very different from a conventional telescope. In the X-ray domain, grazing Wolter telescopes are used: they are composed of ring-shaped mirrors made of heavy metals that are able to reflect the rays hitting the surface at a very large incidence close to 90° . The mirrors are usually a section of a rotated parabola followed by a hyperbola, many rings (typically 30) being nested to reach a reasonable projected surface, and feeding a common focus.

For gamma-ray telescopes, there is no longer an attempt to concentrate the light; the detector defines the collecting surface, and a coded aperture mask made of titanium is put at a certain distance from the detector: the patterns of the shadows the mask creates when illuminated by different sources can be reconstructed to form an image. The angular resolution of this solution is rather poor (typically 1°).

Cross-References

- [Adaptive Optics](#)
- [Imaging](#)
- [Radio Astronomy](#)

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Telluric Planet

- [Terrestrial Planet](#)

Teloempathy

Octavio A. Chon-Torres
Programa de Estudios Generales, Universidad de Lima, Lima, Perú

Definition

According to Cockell (2005a, b) and Cockell (2011) teloempathy is the ability to recognize

the interests of other extraterrestrial living things, in the eventual case that their discovery is confirmed. For example, on Mars, if any form of microbial life were confirmed there, they would have no way of claiming their own rights, so we, in an act of empathy that is not limited to terrestrial life forms, can watch over their integrity and avoid putting them at risk. Teloempathy would represent a way of acting and seeing things that moves us from ethical biogeocentrism (Chela-Flores 2001, 2009; Aretxaga 2004) toward a perspective that brings us closer to astrobiocentrism (Chon-Torres 2020, 2021).

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Template

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

In molecular biology, a template is a molecule that carries genetic information and can be used to make copies of itself. The template molecule is single stranded (ss) DNA in DNA replication – also known as DNA-dependent DNA polymerization, catalyzed by DNA polymerase enzymes – and in transcription – DNA-dependent RNA polymerization, catalyzed by RNA polymerases. In viruses with an RNA genome, ssRNA templates can be used in either RNA replication – RNA-dependent RNA polymerization, catalyzed by viral-encoded RNA polymerases – or reverse transcription – RNA-dependent DNA polymerization, catalyzed by reverse transcriptases in retroviruses. In all cases, the template molecule directs the synthesis of its complementary molecule. In the origin of life field, template-independent and template-dependent – both nonenzymatic and enzymatic – nucleic acid polymerization processes are studied. Additionally, ssRNA template molecules – in the form of mRNA – are used by ribosomes to translate their nucleotide sequences into the amino acid sequences of the encoded proteins.

Cross-References

- DNA
- DNA Polymerase
- Genetics
- Replication (Genetics)
- RNA
- RNA Polymerase
- Template-Directed Polymerization

- [Transcription](#)
- [Translation](#)

Template-Directed Polymerization

Pierre-Alain Monnard
FLinT Center, Institute for Physics and
Chemistry, University of Southern Denmark,
Odense, Denmark

Keywords

Polymerization · Primitive information
system · Replication · RNA world · Sequence
specificity · Template · Watson-Crick base pair

Synonyms

[Nonenzymatic template-directed polymerization](#);
[RNA self-replication](#); [Template-directed RNA
replication](#)

Definition

The concept of template-directed polymerization refers to a chemical reaction in which a polymer is synthesized from monomeric units using a template, i.e., another polymer molecule, as a reaction directing molecule. In nucleic acid replication, the template sequence (i.e., the order of nucleobases in the template) determines the nucleobase sequence of the polymer product because the monomer units, the ► [nucleotides](#), assemble onto the template due to a molecular recognition based on Watson-Crick base pairing with the template before being covalently linked together. Stacking between monomer nucleobases further stabilizes monomer-template complexes. Short oligomers are sometimes viewed as “monomeric” units in template-directed ligations.

History

The nature of primitive metabolism that allowed for nonenzymatic replication of informational polymers is unknown. Many hypotheses regarding its nature have been put forward on the basis of comparisons with contemporary cellular life. Although it was obvious that a simpler system must have preceded today’s cellular biology, the interdependence of proteins and nucleic acids for their replication has long remained a profound puzzle (often depicted as the “chicken and egg” paradox). In fact, a “satisfactory” answer to this dilemma could not be envisioned until the ► [RNA world](#) concept was first hypothesized in the 1960s by C. Woese, F. H. C. Crick, and L. E. Orgel, among others, and later named as such by W. Gilbert. These authors postulated an autonomous RNA-based “organism” in which RNA molecules could perform catalytic functions presently carried out by proteins while also acting as a repository of genetic information. Although the RNA world seems to be ineluctable at some point during the emergence of cellular life from inanimate matter, it is not clear whether it represented the first system during the evolution of life. In fact, the evidence at hand still leaves open questions about the origins and “biochemistry” of the RNA world. A successful implementation of this hypothesis, however, presupposes efficient, nonenzymatic information transfer and amplification based on the template-directed polymerization of nucleotide monomers.

Overview

Two separate issues impact the ability of nucleic acid monomers to ligate during template-directed polymerization: (1) the stability of the hybridized system, which improves as the length of the newly synthesized, complementary chain increases, and (2) the likelihood that the neighboring monomers to be ligated align themselves (i.e., stack) to facilitate polymerization. In addition, phosphodiester bond formation requires energy input, which is often provided by activated monomers, e.g.,

► [nucleoside phosphoimidazolides](#), whose availability on the early Earth is questionable.

In homogeneous (bulk) aqueous solutions, efficient nonenzymatic, template-directed polymerization of activated purines on their complementary pyrimidine strands has been observed. However, activated pyrimidines, in particular uridine ► [ribonucleotides](#), have never been efficiently incorporated into an RNA strand, most likely because of poor stacking interactions due to their high hydrophilicity. In fact, the presence of two consecutive adenosine residues on a template completely inhibits polymerization, as this implies two stacked uridine nucleotides in the complementary strand. Furthermore, it has also been experimentally observed for guanosine monomers that a heteropolymeric template must contain at least 60% of cytidine residues for efficient “replication” to occur. Although the complementary strand can be produced in this case, the cytosine-enriched template itself will not be reproduced, as its own template would contain $\geq 60\%$ G-residues and hence $\leq 40\%$ C-residues. Thus, no nonenzymatic, template-directed amplification of RNA from monomers can take place.

To solve the issues, which appear to prohibit two-way template-directed polymerization as noted above, two main approaches have been proposed: either to create microenvironments amenable to polymerization or to improve the intrinsic properties of the monomers. Among the proposed environments, montmorillonite clays, lipid-bilayer matrices, and eutectic phases in water ice have been investigated. Derivatives of ribonucleotides with higher intrinsic reactivity, in particular 5' or 3' amino-substituted ribonucleotides, or the effects of molecular helpers or “midwives”, such as large heterocycles, that increase stacking between monomers have also been studied. Although these two pathways may not be directly relevant to the emergence of an information system on the early Earth, they have already delivered promising results that suggest that template-directed polymerization of RNAs and RNA analogs may be possible.

Cross-References

- [Chicken or Egg Problem](#)
- [Nucleoside Phosphoimidazolidine](#)
- [Nucleotide](#)
- [Pyrimidine Base](#)
- [Replication \(Genetics\)](#)
- [Ribonucleoside](#)
- [Ribonucleotide](#)
- [Ribozyme](#)
- [RNA World](#)
- [Self-Replication](#)
- [Watson-Crick Pairing](#)

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Template-Directed RNA Replication

- [Template-Directed Polymerization](#)

Terminal Sterilization

J. Andy Spry
SETI Institute, Mountain View, CA, USA

Definition

In planetary protection, terminal sterilization is a process for ► [Bioburden](#) reduction that is

performed on the entire spacecraft system after assembly is completed. For example, the ► [Viking](#) spacecraft in the 1970s were baked at 111.7 °C for 50 h at the end of the assembly phase (as opposed to sterilization of subsystems being sterilized before assembly). Terminal sterilization reduces the risk of recontamination in the assembly and test process. These are, to date, the only interplanetary spacecraft subjected to such a terminal sterilization process.

Cross-References

- [Bioburden](#)
- [Planetary Protection](#)
- [Viking](#)

Terpenoids

- [Isoprenoids](#)

Terra, Terrae

Ralf Jaumann
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Synonyms

[Highland region](#)

Definition

In planetary nomenclature terra (terrae) refers to an extensive rugged land mass. Terrae on ► [Mars](#) are Aonia Terra, Arabia Terra, Terra Cimmeria, Margaritifer Terra, Noachis Terra, Promethei Terra, Terra Sabaea, Terra Sirenum, Tempe Terra, Tyrrhena Terra, and Xanthe Terra ranging from about 8×10^6 to 46×10^6 km². Terrae on ► [Venus](#) such as Aphrodite Terra, Ishtar Terra,

and Lada Terra range from about 49×10^6 to 157×10^6 km². On the ► [Moon](#), the term is used to identify more generally bright regions in contrast to the darker Maria.

Cross-References

- [Albedo Feature](#)
- [Mare, Maria](#)
- [Mars](#)
- [Moon, The](#)
- [Planum](#)
- [Venus](#)

Terraforming

- [Planetary Ecosynthesis](#)

Terrestrial Analog

Felipe Gomez
Centro de Astrobiología (CSIC/INTA), Instituto
Nacional de Técnica Aeroespacial, Madrid, Spain

Keywords

Europa analogues · Extreme environments ·
Extremophiles · Mars analogues

Synonyms

[Analog sites](#)

Definition

A terrestrial analogue is a field site which bears an analogy or similarity in some way to conditions on other planetary bodies of the solar system; e.g., analogues to ► [Mars](#) or Jupiter's moon ► [Europa](#) are the Atacama Desert and Lake Vostok, respectively. Similarities can be related with

physicochemical conditions, such as dryness, low water activity, mineralogy, or chemical composition of the ► [environment](#). Low water activity would be the case for the Atacama Desert's similarity with the Mars surface, while a subsurface ocean under an ice layer applies approximately in the case of Lake Vostok and the moon Europa.

Overview

Solar system exploration takes advantage of some peculiar Earth sites which can serve as field facilities or Earth references. These sites are called Earth analogues and can be used as reference because they have particular similarities or characteristics that resemble those found on an extra-terrestrial planetary body. Normally these places correspond to extreme environments. Terrestrial analogues can share geological similarities with some planetary bodies (e.g., geochemical similarities between ► [Rio Tinto](#) in southwest Spain and Meridiani Planum location on Mars where the NASA Opportunity rover is located).

Terrestrial analogues play at least three important roles in planetary science:

1. As field sites on Earth where one may learn about planetary processes, e.g., geological information to be compared with that reported from space missions, mineralogical databases for comparison with spectral data from Mars orbiters, and comprehension of the processes that originated some particular materials or rocks in particular environments (e.g., lunar igneous rocks) in comparison with similar materials on terrestrial analogues (Drever et al. 1972).
2. To study life's survival limits as a means toward its comprehension and definition. From desert low water availability and high temperature to cold environments in the polar regions, microbial ► [life](#) has been identified that survives in those extreme conditions. As an extrapolation, the evaluation of the habitability of an extraterrestrial planetary body and the search for life out of the planet Earth (one of the main goals of astrobiology and the

national space agencies) could be verified through the research of life in extreme environments.

3. Validation of new technology, protocols, and tools for space missions.

Some Mars and Europa Terrestrial Analogues

An extreme environment can be described as a terrestrial analogue of Mars or Europa based on similarities in geology, mineralogy, chemistry of the system, temperature, salinity, or dryness. Based on these parameters, we consider as analogues the dry valleys in Antarctica; subglacial lakes in Antarctica; Svalbard in Norway, all of them with low temperature and low-water-availability environments; Rio Tinto in Spain as a Martian analogue due to its complex chemistry and mineralogy; and the Atacama Desert as a Martian analogue because it is one of the driest place on Earth (Figs. 1 and 2).

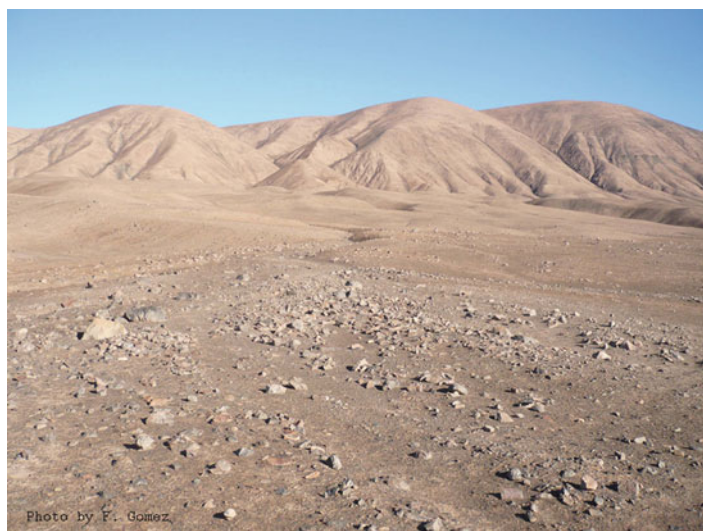
Dry valleys in Antarctica are well-recognized Mars analogues due to the very low temperature and low moisture availability in the environment. These environments have been well used to study very extreme and simple ► [ecosystems](#) with a strong interaction between biology and geological formations. The area is constituted by a ridge crest network with valleys in between, with dimensions of 5–10 km in width and 20–50 km in length. Most of them have neither glaciers on their heads nor snowfall over the year. The temperature in the salty valleys on western Antarctica rarely gets above -30°C , and annual rainfall is less than 10 mm, resembling those conditions found on some locations on the surface of Mars. Well-characterized basalt geological formations constitutive of permanent permafrost areas, with surfaces frozen over all or most of the year, resemble those typically basalt substrates on Mars. Another important similarity with Martian permafrost areas that can be used for studies of geological processes is the formation of polygonal terrains and other permafrost patterns with amazing morphological similarities. The ice polygons of the Antarctica valleys have diameters of 20–30 m with associated frost wedges increasing in thickness with each annual cycle. From narrow cracks in the ground, the wedge width increases

Terrestrial Analog,

Fig. 1 Red water in the Rio Tinto extreme environment. This river is located in the southwest of Spain. The pH value of the water is very low with a mean of 2

**Terrestrial Analog,**

Fig. 2 Atacama Desert in Chile is considered the driest place on Earth



progressively with polygonal permafrost pattern formation as final result.

More than 20 years ago, scientists reported that some organisms were able to colonize particular locations such as the interior of sandstone deposits, the interior of porous rocks, and surface pavements in the Antarctic Dry Valleys. In spite of the harsh and restrictive conditions, algae, fungi, and bacteria were identified in the Antarctic Dry Valleys. In the 1980s, other niches were identified for algae and bacteria. Long-lived algal mats were located submerged under lake ice crust. Bacteria

were also identified in hot volcanic fumaroles of Mount Erebus.

But not only these harsh and restrictive conditions made Antarctica valleys interesting from an astrobiological point of view. The presence of well-protected subsurface ecosystems such as permafrost areas or lakes with frozen surface most of the year made these environments of special interest. Several lakes with subsurface-protected environments are located not only in the valleys but in other Antarctic areas. Some ice landforms at McMurdo Dry Valleys' glaciers have been

suggested as terrestrial analogues for the sublimation behavior of Martian icecaps, where surface melting is absent, but other important processes are key elements for unusual ice feature formations such as dark spirals and circular pits.

Some of the lakes located on the dry valleys are over 20-m deep and have 2-m-thick ice covers. Some organisms living on and in the ice have been reported to be relevant for astrobiology models for Jupiter's moon Europa. These lakes are good venues for technology exploration capacity development in lake-bottom exploration such as SCUBA divers, including core sampling of sediments. These technological developments can be implemented for later space missions in similar environments on other planets or moons.

Also with important implications for Europa moon astrobiological models are the subglacial lakes also discovered in Antarctica (Kapitsa et al. 1996). Using airborne radio-echo survey of ice, more than 140 sub-ice lakes of unknown depth and composition were discovered in the 1970s. These environments completely isolated from the Earth's atmosphere could harbor important new biological discoveries. With an area of 10,000 km² and lying beneath several kilometers of ice, those particular niches are of tremendous interest for the astrobiologist. Data from the Galileo spacecraft reported the possible existence of a salty ocean underneath Europa's ice crust.

Lake Vostok is a particularly interesting case, first noticed in 1973 (Oswald and Robin G de 1973) by a scientist from the Scott Polar Research Institute using ice-penetrating radar. Due to the tremendous interest of the scientific community, the lake has been studied using several penetrating techniques such as airborne radio-echo sounding and penetrating radar imaging, as well as spaceborne radar altimetry. Finally, the lake was delimited in 1996 by British and Russian scientists. Lake Vostok (Siegert et al. 2001) is a 240 × 50-km lake, the largest of more than 140 subglacial lakes found under the surface of Antarctica and located at 4 km beneath the surface of the Central Antarctic ice sheet, with 22 cavities of liquid water. Lake Vostok is divided in two basins, separated by a ridge, and it is speculated to have different water composition in both of

them. Temperature of the water is around -3°C , but it remains liquid due to the high pressure from the weight of ice above it.

To probe the waters of Lake Vostok for life, without contamination, plans were initiated in 2001 by the NASA Jet Propulsion Laboratory to start with a melter probe – the so-called cryobot – which would melt down through the ice over Lake Vostok. The cryobot would carry with it a small submersible, called a “hydrobot,” which can be deployed when the cryobot has melted to the ice-water interface. The hydrobot would then swim off and “looks for signs of life” with a camera and other instruments.

But not only lakes but also an extensive network of waterways beneath the fast-moving Antarctic ice stream were discovered using NASA satellites. The water bodies beneath the ice crust constitute an important protected ecosystem to survey the habitability potential of the moon Europa and the survivability of life in such harsh conditions.

Svalbard in Norway has been the location for several astrobiological campaigns. Svalbard is an important Earth analogue where instruments similar to those that will fly on upcoming missions to Mars have been tested, as well as a field test site for rover prototypes. It is an archipelago in the Arctic, constituting the northernmost part of Norway and the northernmost populated place on the world. It is about midway between mainland Norway and the North Pole. This group of islands is located inside the Arctic Circle ranging from 74 to 81° north latitude and from 10 to 35° east longitude. Spitsbergen is the largest island. Its frozen soils with wide permafrost areas and glaciers allow life under extreme conditions and microbial habitability at very low temperatures to be studied.

This natural facility represents an important laboratory where a field campaign is organized every year by the astrobiological community and national space agencies. These campaigns, called Arctic Mars Analog Svalbard Expeditions (AMASE) (Younse et al. 2010), focus on learning how to search for life on Mars and how to develop and test the appropriate technology to do so, for example, the technology for future Mars missions,

on board of the Mars Science Laboratory (NASA) and the ► [ExoMars](#) (ESA) rovers. The conditions are so harsh that only ► [extremophiles](#) can thrive on the basaltic, carbonate-rich rocks, or in the glacial ice, scenarios that could be similar to equatorial Martian basalts or the icy regions of the Red Planet. If we want to search for life on Mars, we need to develop and test protocols to find past and present habitable environments and to prevent biological contamination that could arrive at Mars from our planet or could come back from Mars to the Earth in any Mars sample return mission. AMASE is developing systems to search for life and prevent contaminations. In fact, this research is not only focused on the planet Mars but also on any other icy planetary bodies that could potentially harbor microbial life, such as Europa, Titan, or ► [Enceladus](#). But not only cold environments are present on Svalbard. Also some hydrothermal sites are located in the Spitsbergen area. Life detection strategies based on antibody microarrays have been tested in those locations.

Rio Tinto, red river in English, takes its name from the dark-wine color of its waters. Rio Tinto is located in the southwest of the Iberian Peninsula, in the Huelva province (Andalusia, Spain), and originates in the Sierra Morena (Sierra de Aracena) mountains in the area called Peña de Hierro. Its waters flow south/southwest along 100 km to the Gulf of Cadiz (Atlantic Ocean). Rio Tinto is an extreme environment with a constant acidic pH (mean 2.3) and a high concentration of heavy metals (Fe, Cu, Zn, As, and Cr) in solution. Oxidized iron in acidic conditions (iron concentration in some locations is 22 g/l) is responsible for the red color of the waters. But their remarkable biodiversity dealing with these harsh conditions is present on the Rio Tinto water body (Bacteria, Archaea, photosynthetic and heterotrophic protists, yeast, and filamentous fungi). Geomicrobiological analysis of the Rio Tinto ecosystem reported that these conditions are the result of the metabolic activity of chemolithotrophic prokaryotes, mainly iron and sulfur oxidizers (Amils et al. [2002](#)). The system seems to be controlled by iron, which is not only used as an

electron donor but also as an electron acceptor, allowing a full iron cycle to operate. Furthermore, ferric ion is responsible for the maintenance of the constant pH of the ecosystem and can protect the different organisms thriving in its waters from damage due to UV radiation (Gómez et al. [2007](#)). Laminar, iron-rich stromatolitic formations are generated by the precipitation of different iron minerals on the surface of the biofilms that cover most of the rocks in the river. These structures are similar to ancient massive bioinduced laminated iron formations formed long before the first mining activities started in the area 5000 years ago (Fernández-Remolar et al. [2005](#)).

It is a terrestrial Mars analogue due to the chemistry and mineralogy of the system. Rio Tinto is located in an area rich in sulfides and iron minerals (Iberian Pyritic Belt), originating from an ancient hydrothermal system. Some locations on Mars are also rich in sulfur and iron oxide minerals. Basaltic volcanism is associated and widespread on Mars as well. On Earth, and Rio Tinto is a very good example of this, sulfide minerals form in hydrothermal systems associated with basaltic volcanism. Another important similarity between this extreme environment and Mars is the presence of some peculiar minerals. A notable case is ► [jarosite](#), an iron and potassium sulfate salt which is precipitated only at low pH solutions. This mineral appears precipitated on the microbial mats and the riverbed in the Rio Tinto system. Recently, the NASA Opportunity rover located jarosite on the Mars surface, a strong indication of the presence of acidic waters on Mars in the past.

Due to those analogies, the source area of Rio Tinto was chosen for the MARTE project implementation. Mars Analog Research and Technology Experiment (MARTE) was an ASTEP NASA co-funded program in collaboration with the Spanish government for Mars exploration technology development. The objectives of MARTE were (1) to search for and characterize subsurface life in Rio Tinto along with the physical and chemical properties and sustaining energy sources of its environment, (2) to perform an accurate simulation of a robotic Mars drilling mission to search for signs of life, and (3) to demonstrate the

maturity of the drilling, sample handling, and instrument technologies relevant to searching for life on Mars.

Also Martian habitability was tested under simulation experiments using acidophiles originally isolated from Rio Tinto in Mars planetary chamber simulation facilities (Gómez et al. 2010).

Atacama Desert is considered the driest place on Earth due to the rain shadow on the western side of the Chilean Coast Range, as well as a coastal inversion layer created by the cold off-shore Humboldt Current. Not only the low water activity level on its soil converts it on a Mars analogue but also the high levels of ultraviolet radiation and huge temperature swings, high winds, and dust storms capable of breaking down organic matter and salt precipitation that occurs due to the “camanchaca” (fog with salts dissolved which are deposited and precipitated during sunrise) coming from the Pacific Ocean in the morning. These physicochemical characteristics made the Atacama Desert a well-recognized Mars terrestrial analogue.

The Atacama Desert is located on a 1000-km strip of land plateau on the west side of Los Andes Mountains extending to the Pacific Ocean. This region is practically sterile because moisture is blocked by the Chilean Coast Range and the Andes Mountains. Several scientific missions have been focused on the Atacama Desert for life under extreme-condition studies as well as for the development and testing of life identification techniques for space missions by several national space agencies. The low microbial life detection level on the desert soil and low organic matter presence have made this environment an excellent natural laboratory for testing detection limits of the equipments (Cabrol et al. 2005). Also several robots and vehicles for Mars missions have been tested in the soil and harsh environmental conditions found in the Atacama Desert (Wettergreen et al. 1997).

Key Research Findings

The use of some extreme environments as terrestrial analogues provides the planetary science

research community and the space agencies with natural laboratories that have tremendous potential for studying the limits of life, the habitability of other planetary bodies, and for testing equipment and instrumentation to be used in the near-future upcoming missions. The resistance/adaptation/survivability of microorganisms at very low freezing temperatures on ice, under very high radiation doses, or high pressure in deep-sea ecosystems, as well as at very low pH in acidic environments, has led to a widening of the habitability potential on other planetary bodies such as Mars or icy Moons such as Europa, Titan, or Enceladus. Since extremophiles have been reported in the most extreme Antarctic conditions (Friedmann 1982) or at the driest place on Earth, Atacama Desert, which resembles the Mars surface or the ocean underneath Europa’s ice crust, our concept about life and its limits has widened considerably.

Applications

The applications from space missions and the knowledge of the limits of life would benefit from the research in the area of field analogues.

Cross-References

- [Atacama Desert](#)
- [Biodiversity](#)
- [Ecosystem](#)
- [Environment](#)
- [Eukarya](#)
- [Europa](#)
- [ExoMars](#)
- [Extreme Environment](#)
- [Extremophiles](#)
- [Jarosite](#)
- [Life](#)
- [Mars](#)
- [Mars Analogue Sites](#)
- [Psychrophile](#)
- [Rio Tinto](#)
- [Thermophile](#)

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Terrestrial Planet

Tilman Spohn
International Space Science Institute, Bern,
Switzerland

Keywords

Planet

Synonyms

[Earth-like planet](#); [Rocky planet](#); [Telluric planet](#)

Definition

A terrestrial planet is a ► [planet](#) that resembles the ► [Earth](#) in size, surface geology, and chemical composition as indicated by its density. In our ► [Solar System](#), the terrestrial planets are ► [Mercury](#), ► [Venus](#), Earth, and ► [Mars](#), in order of distance to the Sun. In other Solar Systems – among exoplanets – a terrestrial planet would resemble the Earth in radius and average density. The term is sometimes used for Earth-like bodies that are not planets, such as the Moon and the Jovian satellite ► [Io](#).

Overview

The terrestrial planets orbit the Sun in the inner Solar System and consist mainly of silicate ► [rock](#) and iron, which make them distinguishable from the gas giants (► [Jupiter](#) and ► [Saturn](#)) and ice giants (► [Uranus](#) and ► [Neptune](#)) in the outer Solar System. The terrestrial planets of our Solar System are mostly solar or chondritic in

composition but depleted in ► [volatiles](#). They all have a similar chemically layered structure with an iron-rich core, a silicate ► [rock](#) ► [mantle](#) (mafic to ► [ultramafic](#) in composition), and a basaltic ► [crust](#). The core is likely to be liquid, but there may be a solid inner core such as in Earth. Although the mantle is solid, it can be viewed as an extremely viscous fluid on geological time scales except for a cold outer shell, the lithosphere. The lithosphere includes the crust and part of the mantle. On Earth, the lithosphere is broken into seven large plates that are continuously created at mid-oceanic ridges and recycled with the mantle at subduction zones through a process called ► [plate tectonics](#). Plate tectonics is driven by mantle convection in what is called the mobile lid regime. The other terrestrial planets of our Solar System have a contingent lithosphere that is pierced here and there by volcanic vents. For these planets, one speaks of single plate tectonics. The mantles underneath the plates in these planets are still convecting; however, it does so in what is called the ► [stagnant lid convection](#) mode. Through tectonic deformation and through volcanic activity, terrestrial planets convert heat and chemical energy into mechanical work. They may further convert heat and chemical energy into magnetic field energy by a ► [dynamo](#) in the core. Of the terrestrial planets, Earth and Mercury do have present-day magnetic fields. Remnant magnetization of Martian crustal rock suggests that Mars was self-sustained in its early history. It is not known whether or not Venus once had a magnetic field, but it has been speculated (Stevenson et al. [1983](#)) that it had one in its early history similar to Mars.

The terrestrial planets have atmospheres with masses that depend on the planet mass (through its gravity) and composition. The main component of Mars' and Venus' atmospheres is ► [carbon dioxide](#), while that of the Earth is molecular ► [nitrogen](#) and ► [oxygen](#), the latter a consequence of bioactivity. The atmospheric pressure on the surface of the Earth is 1 bar (100 kilopascals), and on Venus, it is 93 bar. The average surface temperature is 288 K on Earth and 735 K on Venus. On Mars, the average surface pressure is 0.006 bar, and the average surface temperature is 210 K. The

average surface temperature on Mercury is 440 K, with the temperature varying between 105 K at night and 700 K during daytime.

The terrestrial planets have about 0.0005% of the mass of the Solar System, while the Sun holds 98.8% of the total mass. Mercury is the smallest among this group of planets with almost no atmosphere ($<10^{-12}$ bar), and it has the second highest bulk density (5427 kg m^{-3}). The surface of Mercury is subject to high temperature variations and is extremely cratered. Venus is the sister planet of Earth concerning size, and even the density is similar (5204 kg m^{-3}). Its peculiarity is the very thick atmosphere. It is shielded by a layer of clouds, impenetrable for the visible part of the ► [electromagnetic spectrum](#). This is why Venus' surface is explored using radar and infrared imaging. Earth is the biggest among the rocky planets with the highest density (5515 kg m^{-3}). Furthermore, it is the only planet on which we know to date that life developed. The ► [Moon](#) is about one fourth of the size of Earth and has about two thirds of the bulk density of Earth. The Moon and Earth are locked in a 1:1 spin orbit coupling; thus, the Moon shows almost the same face toward the Earth at all times. Mars is about half the size of Earth, has a very thin atmosphere, and is the least dense terrestrial planet (3933 kg m^{-3}). Nevertheless, it is believed that Mars had, after the Earth, the best chance to develop some primitive form of life in the past.

Cross-References

- [Core, Planetary](#)
- [Crust](#)
- [Dynamo, Planetary](#)
- [Earth](#)
- [Electromagnetic Spectrum](#)
- [Exoplanets, Discovery](#)
- [Gas Giant Planet](#)
- [Io](#)
- [Jupiter](#)
- [Mantle](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)

- [Neptune](#)
- [Nitrogen](#)
- [Planet](#)
- [Plate Tectonics](#)
- [Rock](#)
- [Saturn](#)
- [Solar System, Inner](#)
- [Solar System, Outer](#)
- [Stagnant Lid Convection](#)
- [Sun \(and Young Sun\)](#)
- [Uranus](#)
- [Venus](#)
- [Volatile](#)

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TESS

Emeline Bolmont and Marion Cointepas
Observatoire de Genève, Université de Genève,
Sauverny, Switzerland

Keywords

Transit · Exoplanets · Satellite

Synonyms

[Transiting exoplanet survey satellite](#)

Definition

TESS, or Transiting Exoplanet Survey Satellite, is a NASA satellite which has been observing near and bright stars since 2018. Its goal is to find

transiting planets around these bright stars. These planets are particularly well suited for follow-up studies such as not only radial velocities to derive their mass but also spectroscopy of the planets' atmosphere.

History

TESS was proposed in 2008 as a NASA mission to survey the entire sky for transiting planets in order to find the nearest and brightest systems. TESS was selected by NASA for a Phase A study for a so-called Small Explorer mission in May 2008 but subsequently was not selected for a flight opportunity. TESS was resubmitted as a candidate for what NASA calls an Explorer mission in 2010 and was finally approved in 2013. The satellite was successfully launched in April 2018 on a SpaceX Falcon 9 rocket. Since then, it has been surveying 200,000 stars over the whole sky for transiting planets.

Overview

Today, the field of exoplanets has moved beyond the “simple” detection of planets to their characterization, in particular the characterization of their density, which leads to knowledge of their internal structure and the characterization of their atmosphere. To know the density of planets, one needs to know their radii (through the transit method) and their masses (through radial velocity of transit timing measurements). Most of the Kepler satellite planets were detected around faint stars (by construction of the satellite), and these systems were consequently extremely challenging for radial velocity follow-up.

To circumvent this limitation, and using a strategy comparable to the CHEOPS mission, TESS only targets bright stars. These stars are 30–100 times brighter than the stars observed by the Kepler satellite and K2. Bright stars are then much easier to follow-up with spectrographs on the ground, such as HARPS, HARPS-N, or ESPRESSO. These radial velocity follow-ups

allow to derive the mass of the planets and therefore to constrain their densities.

TESS uses an array of small telescopes and has the sensitivity to detect planets as small as the Earth, even a few in the habitable zones of cool stars. It surveys almost the whole sky, which represents an area 400 times larger than the area monitored by Kepler. The sky area TESS surveys is divided in 26 different sectors. It stares at each sector for at least 27 days before moving to the next. The southern ecliptic hemisphere was observed during Year 1 and 3 of the mission, and the northern ecliptic hemisphere was observed during Year 2 and a part of Year 4. In November 2021, when this entry was submitted, the telescope was pointing toward the ecliptic, observing some of the K2 campaign fields (see <https://tess.mit.edu/observations/>).

Since the beginning of its operation (40 sectors observed), TESS has detected potential transiting signals around 4471 TOIs (TESS Object of Interest), with almost 800 planetary candidates with radii smaller than 4 Earth radii. Of these 4471 signals, 154 were confirmed as TESS planets using follow-up observations (with ground-based photometry, for instance, with the network LCO-GT, or MEarth, TRAPPIST, and SPECULOOS...).

Among them, TOI-700 d (Gilbert et al. 2020) is the first Earth-size exoplanet discovered by TESS in its star's habitable zone, the range of distances where conditions may allow the presence of liquid water on the surface. This habitable-zone planet with a period of around 37 days is one of three orbiting TOI-700, a cool M dwarf with around 40 percent of the Sun's mass and located about 100 light-years from Earth. The climate of the habitable zone planet TOI-700 d has been investigated with 3D climate models to show that it can maintain surface liquid water under a variety of atmospheric compositions (Suissa et al. 2020). Although the atmosphere of this planet will not be characterizable with the JWST, it motivates the community to think about a next generation of instruments which could.

Cross-References

- ▶ [Aeronautics and Space Agency of FFG](#)
- ▶ [CHEOPS](#)
- ▶ [Exoplanets, Discovery](#)
- ▶ [Habitable Zone](#)
- ▶ [James Webb Space Telescope](#)
- ▶ [Kepler](#)
- ▶ [MEarth](#)
- ▶ [Modelling Terrestrial Planetary Atmospheres](#)
- ▶ [Planet Detection: Transit Timing Variation](#)
- ▶ [PLATO 2.0 Satellite](#)
- ▶ [SPECULOOS](#)
- ▶ [Transit](#)
- ▶ [Transiting Planets](#)

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Tessellation Automata

► Cellular Automata

Tessera, Tesserae

Jörn Helbert
DLR, Institut für Planetenforschung, Berlin,
Germany

Definition

Tesserae are tectonically highly deformed landforms on the surface of ► [Venus](#). They are typically embayed in volcanic plains and stand elevated above them. Tesserae predate the plains and are considered as the oldest landforms on Venus. They might be remnants of an earlier ► [crust](#).

Cross-References

- [Crust](#)
 - [Venus](#)
-

Tethys

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Tethys is one of the midsized icy satellites of ► [Saturn](#). Discovered by Giovanni Domenico ► [Cassini](#) in 1684, it orbits at a distance of 294,700 km (or 4.9 Saturnian radii) from Saturn. Its diameter is 1060 km. Images taken by the Voyager 2 spacecraft in 1981 show a variety of terrains,

with some ancient, heavily cratered regions including the large Odysseus basin that is over 400 km in diameter and a more recent, remodeled surface with a large canyon, Ithaca Chasma, which is about 1000 km long and 100 km wide. The density of Tethys is 1.0 g/cm^3 , which indicates a rather pure water-ice satellite. Two other small satellites, Calypso and Telesto, are located on the same orbit as Tethys.

On Earth, the so-called Tethys ocean separated the continents of ► [Gondwana](#) and ► [Laurasia](#) during the Mesozoic.

Cross-References

- [Saturn](#)
 - [Voyager, Spacecraft](#)
-

11,3,5,7-Tetraazaadamantane

- [Hexamethylenetetramine](#)
-

1,3,5,7-Tetraazatricyclo [3.3.1.1^{3,7}]decane

- [Hexamethylenetetramine](#)
-

Tharsis

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

Tharsis is a region on ► [Mars](#) which is the largest known volcanic province in the ► [Solar System](#), with an area of $3 \times 10^6 \text{ km}^2$ and a volume of

$3 \times 10^8 \text{ km}^3$. It is characterized by a huge topographic bulge (up to 10 km above the Martian datum), which is topped by about a dozen very large and hundreds of small volcanoes. Most of the surface consists of basaltic lava flow fields. The current topography of Tharsis is mainly the result of volcanic loading, and only a small part may be due to dynamic uplift, perhaps supported by a mantle (super) plume. Tharsis is very old, and its formation may have reoriented the planet's spin axis, so that the center of Tharsis is now located near the equator. Tharsis-centered tectonics dominate the entire western hemisphere of Mars.

Cross-References

- [Basalt](#)
- [Degassing](#)
- [Igneous Rock](#)
- [Mantle Plume, Planetary](#)
- [Mars](#)
- [Olympus Mons](#)
- [Plume](#)
- [Solar System, Inner](#)

The Galaxy

- [Milky Way](#)

Theia

Daniele L. Pinti
Geotop, Research Centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Orpheus](#)

Definition

Theia is the name given to a hypothetical proto-planet or planetesimal, roughly the size of Mars, which is thought to have collided with the proto-Earth, ejecting material into orbit to form the Moon. The hypothesis of Moon formation by Theia is called the “Moon-forming Giant Impact hypothesis.”

Overview

The impactor's name comes after the mythical Greek goddess *Theia* who gave birth to the Moon goddess, *Selene*. The most widely accepted model for the Moon origin is that Theia struck the proto-Earth at an oblique angle, adding 10% of the Earth's mass and generating a hot, partly vaporized debris disc from which the Moon accreted (Canup and Asphaug 2001). The timing of the impact and the nature of the impactor have been the focus of numerous studies and speculations, not completely solved.

The timing of the impact could be solved either precisely determining the age of the Moon (Halliday 2008) or the age of the Earth's core differentiation, if the impact completely melted the Earth mantle and favored the mantle-core differentiation (Jacobson et al. 2014). It has also been suggested that the early Earth catastrophic degassing of the mantle and subsequent atmosphere formation was triggered by the Moon-forming impact. Thus, dating this earlier episode of Earth evolution might resolve the issue (e.g., Avicé and Marty 2014).

Radiometric dating of lunar samples gave ages of the lunar crust spanning from 4.29 to 4.47 Ga with earlier crust Rb-Sr ages of 4.48 ± 0.02 Ga or 70–110 Ma after the beginning of the Solar system (Halliday 2008). Extinct radiochronometers were also used to determine the timing of the Moon formation, because the high temperature reached during the Moon-forming impact (5000–10,000 K) should have reset any radiometric clock in the colliding bodies. Because Hf is a lithophile element, W is moderately siderophile element, and ^{182}Hf has a short half-

life of 8.9 Ma over which it decays to ^{182}W , the ^{182}Hf – ^{182}W system can be used to constrain the timescale of metal–silicate (i.e., core–mantle) differentiation of planetary objects within ~ 7 half-lives, that is, the first 60 Ma since the Solar system formation. Obtained ^{182}Hf – ^{182}W ages were affected by cosmogenic production of ^{182}W and from erroneous assumption of the initial chondritic $^{182}\text{Hf}/^{180}\text{Hf}$ ratio. However, corrected ^{182}Hf – ^{182}W ages were still younger than the older lunar crust estimate, ca. 45 Ma after the formation of the Solar system. The same ^{182}Hf – ^{182}W chronometer applied to the differentiation of the mantle–core system gave older ages of 93 ± 32 Ma 95 ± 32 Myr after the Solar system condensation (Jacobson et al. 2014). Finally, Avice and Marty (2014) based on the extinct radionuclides ^{129}I – ^{129}Xe (half-life of 15.6 Ma) and ^{244}Pu – 131 – ^{136}Xe (half-life of 80 Ma) concluded that the Xe formation interval for the Earth atmosphere system is ca. 40 Ma after the beginning of Solar system formation, to be assumed as lower limit of the Moon-forming impact.

The composition of Theia and thus its source region within the Solar system is also debated. Support for the Giant Impact hypothesis comes from the similarity between the oxygen isotopic composition of the Earth and the lunar rocks. The oxygen isotopic composition of the Moon is also close to that of the enstatite chondrites, which would indicate that the impactor Theia came from the same inner region of the Solar system where the Earth formed. However, an isotopic similarity between the Earth and the Moon is difficult to reconcile with the fact that the Moon would be made of 90% of Theia and 10% of the proto-Earth. Measurements of isotope ratios of terrestrial, Martian, and meteorite samples show that the bodies in the early Solar system were isotopically heterogeneous. It is therefore expected that Theia and proto-Earth were isotopically distinct. Although several processes could reconcile this view, such as an isotopic re-equilibration in the aftermath of the impact, recent analyses of lunar samples revealed 12 ± 3 parts per million difference in the oxygen isotopic

composition with the Earth (Herwartz et al. 2014). They also showed that the Bulk Silicate Earth has an oxygen isotopic composition different from enstatite chondrites, thus not excluding that these meteorites formed the majority of Theia. An alternative hypothesis to explain these small, but resolvable isotopic differences is that carbonaceous chondrites might be the Theia precursors, implying a source region located in the outer part of the Solar system where water and volatile-rich meteorites would have formed (Herwartz et al. 2014). Resolving the source region and the nature of the Theia impactor has implication far beyond the Moon origin but could also be important for determining the carrier of oceanic water on the telluric planets.

Cross-References

- Bulk Silicate Earth
- Carbonaceous Chondrite
- Extinct Radionuclides
- Moon, Origin of
- Moon, The

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Theoretical Biology

► [Artificial Life](#)

Thermal Copolymers of Amino Acids

► [Proteinoid Microsphere](#)

Thermal Decomposition

► [Pyrolysis](#)
 ► [Thermolysis](#)

Thermal Emission

► [Blackbody](#)

Thermal Escape

► [Jeans Escape](#)

Thermal Radio Jets

Guillem Anglada
 Instituto de Astrofísica de Andalucía, CSIC,
 Granada, Spain

Keywords

Star-formation · Jets · Protostars ·
 Protoplanetary disks · Free-free emission ·
 Radio Astronomy

Definition

Thermal radio jets are sources of free-free emission at radio wavelengths that trace collimated, partially ionized material ejected at high velocities (100–1000 km/s) from a region very close (<10 au) to the protostar. Radio jets are usually weak (<1 mJy) radio sources with positive spectral indices (i.e., with flux density increasing with frequency). When observed with high enough angular resolution they look elongated. Thermal radio jets are preferentially associated with protostars that are deeply embedded in molecular clouds, and trace the base of the larger scale jets (several 1000 au to several pc) observed at optical and infrared wavelengths, and that are associated with bipolar flows.

Overview

Thermal radio jets are partially ionized and are therefore relatively weak sources (a few mJy at most) of free-free radio continuum emission. The slope of the flux as a function of frequency in the logarithmic space is called the “spectral index” and, depending on the optical depth, the free-free spectral index of an ionized region ranges from -0.1 (optically thin) to 2 (optically thick). As shown by Reynolds (1986), a conical thermal radio jet moving at a constant velocity will have a characteristic spectral index of 0.6 , in agreement with the median of observed values which is about 0.5 (Anglada et al. 2018).

Both HII regions and thermal radio jets are free-free radio sources. However, in addition to the characteristic spectral index of thermal radio jets, there are other differences between these two kinds of radio sources. Radio jets are elongated, whereas HII regions do not usually show an elongated morphology. In addition, thermal radio jets present outflow velocities of 100–1000 km/s, while HII regions expand at much lower velocities, of a few km/s. Finally, an important difference concerns the ionization mechanism. While HII regions are ionized by stellar UV photons the proposed ionization mechanism of thermal radio

jets are the shocks associated with the outflowing material (Curiel et al. 1989).

As a consequence of the different ionization mechanism, HII regions are only found to be associated with high luminosity massive stars, which have a high rate of ionizing UV photons, while thermal radio jets are found to be associated with young stars across the whole mass spectrum, from massive protostars to very low mass objects, possibly even to proto-brown dwarfs (Anglada et al. 2018). The radio flux of thermal jets normalized by the distance squared (i.e., the radio luminosity) has been found to be linearly correlated (in log-log space) with both the momentum rate (force) of the outflow and with the bolometric (i.e., integrated over the whole electromagnetic spectrum) luminosity of the protostar (Anglada et al. 1992, 1998, 2018). These correlations are interpreted to be a consequence, respectively, of the ionization mechanism (related to outflow shocks), and of the connection between outflow and accretion (from which most of the protostellar luminosity originates). They can be used to infer the luminosity of protostars, to distinguish between HII regions and thermal radio jets, and to investigate the evolutionary stage of young massive stars.

There are also similarities and differences between the radio sources corresponding to thermal radio jets from protostars and those corresponding to radio jets from black holes. Radio jets from protostars trace material moving at nonrelativistic velocities and are thermal free-free emitters. In contrast, radio jets from black holes trace material moving at relativistic velocities and emit nonthermal synchrotron radiation at radio wavelengths. Nevertheless, in some radio jets from protostars, in addition to the thermal core near the origin, there is evidence for the presence of nonthermal emission, usually in distant knots at distances 10,000–100,000 au from the origin. This nonthermal radio emission is attributed to synchrotron radiation from a small population of electrons that have been accelerated up to relativistic velocities in strong shocks of the jet against dense material in the

surrounding molecular cloud where the protostar is forming (Carrasco-González et al. 2010; Rodríguez-Kamenetzky et al. 2017; Anglada et al. 2018).

Cross-References

- AU
- Bipolar flow
- Free-free emission
- Molecular cloud
- Optical depth
- PC
- Protostars
- Radio astronomy
- Synchrotron radiation

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Thermochemical Equilibrium

► Thermodynamical Chemical Equilibrium

Thermodynamical Chemical Equilibrium

Bruno Bézard

LESIA, Observatoire de Paris, Meudon, France

Keywords

Chemical equilibrium · Kinetics · Planetary atmospheres · Thermochemistry

Synonyms

Law of mass action; Thermochemical equilibrium

Definition

Thermodynamical chemical equilibrium is the state of a closed system in which the concentrations of the various species have no tendency to change with time. This is a dynamical state in which chemical reactions proceed at equal rates in the forward and reverse directions. Under conditions of constant temperature and pressure, the equilibrium composition corresponds to a minimum in the Gibbs free energy of the system.

Overview

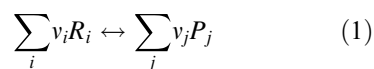
The laws of thermodynamical chemical equilibrium allow us to calculate the equilibrium composition of any chemical system with a given elemental composition as a function of pressure and temperature. However, a chemical system can reach its equilibrium state only if the reactions proceed more rapidly than other processes at

work in the system, such as dynamical mixing. As reaction rates depend sensitively on temperature and species' concentrations, chemical equilibrium overall applies to warm and relatively dense astrophysical objects, such as stars or the deep atmospheres of ► [giant planets](#). On the other hand, cold and less dense objects, for example, the interstellar medium or upper planetary atmospheres, are far from chemical equilibrium due to a variety of disequilibrium processes. Thermochemical calculations applied to giant planets (solar system and extrasolar) and brown dwarfs (BDs) are discussed.

Basic Methodology

The Equilibrium Constant

The equilibrium constant (K) relates the relative concentrations of the compounds (reactants and products) involved in a chemical reaction system at equilibrium. It is defined as the product of the activities of the products divided by the product of the activities of the reactants at equilibrium. For a reaction expressed symbolically as:

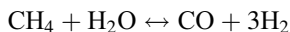


where R_i denotes reactant i , P_j product j , and the ν_i and the ν_j the corresponding stoichiometric numbers, K is expressed as:

$$K = \frac{\prod_j a_j^{\nu_j}}{\prod_i a_i^{\nu_i}} \quad (2)$$

where a_i and a_j are the activities of the reactants and products, respectively. The ► [activity](#) is a thermodynamic property that measures the “active” concentration of a species in a mixture. In nonideal gases or solutions, it differs from other measures of concentration (such as partial pressures and mole fractions) due to electrostatic interactions between the various species.

For gaseous compounds, the activities are often replaced by the partial pressures p_i and p_j expressed in bars, assuming an ideal-gas mixture. For example, the equilibrium constant of the gas-phase reaction



is given by $K = \frac{P_{\text{CO}}P_{\text{H}_2}^3}{P_{\text{CH}_4}P_{\text{H}_2\text{O}}}$. When pure substances, liquids or solids, are involved in the reaction, they do not appear in the equilibrium constant (their activity is 1). In the case of aqueous dilute solutions, the activities can be replaced by the molar concentrations of the solutes, expressed in mol l^{-1} .

At a given temperature T , K is a constant, independent of pressure. For historical reasons, this is known as the law of mass action. The equilibrium constant is related to the standard Gibbs ▶ **free energy of the reaction** ΔG^0 (standard molar Gibbs free energy of formation of the products minus that of the reactants) at temperature T by:

$$K = \exp\left(-\frac{\Delta G^0}{RT}\right) \quad (3)$$

which enables us to calculate the equilibrium constant of any reaction, and thus the equilibrium composition of the system, from tables of thermodynamical data (e.g., Chase et al. 1998). The variation of K with temperature is given by the Van't Hoff equation:

$$\frac{d \ln K}{dT} = \frac{\Delta H^0}{RT^2} \quad (4)$$

where ΔH^0 is the standard ▶ **enthalpy** of the reaction at temperature T (standard molar enthalpy of formation of the products minus that of the reactants) and R is the universal gas constant.

The response of the equilibrium composition to changes in conditions (temperature, pressure, concentration of a species) is summarized by Le Chatelier's principle, which states that a system at equilibrium responds in a way that tends to minimize the effect of the disturbance. For example, the system responds to a compression by

reducing the number of molecules in the gas phase, shifting the reactions to the side with fewer moles of gases. Increasing the temperature favors the products of ▶ **endothermic** ($\Delta H^0 > 0$) reactions and the reactants of ▶ **exothermic** ($\Delta H^0 < 0$) reactions, as evidenced by Eq. 4.

Kinetic Considerations

Thermodynamics do not tell us how fast the equilibrium state of a chemical system has reached or even if it can be attained in less than the age of the solar system. This depends on the reaction mechanisms. A reaction may be highly favored thermodynamically but inhibited kinetically. For a homogeneous ▶ **bimolecular reaction** ($A + B \rightarrow \text{products}$), the reaction rate is given by:

$$-\frac{d[A]}{dt} = k[A][B]. \quad (5)$$

where k is the so-called rate constant and $[A]$ and $[B]$ the reactants' concentrations. In most cases, k can be expressed by the Arrhenius equation:

$$k = Ae^{-\frac{E_a}{RT}} \quad (6)$$

where A is the pre-exponential factor and E_a is the ▶ **activation energy**, which varies typically from tens to hundreds of kJ per mole for gas-phase reactions. High activation energy implies that the rate constant depends strongly on temperature.

Equations 5 and 6 indicate that reactions proceed more rapidly as temperature and concentrations increase (reactions may also be accelerated by the presence of catalysts). For this reason, chemical equilibrium is overall achieved in warm and relatively dense astrophysical objects or regions, that is, stars, brown dwarfs, central regions of circumstellar disks, ▶ **hot Jupiters** and hot Neptunes, the deep atmosphere of giant planets, and to some extent the deep atmosphere of ▶ **Venus**. On the other hand, cold and less dense media are far from chemical equilibrium. These media include the interstellar medium; the outer regions of protoplanetary disks; the comets; the atmospheres of Titan, Mars, and Earth; and the upper atmospheres of all planets.

Disequilibrium Processes

The latter objects can maintain a nonequilibrium chemical composition by exchanging energy of different entropy (or mass) across their boundaries. Important nonequilibrium processes are the following:

- Cosmic ray irradiation. This is the dominant source of ionization in cold interstellar cloud cores, which initiates rich ion-molecule chemistry.
- Photochemistry and electron-induced chemistry. These processes (using photons from the central star and electrons from the planet's magnetosphere) create a wealth of non-equilibrium compounds in the upper planetary atmospheres: hydrocarbons on the giant planets and Titan, nitriles on Titan, oxygen compounds on Mars and Venus (CO, O₂, O₃, and H₂O₂), possibly CO₂, and other species in hot Jupiters.
- Shock chemistry. Shock heating during accretion onto protoplanetary disks leads to some chemical reprocessing of the disk material. Also, cometary impacts in planetary atmospheres produce compounds exogenous to the ambient air (e.g., CO, HCN in ► [Jupiter](#) following the impact of Comet Shoemaker-Levy 9).
- Electrical discharges. Lightning and other electrical phenomena are a source of non-equilibrium species in planetary atmospheres, such as NO on Earth and Venus, and possibly oxidants on Mars.
- Biotic activity. Life substantially affects the chemical composition of the Earth's environment, as reflected, for example, by the high concentration of reactive oxygen in the atmosphere.
- Transport of matter in a thermoclinic environment. Turbulent mixing can transport species from hot regions where they are thermodynamically stable to colder regions where their chemical conversion is kinetically inhibited. It can affect the composition of the outer atmospheres of the giant planets and brown dwarfs. In the solar nebula and protoplanetary disks, chemical "quenching" by outward motion (and

also by overall radiative cooling) is thought to be highly important.

Key Research Findings

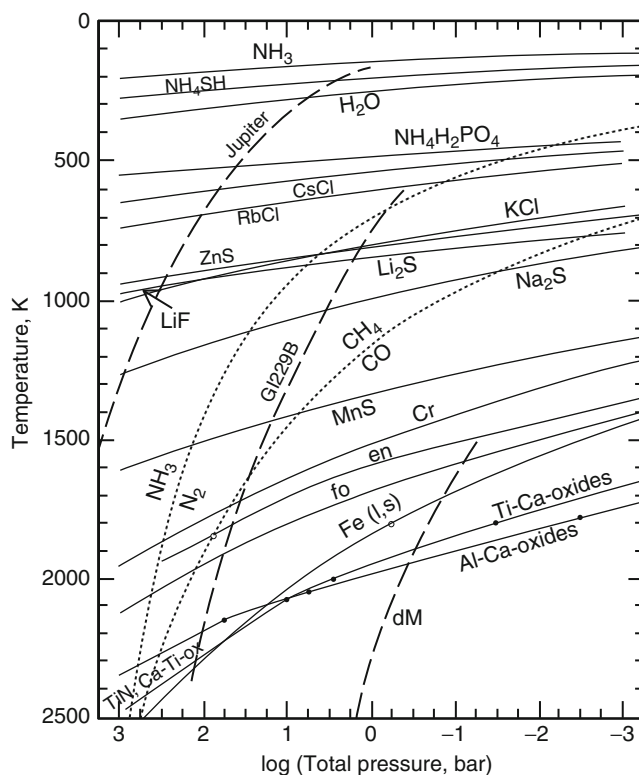
The equilibrium composition of material characterized by a given elemental composition can be calculated, as a function of temperature T and pressure p , from the laws of chemical equilibrium. Gas mole fractions ($x_i = p_i/p$) and the presence of condensates can be derived by writing the mass balance equations, one per element, the equilibrium constants K_i for forming the different gases, and those between gases and condensates.

Thermochemical equilibrium calculations have been used to predict and interpret the composition of giant planets (Fegley and Lodders 1994), extrasolar giant planets (EGPs) (Lodders 2010; Madhusudhan et al. 2016), and brown dwarfs (Lodders and Fegley 2006, Fig. 1). Models of thermochemical equilibria in Venus' deep atmosphere and surface-atmosphere interactions, not discussed here, are presented in Krasnopolsky (2007) and Fegley et al. (1997).

Giant Planets

Assuming solar composition material, the models reproduce the main features of the composition of Jupiter's and Saturn's observable troposphere, namely:

- C and N are predominantly in the form of CH₄ and NH₃, respectively.
- NH₃ and H₂O are depleted in the upper troposphere ($T < 150$ K and $T < 280$ K, respectively) due to condensation.
- H₂S is present in Jupiter below the 2-bar level, a consequence of the condensation of iron at deep levels (preventing the removal of S by FeS formation), but depleted in the upper troposphere due to the formation of ammonium hydrosulfide (NH₄SH) at 210 K.
- Silane (SiH₄) is absent due to the formation of silicates in the deep atmosphere. More generally, refractory elements are sequestered into deep high-temperature clouds.



Thermodynamical Chemical Equilibrium, Fig. 1 Major features of the equilibrium chemistry of solar composition material as a function of temperature and pressure. *Solid lines* delineate the regions above which the labeled condensate is present and the corresponding minor element removed from the gas phase. The *dots* on the Al-Ca-oxides curve correspond to different Al-bearing condensates and those on the Ti-Ca-

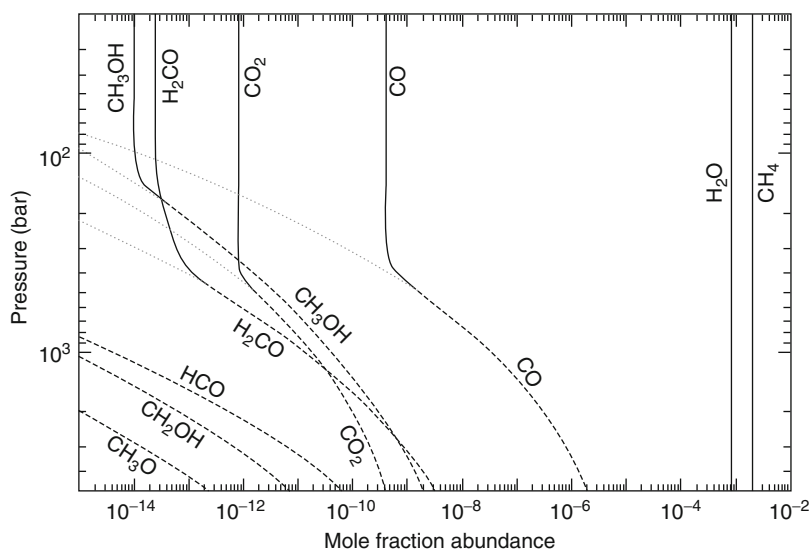
oxides curve to different Ti-bearing condensates. The *white dots* on the enstatite (*en*) and iron (*Fe*) curves indicate melting points. The *dotted curves* indicate equal abundances of CO and CH₄ and of N₂ and NH₃. Also shown are temperature profiles of an M dwarf (*dM*) with $T_{\text{eff}} = 2200$ K, the brown dwarf Gl 229B ($T_{\text{eff}} = 960$ K), and Jupiter. (From Lodders and Fegley (2006))

On the other hand, a few species (CO, PH₃, AsH₃, and GeH₄) have been detected with abundances well above their equilibrium values. Their presence can be explained by transport from the hot deep atmosphere, where they are stable, to colder observable levels where the timescale for chemical conversion is larger than the mixing time (Fig. 2). These nonequilibrium species can be used as probes of the convective mixing and of deep elemental abundances (e.g., O/H in the case of CO, Visscher et al. 2010).

Hot Jupiters and Brown Dwarfs

Thermochemical models of extrasolar giant planets (EGPs), assuming radiative-convective

equilibrium and a Jupiter-like composition, predict that EGPs with effective temperature (T_{eff}) below 150 K have, like Jupiter and Saturn, high NH₃ clouds and those in the range 150–250 K high H₂O clouds. EGPs with T_{eff} in the range of 250–1000 K are relatively cloudless above the 10-bar level, whereas hot Jupiters with T_{eff} in excess of ~ 1200 K exhibit high iron and silicate clouds in their atmospheres, which has important consequences on their emission spectra. In cool EGPs ($T_{\text{eff}} < \sim 500$ K), the dominant carbon- and nitrogen-bearing compounds are CH₄ and NH₃, whereas in hot Jupiters ($T_{\text{eff}} > \sim 1200$ K), CO and N₂ dominate at all levels. Na and K are in gaseous form above,



Thermodynamical Chemical Equilibrium, Fig. 2 Vertical profiles of oxygenated compounds in Jupiter's deep atmosphere derived from thermochemical equilibrium and kinetic-diffusion model calculations. A solar O/H elemental ratio is assumed. *Dotted grey lines* indicate

thermochemical equilibrium. *Solid lines* show the profiles when reaction kinetics and vertical eddy mixing is included. (From Visscher et al. 2010; reprinted from Icarus, with permission from Elsevier)

respectively, ~ 1000 and ~ 800 K, so that these gases, that are strong absorbers of visible light, play a major role in the heat balance of hot Jupiters. Their upper atmospheres may also contain TiO and VO, molecules with strong optical bands, leading to very intense stellar heating. Tidally locked hot Jupiters are predicted to exhibit a large day-to-night thermal contrast, leading to horizontal variations in the equilibrium chemistry, such as the conversion of CO to CH₄ or the condensation of sodium at night. The detection of large amounts of CO in relatively cool irradiated EGPs ($T_{\text{eff}} < \sim 1000$ K) suggests that chemical quenching of the CO–CH₄ system occurs as on Jupiter.

The equilibrium chemistry of brown dwarfs (BDs), from the coolest T dwarfs at $T_{\text{eff}} \sim 700$ K to the hottest M dwarfs at 2000–2500 K, resembles the molecular gas and condensate chemistry of hot Jupiters as concerns, for example, the condensation of silicate and Fe clouds, the presence of alkali metals and that of TiO and VO at high temperature (Fig. 1). On the other hand, isolated BDs have steeper temperature profiles than

irradiated EGPs, which leads to differences in the equilibrium chemistry, such as carbon being in the form of methane in the outer atmosphere of BD Gliese 229B and in the form of CO in an EGP with the same T_{eff} (960 K). The detection of CO in Gliese 229B also points to nonequilibrium chemistry.

Cross-References

- [Activation Energy](#)
- [Activity](#)
- [Bimolecular Reaction](#)
- [Brown Dwarf](#)
- [Endothermic](#)
- [Enthalpy](#)
- [Exothermic](#)
- [Free Energy](#)
- [Giant Planets](#)
- [Hot Jupiters](#)
- [Jupiter](#)
- [Saturn](#)
- [Venus](#)

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(Py-GC) and ► [pyrolysis GC/MS](#) are used to characterize organic polymers. Thermolysis of petroleum is called *cracking*.

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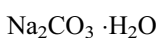
- [Gas Chromatography](#)
- [Pyrolysis](#)
- [Pyrolysis GC/MS](#)

Thermonatrite

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Chemical Formula



Definition

Thermonatrite is a non-marine evaporite mineral of the orthorhombic crystal system. It is often found in association with halite (NaCl), trona ($\text{Na}_3(\text{CO}_3)(\text{HCO}_3) \cdot 2\text{H}_2\text{O}$), and natron ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) in alkaline lakes formed in arid climates (► [soda lakes](#)). It can also form as an exhalative product of fumaroles or from alteration of natrite (Na_2CO_3). Detection of thermonatrite on Mars or other planetary surfaces could be an indication that alkaline or hypersaline lakes had formed in the past under reducing and dry environments.

Cross-References

- [Evaporite](#)
- [Natron](#)
- [Oceans, Origin of](#)
- [Soda Lake](#)

Thermolysis

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Synonyms

[Thermal decomposition](#)

Definition

Thermolysis is chemical decomposition by heating. If a reaction is endothermic, heat is required for the reaction to proceed. If the reaction is exothermic, the reaction proceeds spontaneously after initiation, which sometimes causes explosion. The term ► [pyrolysis](#) is often used in place of *thermolysis* when organic compounds are decomposed at high temperature. Pyrolysis gas chromatography

Thermophile

Jose Berenguer

Centro de Biología Molecular Severo Ochoa,
UAM-CSIC, Madrid, Spain

Keywords

High temperature · Hot springs · Thermal environment

Synonyms

Caldophile

Definition

Thermophiles (literally heat lovers) are organisms that grow at temperatures above those (25–40 °C) that sustain most life forms. Typically, a thermophile shows maximum growth rates at temperatures above 45 °C. Most are prokaryotes although a few thermophilic eukaryotes also exist. Depending on the temperature range for growth, thermophiles are divided into different categories like moderate or facultative thermophiles, which are able to grow below 40 °C, extreme or obligate thermophiles, which grow at temperatures from 55 °C to 80 °C, and ► [hyperthermophiles](#), with optimum growth temperatures above 80 °C.

History

The first thermophiles were described at the end of the nineteenth century in isolates from the Seine River and in studies on cyanobacteria in hot springs. In the early twentieth century, moderate thermophiles were identified as contaminants in the sugar industry and in compost. In the second half of the twentieth century, thermophilic enzymes started to be used in industry, especially for detergents. Following the description of the DNA structure, it was proposed that the upper

limit for life was around 73 °C, the melting temperature of DNA. However, Thomas D. Brook and coworkers isolated and described organisms thriving at well over this limit in hot springs of Yellowstone National Park. The subsequent work by Wolfrang Zillig and Karl Stetter among others and improvements in submersibles and isolation methods allowed the identification of (hyper)thermophiles able to grow above 110 °C.

Overview

In contrast to the heat resistance (thermotolerance) shown by plant seeds or bacterial spores, (based on specific properties such as cytoplasmic dehydration and viscosity increase limiting the thermal movements of molecules), the macromolecular components of thermophiles have adapted to function optimally at high temperatures. Strategies of thermal adaptation include modified composition of their cytoplasmic membranes to keep appropriate fluidity under the temperature range of optimum growth and increased compactness of their proteins through appropriate changes in their amino acid sequence or specific modifications of bases in small RNA segments. Most thermophiles have an elevated G + C content in their DNA compared to organisms that grow at lower temperatures, leading to the hypothesis that this is a specific trait of thermophiles. However, the existence of hyperthermophiles with a low G + C content invalidates this conclusion. Further adaptations to higher temperatures require the presence of increased concentrations of ► [compatible solutes](#) like ectoine or polyol-phosphate derivatives, or the presence of reverse gyrase, to decrease the melting effects of temperature on DNA. Thermostable enzymes, the enzymes of thermophiles, have applications of great relevance such as the development of the polymerase chain reaction (PCR) and derived techniques that use DNA polymerases from thermophilic organisms (e.g., ► [Taq polymerase](#)). In addition, thermostable enzymes are usually more resistant than conventional enzymes to organics and detergents, making them excellent candidates for industrial applications where severe conditions are encountered. From a biological point of view, the relationship between

thermophilic character and an ancient phylogenetic origin is commonly discussed, leading to the idea that these organisms are a window to the time when life first originated on earth.

Cross-References

- ▶ [Hot Spring Microbiology](#)
- ▶ [Hydrothermal Environments](#)
- ▶ [Hydrothermal Vent Origin of Life Models](#)
- ▶ [Hyperthermophile](#)
- ▶ [Plasma Membrane](#)
- ▶ [Prokaryotes, Origin of](#)
- ▶ [Taq Polymerase](#)
- ▶ [Yellowstone National Park, Natural Analogue Site](#)

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Thermosphere

Amanda Brecht

NASA Ames Research Center, Moffett Field,
CA, USA

Definition

The region of an atmosphere called the thermosphere is characterized by an increase in neutral

temperature as a function of altitude and asymptotes to a relatively constant temperature. The corresponding neutral atmospheric density is decreasing with altitude. The top of the region is bounded by the thermopause (or exopause/exobase), defined to be the region where the mean free path of particles is longer than a scale height. The bottom boundary is the mesopause, which is defined by the change in the thermal gradient from negative to positive (i.e., temperature begins to increase above the mesopause).

Energy is transported between the lower atmosphere (i.e., troposphere, mesosphere) and space (exosphere) through the thermosphere. The processes involved in the energy transport heavily influence the behavior and structure of the thermosphere. The relative importance of these processes depends greatly on the planetary environment and is related to how energy is absorbed, dissipated, and transported in the thermosphere. As can be imagined energy transport is a complex process. In the paragraphs below a brief description of the major processes is provided.

For planets closer to the Sun, the main source of energy (heat) entering the thermosphere comes from EUV/UV radiation, which varies depending on the solar activity. The Sun has a dominant ~11 Earth year cycle variation, which alone provides large variations. However, the Sun can have shorter and more sporadic variations; such as solar flares and coronal mass ejections. Therefore, the thermosphere temperature and structure will also vary depending on the solar activity by expanding during active times (more energy absorbed by the atmosphere) and compressing during quiet times (less energy absorbed by the atmosphere). Furthermore, EUV/UV radiation and other high energy particles from the Sun generates an ionosphere. An ionosphere is a region of atmosphere with a high concentration of ionized particles that usually coexists with the thermospheric neutral atmosphere, and they are coupled through nonlinear connections (e.g., chemical reactions, ion-neutral drag).

The thermosphere also absorbs energy from auroral processes (e.g., Joule heating) and

particle precipitation from the magnetosphere. The magnitude of these two processes is connected to the size of the planet's intrinsic magnetic field. For example, auroral processes at Earth are a dominant heat source during magnetic sub-storms while EUV/UV dominates during non-storm times, and for Jupiter auroral processes are just as important as EUV/UV heating. Conversely, Venus and Mars thermospheres are driven by EUV/UV radiation and particle precipitation.

The main processes of heat loss in the thermosphere are thermal IR (Infrared) radiation and thermal conduction. The magnitude of cooling by thermal IR radiation in the thermosphere is related to the atmospheric constituents and density. Due to the general decrease of density within the thermosphere (low collision rates), specific chemical species radiating in the IR will depart from the Local Thermodynamic Equilibrium (LTE) assumption and depend on the Non-LTE assumption. Non-LTE occurs when energy is exchanged more rapidly with the radiation field (or other energy sources) rather than through collisions with other molecules. The cooling of the thermosphere, via IR radiation, is most effective in the mid-lower thermosphere. Thermal conduction effectively cools an atmospheric region by transporting heat from areas of large vertical temperature gradients down to lower altitudes, so the larger the gradient the more efficient thermal conduction cools.

Varying processes produce irregular energy absorption and dissipation, which in turn produces pressure gradients that drive neutral winds. Furthermore, the pressure gradients contribute to energy transport and impact the thermospheric structure and composition. The dayside of a planet will warm and expand the atmosphere with corresponding upwelling motions. This atmospheric expansion generates adiabatic cooling. While the nightside tends to be cooler due to a lack of a major energy source (the Sun), the atmosphere compresses with downwelling motions. This will produce adiabatic heating. The adiabatic cooling and heating processes will compete with other

energy processes to regulate the thermal structure but are most effective with large, varying global scale neutral winds (relative to the planet).

The thermosphere is connected to the lower atmosphere predominantly through wave mechanisms; tides (migrating and non-migrating), large-scale planetary waves, and small-scale gravity waves. Waves propagate upwards and deposit momentum and energy when they become unstable ("break"). The wave deposition perturbs pressure, neutral wind, temperature, and density fields. The sources of waves range from auroral process to topography, and convection in the middle/lower atmosphere.

Lastly, the method by which the energy is directed within a thermosphere is also dependent on the density and chemical species (such as the thermal IR radiation). It is important to note that the distribution of the thermospheric composition can be split into homosphere (gases homogeneously well mixed) and heterosphere (gases diffusively separate). The homosphere is dominated by heavier chemical constituents and is driven by eddy or turbulent diffusion. The heterosphere is dominated by lighter chemical constituents and is typically driven by molecular diffusion, where compounds are separated by molecular weight. The boundary between a diffusive separated region and a well-mixed region, the homopause, varies based on temperature so the boundary can vary in altitude.

Cross-References

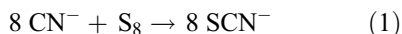
- ▶ [Absorption Cross Section](#)
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- ▶ [Atmospheric Circulation](#)
- ▶ [Atmospheric Processes, Escape](#)
- ▶ [Mesosphere](#)
- ▶ [Radiative Transfer \(Atmospheres\)](#)
- ▶ [Scale Height](#)
- ▶ [Stratosphere](#)
- ▶ [Troposphere](#)

Thiocyanate

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Meguro-ku, Tokyo,
 Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In chemistry, thiocyanate is the small molecule SCN^- (the conjugate base of thiocyanic acid HSCN). Organic compounds containing the functional group SCN are also called thiocyanates. Thiocyanate may be an important prebiotic compound as it forms robustly from cyanide and elemental sulfur:



It is relatively stable to hydrolysis but is oxidized by H_2O_2 . SCN^- has also been found to be an effective yet unpredictable condensing agent for peptide bond formation. SCN^- may be a significant [precursor](#) to thioesters in prebiotic chemistry and has been shown, when oxidized with H_2O_2 , to form condensed phosphates in high yield. SCN^- shares its negative charge approximately equally between sulfur and nitrogen; thus SCN^- can act as a nucleophile at either sulfur or nitrogen. It may react with amines and other nucleophiles at the central carbon atom. Reaction with amino acids may yield thiocarbamates, thiohydantoin, and ultimately hydantoin.

Cross-References

- [Hydantoin](#)
- [Precursor](#)

Thioester

Henderson James Cleaves
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

Thioesters are esters in which the linking oxygen atom is replaced by sulfur. They are the product of dehydration reaction between a carboxylic acid derivative and a [thiol](#). Thioesters are common intermediates in biochemistry, for example, in acetyl-CoA, malonyl-CoA, acetoacetyl-CoA, and propionyl-CoA. Thioesters are intermediates in several key processes in which ATP is either used or regenerated. Thioesters are involved in the synthesis of all biological esters, including those found in lipids. They also participate in the synthesis of a number of other cellular components, including peptides, fatty acids, sterols, terpenes, and porphyrins. The carbonyl group in thioesters is electrophilic; thus, thioesters and amines combine to give amides:



The protons on the carbon atoms adjacent to the carbonyl group in thioesters are mildly acidic and undergo aldol condensations, a reaction which occurs in the biosynthesis of fatty acids. Thioesters have been proposed to be important for the origin of life, for example, in de Duve's "Thioester World" model. In this model, it is proposed that thioesters could have played the role of ATP. Eventually, thioesters could have served to generate ATP through their ability to support the formation of bonds between phosphate groups.

Cross-References

- [Ester](#)
- [Thiol](#)

Thioformaldehyde (H₂CS)

Didier Despois
Laboratoire d'Astrophysique de Bordeaux,
CNRS-Universite de Bordeaux, Bordeaux,
France

Synonyms

[H₂CS](#); [Methanethioaldehyde](#); [Methanethiol](#)

Definition

Thioformaldehyde is the simplest thial or thio aldehyde (an organic compound containing a formyl group and analogous to aldehydes, with CS replacing CO). It is unstable under usual laboratory conditions, but forms a stable cyclic trimer (H₂CS)₃, 1,3,5-Trithiane. H₂CS has been detected in the ► [interstellar medium](#) and in ► [comets](#).

History

The 2₁₁–2₁₂ transition of thioformaldehyde was observed in absorption in the direction of the Galactic Center source Sagittarius B2 by Sinclair et al. in 1973. It was later also detected also in comets by Woodney et al. (1997).

Cross-References

- [Comet](#)
- [Methanethiol](#)
- [Molecules in Space](#)

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Thiol

Henderson James Cleaves II
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In organic chemistry, a thiol is a compound that contains the -SH functional group, which is the sulfur analogue of a hydroxyl or alcohol group. The functional group is referred to as either a *thiol group* or a *sulfhydryl group*. Thiols are more traditionally referred to as mercaptans. Thiols and alcohols have similar molecular structure, although the C-S-H bond angle is closer to 90° than the C-O-H bond angle of an alcohol. In the solid or liquid state, the hydrogen bonding between individual thiol groups is weak, the main cohesive force being van der Waals interactions between the polar sulfur centers.

Due to the similar electronegativities of sulfur and hydrogen, thiols are less polar and have a lower dipole moment than the corresponding alcohols. Thiols only weakly hydrogen bond with both water and other thiols. Hence, they have lower boiling points and are less soluble in water and other polar solvents than the corresponding alcohols. Akin to the chemistry of alcohols, thiols form thioethers, thioacetals, and thioesters. Thiols and alcohols are very different

in their reactivity, however, as thiols are easily oxidized and thiolates, the conjugate bases of thiols, are good nucleophiles. Thiolates also form strong complexes with many metal ions.

The important biological amino acid cysteine contains a thiol group. The thiol groups of cysteine residues in polypeptides assist in protein folding by forming disulfide bonds. Thiols in enzyme active sites can form noncovalent bonds with enzyme substrate as well, contributing to catalytic activity. Many important biological cofactors are thiols. The biosynthesis and degradation of fatty acids and related long-chain hydrocarbons are conducted on a scaffold that anchors the growing chain through a thioester derived from the thiol coenzyme A. The biosynthesis of methane is mediated by coenzyme M, 2-mercaptoethyl sulfonic acid.

► [Methanethiol](#) (methyl mercaptan) is the heaviest sulfur-containing molecule that has been detected in interstellar molecular clouds.

Cross-References

- [Cofactor](#)
- [Cysteine](#)
- [Disulfide Bond](#)
- [Methanethiol](#)

Thiomethanol

- [Methanethiol \(CH₃SH\)](#)

Tholins

François Raulin
Faculté des Sciences et Technologie, Université
Paris Est Créteil et Paris Diderot, Creteil, France

Keywords

Khare · Laboratory simulation experiment · Plasma experiment · Refractory organics · Sagan · Solid organic product · Titan's aerosols · Titan's haze

Synonyms

[Complex organic product](#)

Definition

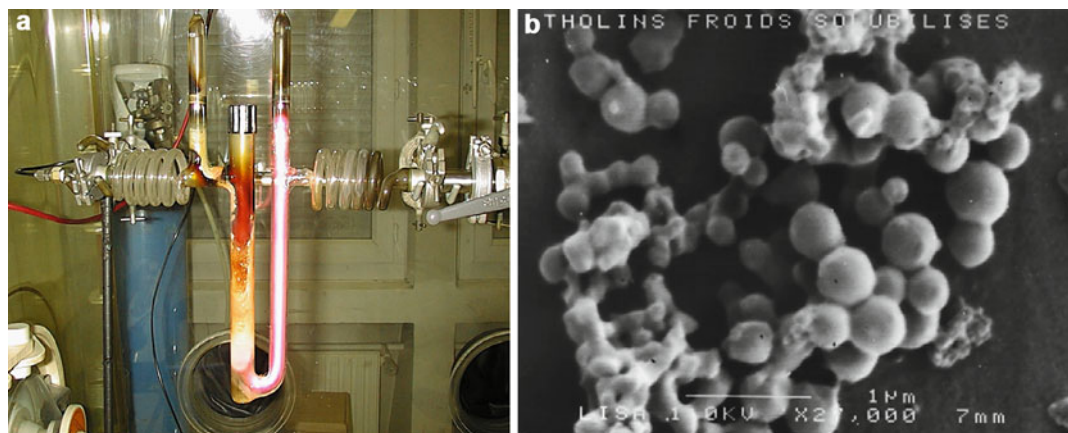
“Tholins” designates the solid refractory organics that are produced during the irradiation of gases or ice mixtures of simple compounds by a variety of energy sources, which are also of astrophysical significance.

History

The word tholins was coined by Carl Sagan and Bishun Khare in the late 1970s (Sagan and Khare [1979](#)), when they realized that in many laboratory experiments, simulating the chemical evolution of astrophysical environments starting from simple organic compounds, nonvolatile complex macromolecular organics were systematically formed. They proposed in particular that tholins play a key role in the organic chemistry of interstellar grains and gas. Since these products often looked like mud or tar, Sagan and Khare decided to call them “tholins,” which comes from the Greek word “tholos,” meaning “muddy” or alternatively “domed.”

Overview

Tholins are produced in a large variety of experiments simulating the complexification of organic matter from simple low molecular weight volatile organics under irradiation by various types of energy flux. Miller-Urey type experiments (Miller [1953](#)) simulating the chemical evolution of the primitive Earth atmosphere produce tholins (“primitive Earth tholins”) which may in part be the precursors of molecules of biological importance such as amino acids and nucleic acid bases obtained in such experiments. “Jovian tholins” are formed during laboratory experiments simulating the chemistry of the atmosphere of Jupiter, and “interstellar tholins” are produced during the experiments simulating the organic chemistry in the interstellar medium.



Tholins, Fig. 1 Titan's tholins experiment (Courtesy: Patrice. Coll): (a) The "PLASMA" experiment is used at LISA (Laboratoire Interuniversitaire des Systèmes Atmosphériques, France) to mimic Titan's atmospheric chemistry. A low pressure (~ 1 hPa) gas mixture of N_2 (98%) and CH_4 (2%) flows continuously through a U-tube

reactor, maintained at low temperature (~ 150 K) and installed in a glove box. Titan tholins are deposited on the wall of the reactor and recovered at the end of the irradiation in an inert atmosphere. (b) Image of these tholins from scanning electron microscopy

The most studied tholins are ► **Titan** tholins (Cable et al. 2012; Raulin et al. 2012), the solid macromolecular product formed during laboratory experiments simulating the chemistry of Titan's atmosphere, usually starting from gas mixtures of N_2 and CH_4 and using electron impact as energy source (Fig. 1). Titan tholins have been assumed to be good laboratory analogues of Titan's actual aerosols. Consequently, several laboratories have developed detailed experiments on these tholins, to get information which could be extrapolated to the particles of Titan's atmosphere. This is essential to facilitate the interpretation of the retrieved data from Titan observations. This includes the measurement of the spectral characteristics of Titan tholins in the visible, IR, and UV; the determination of their index of refraction, of their size, and of their morphology; and the determination of their molecular structure. Since the first work by Sagan's group (Khare et al. 1984, 1986), Titan tholins have been extensively studied. They exhibit quite different properties depending on the experimental conditions used for their production, as shown by their average C/N ratio, which varies from less than 1 to more than 11. Experiments at low pressure and low temperature (PLASMA experiment)

closer to Titan's upper atmosphere conditions (Ramirez et al. 2002; Bernard et al. 2006 and references therein) and using a glove box purged with pure N_2 to sample Titan tholins without oxygen contamination have been developed to provide more representative laboratory analogues of Titan's aerosols. Experiments producing tholins in levitation (PAMPRE experiment) have also been done (Szopa et al. 2006). The influence of the pressure of the starting gas mixture on the elemental composition of the tholins has been systematically studied: depending on the pressure, two different chemical-physical regimes with a transition pressure around 1 mbar (Imanaka et al. 2004 and references therein) seem to occur. In spite of the many studies, the molecular composition of Titan tholins is still poorly known. However, they seem to be made of macromolecules of largely irregular structure, with molecular weight from several hundreds to several tens of thousands of daltons. Their structure includes aliphatic and benzenic hydrocarbon groups, CN, NH_2 , and $C=NH$ groups. Their hydrolysis yields a large variety of amino acids (Khare et al. 1986), even when conducted at low temperatures (Ramirez et al. 2010; Neish et al. 2010). Experiments using VUV irradiation

(from tunable synchrotron radiation) and high-resolution mass spectrometry for molecular analysis have been recently carried out (Imanaka and Smith 2010). Extrapolation of their results to Titan suggests that nitrogenated organic aerosols are formed in Titan's upper atmosphere.

The Ion and Neutral Mass Spectrometer (INMS) on ► [Cassini](#) has detected high molecular weight negative ions in the ionosphere of Titan, which may be linked to the formation of Titan's aerosols and tholins (Waite Jr et al. 2007). Data from the Aerosol Collector and Pyrolyzer (ACP) on the ► [Huygens](#) probe suggest that Titan's aerosols release HCN and NH₃ when pyrolyzed at 600 °C (Israël et al. 2005). Although still debated (Biemann 2006; Israël et al. 2006), this supports the hypothesis that laboratory Titan tholins are similar to Titan's haze particles (Coll et al. 2013).

Cross-References

- [Aerosols](#)
- [Atmosphere, Structure](#)
- [Cassini](#)
- [Gas Chromatography](#)
- [GC/MS](#)
- [HCN Polymer](#)
- [Huygens](#)
- [Hydrocarbons](#)
- [Methane](#)
- [Nitrogen](#)
- [Pyrolysis](#)
- [Refractory Molecule](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Spectroscopy](#)
- [Titan](#)
- [Volatile](#)

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Tholus

Daniela Tirsch

German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Volcanic mountain](#)

Definition

A tholus (pl. tholi) is a descriptor term for a small domical mountain or hill of volcanic origin as defined by the International Astronomical Union (<http://planetarynames.wr.usgs.gov/DescriptorTerms>). Volcanic edifices named tholus can be found on ► [Mars](#), ► [Venus](#), and ► [Io](#).

Cross-References

- [Io](#)
- [Mars](#)
- [Mons, Montes](#)
- [Patera, Paterae](#)
- [Venus](#)

Threonine

Kensei Kobayashi

Yokohama National University, Yokohama, Japan

Definition

Threonine is one of the protein ► [amino acids](#) whose chemical formula is $\text{HO}_2\text{CCH}(\text{NH}_2)\text{CH}(\text{OH})\text{CH}_3$. Its three-letter symbol is Thr, and its one-letter symbol is T. As in the case of serine, it has a hydroxyl ($-\text{OH}$) group in its side chain, and

it is classified as a polar amino acid. Its molecular weight is 119.12, and its isoelectric point is 6.16. Threonine has two asymmetric carbons (α -carbon and β -carbon) as does isoleucine. Thus, threonine has four stereoisomers: L-threonine, D-threonine, L-*allo*-threonine, and D-*allo*-threonine. Only L-threonine is used in biosynthesis of ► [proteins](#), and it is widely distributed in the biosphere.

Cross-References

- [Amino Acid](#)
- [Chirality](#)
- [Isoleucine](#)
- [Protein](#)

Thymine (T)

Shin Miyakawa

Kamagaya, Chiba, Japan

Definition

Thymine ($\text{C}_5\text{H}_6\text{N}_2\text{O}_2$, molecular weight: 126.12) is one of the four nucleic acid bases found in DNA. Thymine has a methyl group ($-\text{CH}_3$) at the 5'-position of the pyrimidine ring. In double-stranded DNA, thymine pairs with adenine via Watson-Crick base pairing with two hydrogen bonds. The half-life of thymine in water is 56 years at 100 °C and 20×10^8 years at 0 °C at pH 7. Thymine has a UV absorption maximum at 265 nm and may dimerize when it is irradiated with ultraviolet light.

Cross-References

- [Adenine](#)
- [Nucleic Acid Base](#)
- [Uracil \(Ura\)](#)

Tianwen-1

Michel Viso
Innovaxiom, Paris, CX, France

Keywords

Mars exploration · Utopia Planitia · Rover · Orbiter

Definition

Tianwen-1 is the first Chinese mission to the planet Mars. Launched, by a Long March 5 rocket, on July 23, 2020, the spacecraft has been placed on a Martian orbit on February 10, 2021. The lander has separated from the orbiter and landed in *Utopia Planitia* on May 15, 2021. The lander delivered a platform and a rover, Zhurong, on the Martian surface. The rover egressed from the landing platform on May 22, 2021. The orbiter carries seven scientific instruments and the rover six. Two years is the nominal lifetime of the orbiter while the rover has a nominal lifetime of 90 days. ESA, CONAE, FFG, and CNES are the four international partners contributing to the mission.

History

The first Chinese mission to Mars was an orbital probe (Yinghuo) to be delivered to Mars by the Russian mission Phobos-grunt which failed few minutes after the launch in 2011. The mission Tianwen-1 was formally approved in 2016 (Geng et al. 2018) for a launch 4 years later. In parallel, some international cooperation was developed. The European Space Agency supported the telecommunication system during the launch and the travel to Mars; the Argentinian Space Agency (CONAE) hosts a Chinese deep space telecommunication antenna (the only one in the south hemisphere); The Austrian Research Promotion Agency (FFG) cooperates on the

calibration of the magnetometer placed on the orbiter. Under the auspices of the French space agency (CNES), the “Institut de Recherche en Astrophysique et Planétologie” (IRAP) cooperates on the calibration of the Chinese LIBS (Laser-Induced Breakdown Spectroscopy) on the rover, while the “Institut d’Astrophysique Spatiale” (IAS) shares expertise in the characterization of possible landing sites.

Overview

The scientific objectives of Tianwen-1 mission are (i) to map the geological and morphological structures of Mars; (ii) to study the structure of the Martian ground and study the ice water distribution; (iii) to analyze the surface rocks composition; (iv) to collect data on the ionosphere and to characterize the Martian climate and the surface environment; and (v) take measurements of the electromagnetic field and the gravitational field of Mars and study the Martian internal structure.

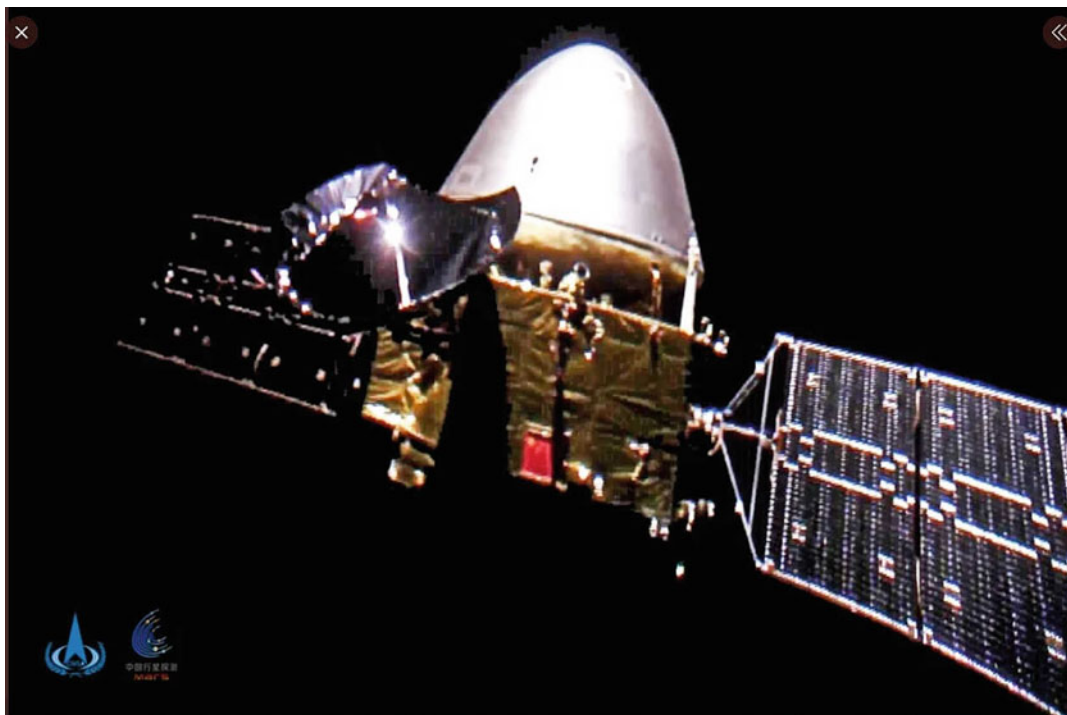
The spacecraft is composed of an orbiter (mass 3710 kg) (Fig. 1) and a landing module (mass 1300 kg) (Fig. 2).

The orbiter hosts 7 scientific instruments (Yongliao et al. 2021) (Table 1).

The rover hosts six instruments for science (Yongliao et al. 2021) (Table 2).

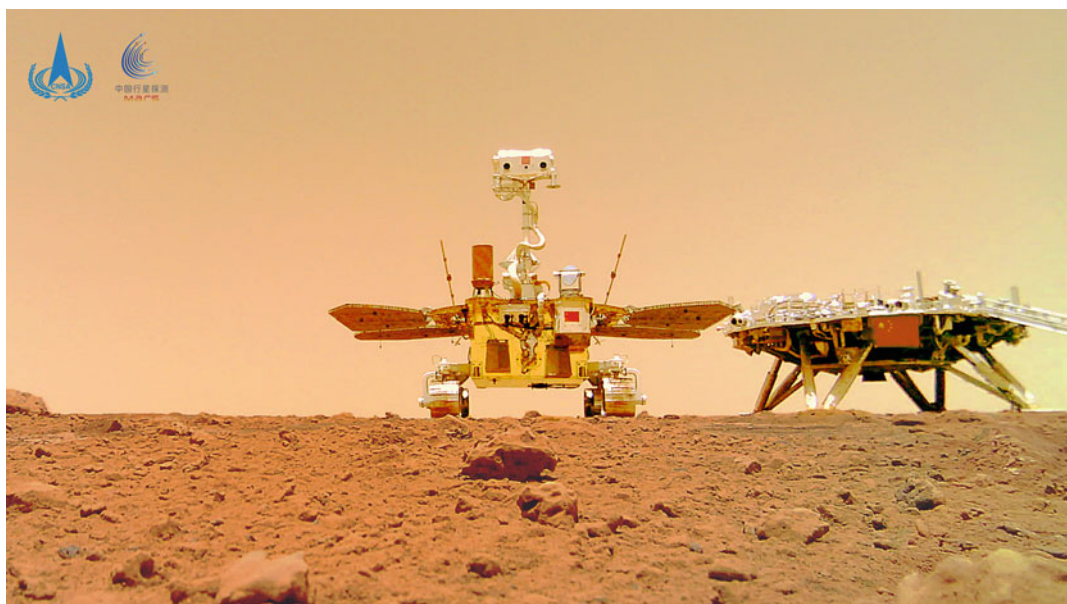
The orbiter Tianwen-1 and the rover Zhurong resumed operations in October 2021 after a month of radio communication blackout due to the sun conjunction.

During the primary mission, Zhurong traveled around 1300 m, and the mean speed was 10 m/d with a maximum at 20 m/d. While Tianwen-1 orbiter is changing orbit to prepare for a global mapping of Mars, the oldest ESA spacecraft around Mars, → MarsExpress, performed communication tests with the rover. Mars Express is not able to send radio signals receivable by the rover (frequency incompatibility), but it can receive and transmit to the Earth signals from the rover. The rover is not aware of the position of the receiving satellite, and it transmits data without the usual “handshake” between the emitter and the



Tianwen-1, Fig. 1 Photo taken by a daughter nano-satellite of the spacecraft Tianwen 1 into deep space during its travel to Mars. The spacecraft with the deployed solar

panels and the landing module with its “egg shape” white rear heat protection are clearly visible. (Credit: China National Space Administration)



Tianwen-1, Fig. 2 Photo by a wireless camera of Zhurong and of the landing platform in June 2021 in *Utopia Planitia*. (Credit: China National Space Administration)

Tianwen-1, Table 1 Description of the instruments of the science payload of the orbiter Tianwen-1

Medium resolution camera	MoRIC	Standard RGB, 4000 × 3000 pixels. Space resolution 100 m at altitude Fig. 1: Tianwen 1 released two CubeSats to take this selfie in august 2020. It was send to the mother spacecraft using Wi-Fi and then transmitted to Earth This is a première photo of a spacecraft in deep space, while traveling to Mars 400 km
High-resolution camera	HiRIC	Resolution in panchromatic mode 2,5 m down to 0,5 m Panchromatic: 0.45–0.9 µm Resolution in color mode 20 m down to 2 m; blue 0.45–0.52 µm, green 0.52–0.60 µm, red 0.63–0.69 µm, and near-infrared 0.76–0.90 µm
Subsurface-detecting radar	MOSIR	Frequency 10–20 MHz and 30–50 Mhz penetrating depth: 100 m in soil, and 1000 m in ice with a vertical resolution of about 1 m
Mars mineral spectrometer	MMS	Hyperspectral imager with two channels V-NIR: 0,379–1076 µm N-MIR: 1033–3425 µm Resolution of 2,1 km/pixel at altitude 265 km
Mars orbital magnetometer	MOMAG	Two triaxial flux gate: measuring up to 10,000 nT with a resolution 1,19 pT
Mars ion and neutral particle analyzer	MINPA	Combine and electro-static analyzer and a time of flight spectrometer to measure the solar wind and the ionic and neutral composition of the Martian space environment. Range 1–70 amu for low-energy ions 1–32 amu for neutral particles
Mars energetic particle analyzer	MEPA	To analyze the flux and the spectrum of various particles. Range varying with their nature: electronics: 0.1–12 MeV; protons: 2–100 MeV; α-particles, heavy ions: 25–300 MeV

Tianwen-1, Table 2 Description of the instruments of the science payload of the rover Zhurong

Topography camera	NaTeCam	Visible spectrum; 2000x2000 pixel, for high-resolution 3D images
Multispectral camera	MSCam	9 spectral band (nm, numbers in brackets are FWHM) 480(20), 525(20), 650(12), 700(15), 800(25), 900(30), 950 (50), 1000 (50), and a panchromatic mode
Subsurface-detecting radar	RoPeR	Dual channel 15–95 MHz and 450–2150 MHz, penetrating, respectively, 100 m in ice and 10 m in soil, and 10 m in ice 3 m in soil
Surface composition analyzer	MarSCoDe	To identify either elementary composition and mineral composition of targets. LIBS spectrometer to detect at least 12 elements: Si, Al, Fe, Mg, Ca, Na, O, C, H, Mn, Ti, S . . . ; Laser 1024 nm; pulse energy density $\geq 10 \text{ MW/mm}^2$; spectrometer with spectral range 240–850 nm; Passive spectrometer: 850–2400 nm
Surface magnetic field detector	RoMAG	To measure local magnetic field, working with MOMAG Measurement range $\pm 2000 \text{ nT}$ with a resolution better than 0,01 nT
Mars climate station	MCS	Measurement and recording of: temperature ($-130 + 70 \text{ }^\circ\text{C}$), pressure (1–2000 pa), wind speed (0–70 m/s) and direction (0–360°), and sound (20 Hz-20 kHz)

receiver. This was the first test of such a blind transmission. On November 20, 2021, the test was successful, and further tests and operations are planned.

Cross-References

- [Mars](#)
- [Mars Express](#)

Further Reading

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Tidal Locking

► [Synchronous Rotation](#)

Tidal Migration

► [Planetary Migration](#)

Tides, Archean

Christoph Heubeck

Institut für Geowissenschaften, Friedrich-Schiller-Universität Jena, Jena, Germany

Keywords

Tides · Archean · Moon · Tidal friction · Tidal range

Definition

Tides are periodic deformations of a planet's solid, liquid, and gaseous substances due to their locally changing gravitational attraction to an orbiting object. This article will limit itself to marine tides on Earth caused by the Moon.

Overview

Tides are highly productive ecologic zones, providing an ideal and variable mix of nutrients, water, and energy for life. Wetting and drying cycles in sandy pore spaces in tidal zones make ideal biochemical laboratories, and the strong abrasive forces provided by rolling sand grains result in high rates of lateral gene transfers between injured or squashed cells. Recent and ancient tidal zones have thus long attracted the attention of biologists, prebiotic chemists, and geneticists. Nevertheless, the dynamics of tidal zones in the deep geologic past are difficult to quantify.

Basic Methodology

Apollo Lunar Laser Ranging since the 1970 has established that the radius of the Moon's orbit about Earth currently grows at a rate of about 3.74 cm/year. However, this rate is considered anomalously high (Kagan 1997; review in Coughenour et al. 2009). If it had been constant and its orbit be reconstructed, the Moon could not have been older than about 2 Ga, at which time it would have reached the ► [Roche limit](#). This conflicts with the established geological age of the Moon of ca. 4.54 Ga. Thus, the lunar recession rate must have been significantly lower at some time in the geologic past. It is safe to say, though, that the Moon must have orbited Earth in a nearer orbit, that its period consequently must have been shorter, and that the gravitational attraction of water to the Moon must have been higher than at present.

The reason for the Moon's spiraling orbit is the gradual transfer of angular momentum from Earth to Moon due to (among other) tidal friction between water and solid Earth, slowing Earth down and transferring its angular momentum to the Moon, a concept which goes back to Kant and Laplace. (If all of that angular momentum was put back into the Earth, it would rotate with a period of only about 4–6 h.) This transfer also reduces the eccentricity and potentially the inclination of Moon's orbit. But how did tidal friction change

through time? This question is almost impossible to answer. Because tidal friction originates mostly where tidal currents move over a solid surface and thus lose energy, which occurs mostly on continental shelves, the past area of shelves and local tidal forces enter the equation (Brosche 1984; Archer 1996b). The shape of ocean basins through time as well as the rate and mode of growth of continental crust, however, which will determine this factor, are a matter of controversy (see, e.g., Kagan 1997). The despinning of Earth by transfer of angular momentum to the Moon slows down Earth's rotation rate, increases the length of the solar day, and reduces the number of tides at a given point per time period (Kvale et al. 1999). However, as Earth's spin rate slows down, so does Moon in its growing orbit about Earth, so that the number of lunar days per month (the synodic month, that is, New Moon to New Moon which largely controls neap–spring cycles) may have changed little; it is presently 29.53 days (see review in Mazumder and Arima 2005). The influence of the Moon on Archean tidal range and frequency is thus difficult to quantify because the determination of absolute Earth–Moon distances and Earth's paleorotational parameters in the distant geological past from tidal rhythmites is ambiguous. This, in turn, is because of the difficulties in determining the absolute (not relative) length of the ancient lunar sidereal month accurately (Mazumder and Arima 2005).

Key Research Findings

Aside by the parameters of celestial mechanics, the global tidal range in the Archean was likely also affected by a number of terrestrial factors:

1. Due to the high heat flow, lithospheric thickness may have been thinner and lithospheric flexural strength reduced. ► **Continents** were on average less capable of supporting high elevations and had an overall lower topography and a higher percentage of wide, low-lying coastal plains.

2. Continents and continental fragments may have been smaller and presented only weak obstacles to the tidal bulges circling Earth. In contrast, today, tidal bulges mostly rotate about amphidromic points in rather isolated ocean basin, driven by the Coriolis force (Archer 1996a).
3. The complete absence of stabilizing vegetation, baffling and dissipating tidal currents, enabled tides to reach farther inland than at present. This may have been aided by an unknown degree of tidal flat sealing by thick and cohesive microbial mats which may have locally reduced the basal friction of in- and outgoing tides.
4. The higher degree of partial asthenospheric melting thickened ► **oceanic crust** so that it floated higher on the ► **asthenosphere**. This displaced water inundated a large proportion of continental margin (“reduced continental freeboard”). The wide shelves thus created are known to favor high tidal ranges, and tidal height may, in fact, increase as open-ocean tides approach a wide, shallow water platform (Klein 1982; Pratt and James 1986).
5. High tides cause embayments and estuaries which in turn amplify the tidal range (funnel effect) when the time required for the tide to move in and out of the basin is close to one of the astronomical tide periods. Open-ocean tides of about 1 m/day may reach up to 16 m/day.

Because the patterns and controls on tidal range at any one location are complex and vary highly even on modern Earth (including topographic geometries, bathymetric changes, astronomical parameters) and because only a tiny fraction of Archean time has been preserved in very few remnants of Archean surface (so-called ► **green-stone belts**), it is unlikely that we will be able to reach valid conclusions about Earth's Archean tides from isolated outcrops; this, of course, does not free geologists from investigating the few occurrences recording ► **Precambrian** tidal signatures.

In attempting to quantify the Archean tidal record, geologists distinguish between tidal bundles (laterally accreted cyclic foreset beds separated by mud laminae) and tidal rhythmites (vertically accreted planar laminae that alternate between coarse- and fine-grained sediments; see review by Longhitano et al. 2012). Both commonly occur in inter- or subtidal depositional environments and show a rhythmic thickness variation because their mode of deposition (e.g., saltating sand interbedded with suspension-settled mud) is primarily determined by current velocity and tidal range. However, the unequivocal recognition and quantitative analysis of Precambrian tidal deposits is fraught with uncertainty. It requires a specific setting with a moderate to significant tidal range, significant accommodation space, high sedimentation rates, significant suspended load, and the general absence of bioturbation (Archer 1996b).

From the Archean, only two such records are published (Eriksson and Simpson 2000; Mueller et al. 2002). Eriksson and Simpson (2000) analyze tidal deposits in the ► **Moodies Group** (ca. 3,225–3,215 Ma) of the ► **Barberton Greenstone Belt** from the thickening and thinning patterns of tidal bundles exposed over ca. 1.2 m thickness of a subaqueous sand bar. They interpret a periodic pattern of 9–10 as reflecting semi-monthly neap–spring–neap cycles (compared to a recent semimonthly periodicity of about 14). However, the syntectonic character of the Moodies Group suggests that the tidal signal may be more influenced by local orogenic conditions rather than by globally operating processes.

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Tides, Planetary

Tilman Spohn¹ and Michaela Walterová²

¹International Space Science Institute, Bern, Switzerland

²Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany

Keywords

Tidal deformation · Tidal dissipation · Tidal locking · Tidal potential · Tides

Definition

Tides are deformations of a ► **planet** or natural satellite caused by periodic variations of the local gravity acceleration as the planet or satellite rotates and revolves in the gravity field of a (disturbing) body. Tidal disturbances of a planet are primarily caused by the Sun and by the planet's satellites. The planet will – in turn – also tidally disturb the satellites. On the Earth, tides are caused by the Sun and the Moon. Marine tides – the tidal deformation of the surface of the oceans – are most obvious and well known. In addition, there are atmospheric pressure variations caused by tidal accelerations and tidal deformations of the

solid planet. Dissipation of tidal deformation energy can be a substantial heat source for planets and satellites and can cause changes in the rotation and orbital parameters.

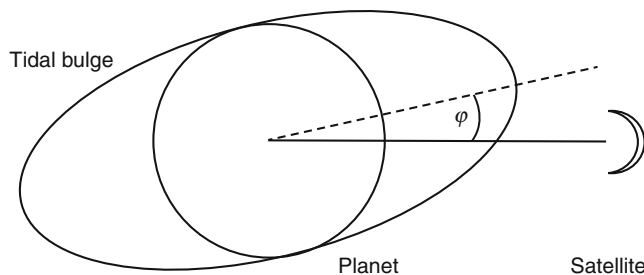
Overview

The equilibrium surface of a planet depends on the distribution of mass in its interior (interior structure) and its rotation rate. The gravitational and centrifugal forces combine to define an equilibrium surface that the planetary surface would attain were the planet in hydrostatic equilibrium and in empty space. In addition to these internal forces, there may be external forces caused by the gravity of a satellite – such as the ► [Moon](#) on Earth – and/or by the gravity of the primary body about which the planet is orbiting. For the planets of our ► [solar system](#), the latter is the Sun. For the satellites, these bodies are their primary planets such as Earth for the Moon and ► [Jupiter](#) for, e.g., ► [Io](#) and ► [Europa](#). Because the planet-satellite pair is rotating about a common center of mass, the centrifugal force contributes to the tidal force causing tidal deformations to be symmetric (compare Fig. 1) with one bulge roughly pointing toward the disturbing body and a second bulge pointing in the opposite direction. For perfectly elastic or fluid bodies, the bulges would point exactly to and away from the disturbing body.

For real planetary bodies, their viscoelastic rheology causes the tidal deformation to lag behind the disturbance. As a consequence, the tidal bulge will precede the disturbance for a planet that rotates faster than the satellite is orbiting (Fig. 1). In this case, the satellite is above its so-called synchronous ► [orbit](#) (all of the large satellites in the solar system). The bulge will lag behind the disturbance if the satellite orbits faster than the planet rotates. In this case, the satellite is below its synchronous orbit (e.g., ► [Phobos](#) and several small satellites of the giant planets).

In principle, neighboring planets can also have a tidal effect. In the solar system, their gravitational accelerations are small in comparison with those of the Sun and the mutual gravitational attractions between planets and their satellites. However, in some multiplanetary systems (e.g., TRAPPIST-1), the planet-planet tides are expected to play a role comparable with the tides raised by the host star (Lingam and Loeb 2018).

On Earth, the most notable tidal effects are the marine tides with amplitudes of high and low tides, particularly strong in epicontinental seas such as the North Sea. Although atmospheric pressure will vary with the tides, much more pronounced are atmospheric pressure variations caused by the time variation of the solar heating during a solar day. These variations are often termed atmospheric tides (e.g., Lindzen and Chapman 1969), but these are not further considered here.



Tides, Planetary, Fig. 1 Tidal bulge raised on a planet by an orbiting satellite. It is assumed that the planet rotates faster than the satellite orbits the planet. That is, it is assumed that the rotational angular velocity ω exceeds the orbital angular velocity (or mean motion) n . In this

case, tidal dissipation causes the tidal bulge to precede the satellite. The torque exerted by the satellite on the bulge will reduce the planetary rotation rate. The torque exerted by the bulge on the satellite will accelerate the latter and increase the orbital distance

Tidal Potential and Deformation of the Equipotential Surface

In the following, we focus on body tides and start for simplicity with an ideal spherical and fluid planet or satellite and take the disturbing body to be a point mass. The tide-raising potential at any point on the surface of the planet can be cast in terms of a spherical harmonic expansion. Considering the most important term of second order only and assuming rotational symmetry for the planet, we have for the tide-raising potential (compare, e.g., Stacey and Davies 2008)

$$\psi = -\frac{3}{4} \frac{GM r^2}{a^3} \left(\cos 2\theta - \frac{1}{3} \right) \quad (1)$$

In Eq. 1, G is the universal gravitational constant, M the mass of the tide-raising body, a the distance between the center of mass of the planet and of the tide-raising mass, r the radial distance from the center of mass of the planet to the point under consideration, and θ the angular distance between the point under consideration and the line connecting the centers of mass of the planet and the tide-raising body. From Eq. 1, we can conclude that the tidal potential decreases with the third power of the distance to the tide-raising body. We further conclude that the potential is symmetric with respect to a line through the two centers of mass and with respect to a plane that contains the center of mass of the planet and whose normal vector is colinear to the connecting line. Therefore, if the planet rotates much faster than the satellite orbits the planet, the tides will have a period of about half the planetary rotation rate.

The deformation δ of the equipotential surface above the undisturbed surface is

$$\delta = \frac{\psi}{g} = \frac{3}{4} r \frac{M}{m} \left(\frac{r}{a} \right)^3 \left(\cos 2\theta - \frac{1}{3} \right) \quad (2)$$

where m is the mass of the planet. For the lunar tide of the Earth, the peak-to-trough value calculated from Eq. 2 is about half a meter. This is about

twice the value that is actually observed as the peak-to-trough deformation of the solid body of the Earth. Tidal deformations of the solid planetary surface can be measured with tiltmeters or with laser ranging from satellites. The equipotential surface can be tracked with satellites through Doppler ranging and with gravimeters on the planet's surface.

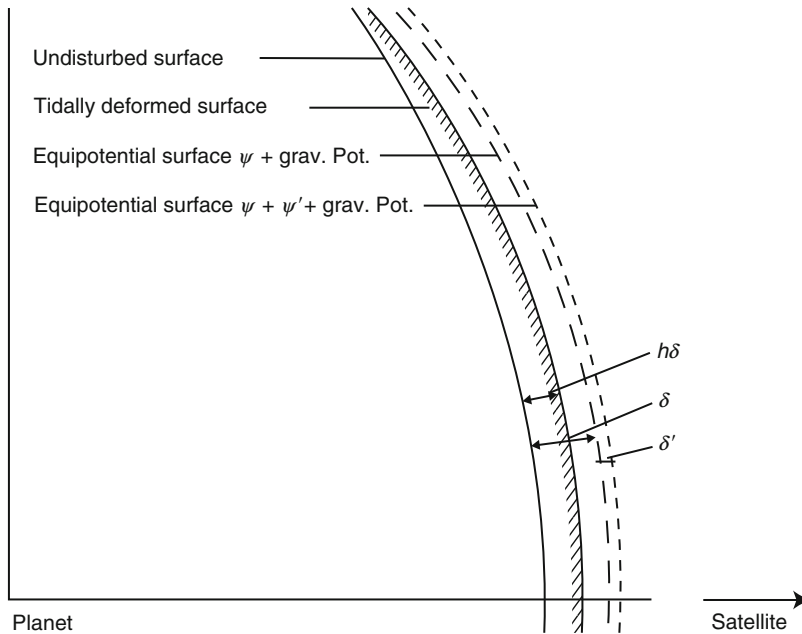
Tidal Love Numbers

As the planet deforms, a further potential Ψ' will be raised that is due to the gravity of the deformed mass. This potential will cause an additional deformation δ' (compare Fig. 2). A.E.H. Love introduced two dimensionless numbers named after him. The first, k , is the ratio Ψ'/Ψ . The second Love number h is defined as the ratio between the height of the body tide above the undisturbed surface and δ . There is a third number, the Shida number l , that gives the ratio of the horizontal component of the deformation of the planetary surface to that of the deforming potential.

For an ideally fluid planet in tidal equilibrium, $k = 3J_2/q$ and $h = 1 + k$, where J_2 is the coefficient of the second-order term of the gravitational potential (see the discussion in ► [Interior Structure](#)) and $q \equiv \omega^2 R_p^2 / Gm$. In addition to already defined quantities, ω is the planetary rotation rate. These Love numbers are usually called the fluid tidal Love numbers k_{2f} and h_{2f} and can be used to constrain models of the interior structure of planets and satellites. For a constant-density planet in hydrostatic equilibrium, $J_2 = 1/2q$, $k_{2f} = 3/2$, and $h_{2f} = 5/2$.

For viscoelastic planets, the Love numbers depend on the rheology and on the internal mass distribution. In particular, the viscoelastic Love number k_2 of a homogeneous planet is defined as

$$k_2 = \frac{3}{2} \frac{1}{1 + \frac{19}{2} \frac{\bar{\mu}}{\rho g R_p}}$$



Tides, Planetary, Fig. 2 Sketch of the tidally deformed surfaces of a planet or satellite. Shown are the undisturbed surface, the tidally deformed surface, the equipotential surface of the gravitational potential Φ plus the tidal disturbance potential Ψ , and the equipotential surface of the sum of the potentials including Ψ' . The latter is the contribution

to the potential of the tidally deformed masses. Also shown are the local heights of the surfaces $h\delta$, δ , and $\delta' = k\delta$. The height of the equipotential surface $\Phi + \Psi + \Psi'$ above the tidally deformed surface is an observable factor and is equal to $(1 + k - h)\delta$. It is called the tidal tilt factor

where $\tilde{\mu}$ is complex rigidity, which defines the viscoelastic behavior, ρ is mean density of the planet, and g is the surface gravity. Because the rheology parameters are temperature and frequency dependent, there is also a dependence on the interior temperature and on the rotation and revolution rates. The rigidity of the mantle rock precludes values of the Love numbers larger than unity for terrestrial planets. For Earth, $h \approx 0.6$, $k \approx 0.3$, and $l \approx 0.04$; for the Moon, the Love numbers are about an order of magnitude smaller.

The tidal Love number h for icy satellites with substantial subsurface oceans decoupling the ice shell from the satellite bulk can be larger than unity. For Europa, for example, Hussmann et al. (2010) obtain $h = 1.172$ and $k = 0.245$ for a model with a 30-km-thick ice layer on top of the ocean.

Tidal Dissipation

Because planets are viscoelastic bodies, tidal deformation is accompanied by dissipation of

deformation energy. This is – potentially – an important heat source in the interiors of planets and satellites. The dissipation rate is often taken to be proportional to the inverse of a dimensionless quality factor Q , with

$$\frac{1}{Q} \equiv \frac{\Delta E}{E} \quad (3)$$

where ΔE is the energy loss per tidal cycle and E is the elastic deformational energy stored in the planet per cycle. An alternative approach takes the Love number k to be a complex number with the imaginary part measuring the dissipation rate (e.g., Spohn 1997). The tidal dissipation rate then depends on the deformation $h\delta$, the period of the forcing τ , and the viscoelastic properties (shear modulus μ and Q) of the planet. To orders of magnitude, we have, following Hubbard (1984),

$$\frac{dE}{dt} \sim \frac{2\pi}{\tau} \frac{4}{3} R_P^3 \frac{\mu}{Q} \left(\frac{h\delta}{R_P} \right)^2 \quad (4)$$

It should be noted that the viscoelastic properties of the planet are usually temperature dependent, potentially leading to feedback between the dissipation rate and internal temperature: An increase in temperature will cause a decrease in Q of solid rock, which will lead to an increase in the dissipation rate and, thereby, to a further increase in temperature. One should be aware, however, that the heat transfer rate will also depend on temperature and may counterbalance the heating. Since Q must be proportional to the mantle rock $\blacktriangleright$ [viscosity](#), the heat transfer rate can increase with increasing temperature, potentially resulting in a stable equilibrium between tidal heating and heat transfer. Such equilibrium states have been described by, e.g., Fischer and Spohn (1990) and Spohn (1997) for Io and by Hussmann and Spohn (2004) for Io and Europa. The decrease in Q with increasing temperature can also be stopped by partial melting of the mantle or by a transition to a less dissipative low-viscosity state (Henning et al. 2009).

Tidal dissipation rates can be substantial. Io, a satellite of Jupiter of approximately the size of the Moon, has a surface heat flow of 2 W m^{-2} (or 80 TW, e.g., Spencer et al. 2000), 20 times the Earth's heat flow per unit area and about 100 times the lunar value, together with an enormous volcanic activity. It is universally agreed that the activity is due to tidal heating. It should be noted, however, that the large dissipation rate is maintained by an orbital resonance (the $\blacktriangleright$ [Laplace resonance](#)) with the two other Jovian satellites Europa and $\blacktriangleright$ [Ganymede](#). Europa may also experience tidal dissipation which may be contributing to its energy balance and help keep a liquid ocean beneath the near-surface ice shell (e.g., Hussmann and Spohn 2004). The vapor plumes observed at the Saturnian satellite $\blacktriangleright$ [Enceladus](#) have also been explained as being caused by tidal dissipation (Tobie et al. 2008). On Earth, a significant part of the total dissipation of about 2 TW occurs at the bottom of shallow and deep oceans (Lambeck 1977; Egbert and Ray 2000). This effect defies a simple treatment because of the complicated ocean bottom topography and is estimated using Earth observation satellite data and computer simulations.

Tidal Dissipation and Orbital and Rotational Evolution

Tidal dissipation will not come for free. The power that is dissipated in a planet or satellite will be taken from the rotational and orbital energies. A thorough discussion of the interactions must be based on conservation of energy and $\blacktriangleright$ [angular momentum](#) considerations and may have to include the temperatures of the interiors and the temperature dependence of the viscoelasticity (e.g., Spohn 1997). Tidal dissipation in the planet reduces its rotation rate and increases the orbital distance of the satellite and the $\blacktriangleright$ [eccentricity](#) (and potentially the inclination) of its $\blacktriangleright$ [orbit](#) (compare Fig. 1) if the planet rotates faster than the satellite orbits. Tidal dissipation in the satellite will decrease the satellite's rotation rate and reduce the rate of orbital expansion and the orbital eccentricity. This is why most major satellites are locked in a 1:1 spin-orbit coupling. But how can there be tidal dissipation in a satellite with 1:1 spin-orbit coupling? The answer lies with the orbital eccentricity. If a satellite were on a circular orbit with a 1:1 spin-orbit coupling, the tidal deformation would be a constant bulge that would point toward the planet. If the orbit is eccentric, the satellite will move toward the planet as it approaches pericenter and away from the planet as it approaches apocenter. Because of the strong dependence of the tidal disturbance potential (Eq. 1) on the distance, the tidal deformation will increase and decrease periodically. As the orbital velocity varies along the eccentric orbit with a maximum at pericenter and a minimum at apocenter, the difference between the orbital and the rotational speed will oscillate about zero as will the tidal bulge oscillate about its average orientation. The energy will have to come from the orbital energy in this case, and as a consequence of energy and angular momentum conservation, the semimajor axis and the eccentricity will decline.

Tidal dissipation is thus subject to a rule qualitatively similar to the Lenz rule of induction: The dissipation acts such that it will reduce its origin. How rapidly are eccentricities damped and rotations synchronized with orbital periods? The answer will depend largely on the viscoelastic

properties of the planet and satellite, their masses and radii, and the distance between the two. For a satellite orbiting on a circular orbit ($e = 0$), the time rate of change of the difference between the satellite's rotation angular velocity ω_S and the orbital angular velocity of the satellite n is (Peale and Canup 2015)

$$\begin{aligned} \frac{1}{(\omega_S - n)} \frac{d(\omega_S - n)}{dt} &= -\frac{15}{2} \frac{k_S}{Q_S} \frac{m_P}{m_S} \left(\frac{R_S}{a}\right)^3 n \\ &= -\frac{1}{\tau_R} \end{aligned} \quad (5)$$

where the subscript S refers to the satellite and the subscript P to the planet. The solution of Eq. 5 indicates that $(\omega_S - n)$ decays exponentially with a decay time equal to τ_R . For the satellites of Jupiter, the decay time is of the order of thousands to some 10,000 years but could be billions of years for a gaseous exoplanet orbiting a star. The damping of the eccentricity e_S of a satellite orbit follows, simplified from Peale and Canup (2015):

$$\begin{aligned} \frac{1}{e_S} \frac{de_S}{dt} &= -\frac{21}{2} \frac{k_S}{Q_S} \frac{m_P}{m_S} \left(\frac{R_S}{a}\right)^5 n \\ &= \frac{21}{15} \left(\frac{R_S}{a}\right)^2 \frac{1}{\tau_R} \end{aligned} \quad (6)$$

where again the subscript S refers to the satellite and the subscript P to the planet. In the above form, Eq. 6 should be applicable as long as the mass of the primary is much larger than the mass of the satellite. The time constant for the exponential damping of the satellite eccentricity τ_e is by a factor of roughly $(a/R_S)^2$ larger (since $R_S/a \ll 1$) than the damping of the rotation rate. For satellite-planet pairs like Io-Jupiter or Europa-Jupiter, this translates into damping times of the order of 10–100 Ma. However, in the Jupiter satellite system, the Laplace resonance between the Galilean satellites works against the decrease of the orbital eccentricities.

All major satellites in the solar system are tidally locked in a 1:1 spin-orbit resonance (also called synchronous rotation). However, the rotation rates of planets with a high orbital

eccentricity, such as that of planet [Mercury](#) with $e = 0.2$, are naturally driven to higher-order spin-orbit resonances. In the case of Mercury, the current rotation state is a 3:2 spin-orbit resonance, in which the planet turns around its spin axis three times during two orbital periods. Low-mass exoplanets with viscoelastic mantles and high orbital eccentricities might be locked in 2:1, 5:2, or even higher spin-orbit resonances, depending on the exact eccentricity, tidal frequency, interior properties, permanent deformation of the planet, and past rotational and orbital evolution (e.g., Ferraz-Mello 2015). On the other hand, hot Jupiters, or gaseous exoplanets orbiting close to their host star, might either be locked in synchronous rotation (on a circular orbit, $e = 0$), or they could undergo so-called pseudo-synchronous rotation (if $e > 0$). In this spin state, the stationary rotation is faster than the mean motion and the exact rate depends purely on the eccentricity. Again, the time required for evolving into the tidal locking strongly depends on the planet's distance from the host star. In addition to the effect of the eccentricity, the stable spin state also depends on the axial tilt of the moon or planet, with high axial tilts enabling a higher-order spin-orbit resonance even on circular orbits (Boué et al. 2016).

Tides and Planetary Habitability

Strong tidal dissipation and the resulting orbital and rotational evolution may also present a constraint on planetary habitability. A moon or a planet is considered habitable if it enables the emergence or existence of life: i.e., if it can support liquid water on the surface or in the subsurface and its environment is stable.

Tides can affect the habitability of moons and (exo-)planets in both positive and negative ways. First, the tidal heating may help to maintain subsurface liquid oceans on icy worlds or to support the formation of a secondary atmosphere on massive exoplanets (Noack et al. 2017). On the other hand, the excessive volcanic activity driven by the increased interior heating rate may transform the planet to an inferno. Second, the tidal evolution of

axial tilt and the planet's spin rate may have profound effects on the stability of the climate. A planet with aligned spin axis, orbiting close to its host star on a circular or almost circular orbit, is inevitably driven by the tidal forces to synchronous rotation (e.g., Boué et al. 2016). Once in this spin state, the planet experiences eternal day on the hemisphere facing the star, while the other hemisphere is immersed in eternal night. The continuous day-night dichotomy leads to great differences in surface temperature and atmospheric pressure, which may eventually lead to a destabilization of the climate (e.g., Kite et al. 2011). Finally, the tidally induced orbital evolution may transform a previously habitable planet to a dead world simply by driving its orbit too close to the host star and triggering a runaway greenhouse effect. In other cases, however, the decrease in the semi-major axis and the eccentricity can also enliven a previously uninhabitable planet into the circumstellar **▶ habitable zone** (Barnes et al. 2009).

All the tidal effects mentioned above are particularly relevant to potentially habitable exoplanets orbiting low-mass (M-type) stars, for which the habitable zone lies at short astero-centric distances. The influence of tides has also been discussed in connection to the habitability of moons that are, otherwise, orbiting planets at large semi-major axes outside the conventional habitable zone. If these moons are locked in mean-motion resonances (such as the Laplace resonance), they can maintain nonzero orbital eccentricities and remain tidally active – and potentially habitable – for long periods of time.

Cross-References

- ▶ **Angular Momentum**
- ▶ **Eccentricity**
- ▶ **Enceladus**
- ▶ **Europa**
- ▶ **Ganymede**
- ▶ **Habitability on Mars**
- ▶ **Habitable Zone**
- ▶ **Heat Flow, Planetary**
- ▶ **Heat Transfer, Planetary**

- ▶ **Inclination (Astronomy)**
- ▶ **Interior Structure, Planetary**
- ▶ **Io**
- ▶ **Jupiter**
- ▶ **Laplace Resonance**
- ▶ **Mercury**
- ▶ **Moon, The**
- ▶ **Orbit**
- ▶ **Phobos**
- ▶ **Planet**
- ▶ **Rheology, Planetary Interior**
- ▶ **Rotation Planet**
- ▶ **Satellite or Moon**
- ▶ **Solar System**
- ▶ **Sun (and Young Sun)**
- ▶ **TRAPPIST-1 System**
- ▶ **Viscosity**

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Time Series

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

A time series is a sequence of data points, measured at successive regular time intervals, in the case of astronomy generally over long periods of several months to several years. Time series are used in astronomy to record position or brightness of celestial objects in order to detect, for example, motion or periodicity. For instance, planetary transits can be detected by analyzing time series of stellar brightness measurements and looking for tiny periodic dips in the signal.

Tirez Lagoon System

Felipe Gómez

Centro de Astrobiología (CSIC-INTA), Instituto de Técnica Aeroespacial, Madrid, Spain

Keywords

Earth analogues · Mars · Europa Moon

Definition

Located in Spain, Tirez Lagoon system is an ecological area composed of seven small salty lakes. These lakes are very diverse in depth but some of them have a depth of 20 meters. This area is located at a distance of 110 km from Madrid (central Spain). The thermal range varies between $-0,4^{\circ}\text{C}$ and $25,8^{\circ}\text{C}$. The site is located near the town of Villacañas. The most representative lagoon in the system is Tirez Lake. It is a dry surface composed by NaCl which is a chloride salt. Analyzing the salts deposits in Tirez Lake would help constraining the phase development of the liquid chemical composition and the crystallization of various chloride salts. This lake has also a biodiversity (e.g., halophilic bacteria) which tolerates the extreme environment of the lake.

Overview

The astrobiological interest of Tirez systems is due to the fact that aqueous minerals and evaporites have been widely detected on the surface of Mars and are a major evidence of the past presence of liquid water on the Martian surface. At the same time, Tirez system is a well-studied Earth analogue for the Jupiter's moon Europa (Prieto-Ballesteros et al. 2003). They offer a paleo-environmental record of their geological formation and chemical conditions, as well as subsequent modification and alteration processes. The evaporite minerals (i.e., sulfates and chloride salts) have been mainly detected stratigraphically

on top of the aqueous minerals (i.e., phyllosilicates), which suggest their posterior formation. As both these mineral groups require liquid water for their formation, and that each group is a result of different chemical conditions, this stratigraphic relation points to a major change of surface chemical environment. Moreover, it reveals various liquid water activities on the surface of Mars occurring in repetitive and probably episodic phases.

Phyllosilicates have been hypothesized as a major element in the chemical evolution resulting in the origin of life on Earth, because of their ability to concentrate and catalyze complex organic molecules, and thus to protect against UV radiation they have a preservation capacity. Therefore, the phyllosilicate-bearing deposits on Mars have been investigated as a potential target for the investigation of past habitable sites. Evaporites, on the other hand, can also preserve traces of life, e.g., salt crystals which can preserve amino acids for a few million year and biosignatures found in sedimentary evaporitic layers (e.g., in dry Rio Tinto). Analogue studies in the Atacama desert show that even highly saline environments may offer temporary habitable conditions to certain types of bacteria.

Evaporite deposits represent significant sinks of mobile cations (e.g., Ca, N, Mg, and Fe) and anions (e.g., those of C, N, S, and Cl) which are partly composing the Martian surface and upper crust. The salt-rich deposits appear to be the product of last-stage water activities on the Martian surface, as it is suggested by their undegraded, uneroded, and unaltered appearance. Hence, where phyllosilicate-rich materials are covered and preserved by evaporites, it may be a prime location for search for traces of life on Mars, and in situ rover measurements. In addition, understanding the formation mechanism, conditions, and timeframe of evaporites would highly increase our knowledge about the past geological events of Mars, and would constrain the history of surface liquid water.

The microbial biodiversity of Tirez athalassohaline (saline aquatic environment with ionic proportions quite different from the dissolved salts in seawater) environments has been studied (Montoya et al. 2013). Microbial

populations present in the water column and the sediments reported the presence of algae and *Cyanobacteria* as the main photosynthetic primary producers identified in this natural environment in the rainy season. Others microbes were identified in the high salt concentrated solutions as dinoflagelates and filamentous fungi. The most abundant phylotype in water and sediments were *Proteobacteria*, mainly *Gamma*- and *Alphaproteobacteria* classes. *Firmicutes* and *Actinobacteria* were isolated from Tirez brines and sediment samples. Halophilic sulfate reducing *Deltaproteobacteria* were also detected (*Desulfohalobium*) (Montoya et al. 2013).

This system is the appropriated environment for the following research:

- (1) To investigate various evaporite minerals precipitation mechanism and their environment in a comparable analogue site to the Martian conditions. This helps us to understand the chemical environment needed for precipitation of each mineral.

In addition to the chemical composition of the brine liquid water, further investigation of the evaporite samples in the lab would allow us to compare the remotely sensed spectroscopical data from the surface of Mars with our in situ measurements, and therefore better interpreting those data.

- (2) To analyze the paleo-evaporitic deposits and their chemical exchange, alteration and preservation conditions. Understanding how the paleo-evaporite deposits have been altered or preserved would hint to whether this material could have hosted a local habitable environment, even though for a short time.
- (3) Stratigraphical relation within a deposit, and its comparison with Mars to understand whether different atmospheric condition and volatile would affect the sequence of minerals precipitation.
- (4) Comparing alkaline and acidic environments with the goal of identifying which condition is more likely to have formed on the Martian surface during the evaporites formation.
- (5) To assess the impact of a hyper saline and hyper arid area on the preservation of the past life forms.

Cross-References

- [Extreme Environment](#)
- [Rio Tinto](#)
- [pH](#)

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Titan

Athena Coustenis¹ and François Raulin²

¹Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, Meudon Cedex, France

²LISA – UMR CNRS/IPSL, Faculté des Sciences et Technologie, Université Paris Est-Créteil & Denis Diderot, Créteil, France

Keywords

Titan · Cassini-Huygens · Titan's atmosphere · Titan's surface · Titan's astrobiology · extraterrestrial organic chemistry · liquid surface

Synonyms

[Titan as an Earth analog](#); [Titan bioastronomy](#); [Titan exobiology](#); [Titan organic chemistry](#)

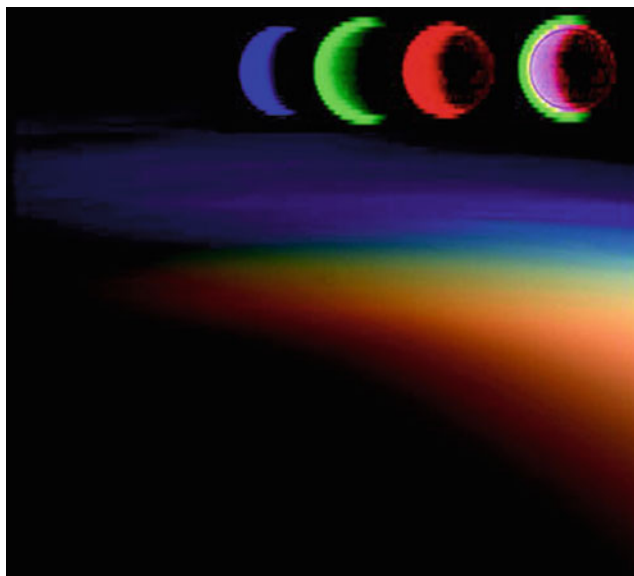
Definition

Titan, Saturn's moon, is the second largest and only satellite of the solar system having a dense atmosphere composed essentially of dinitrogen (~97%) and methane (~2%). These two molecules give rise to a host of organic compounds, rendering Titan one of the most astrobiologically interesting bodies. In addition, Titan is subject to the effects of seasons and meteorology, shaping the geomorphology of the surface, with unique hydrocarbon liquid bodies and other terrestrial-like features (dunes, channels, mountains). With these properties and the probable existence of an internal liquid water ocean, Titan is a very promising Earth analog which can inform us about the emergence and evolution of life.

Introduction

Astrobiology, the study of life in the universe, is not only the study of the origins, distribution, and evolution of life in the whole universe but also that of structures and processes related to life and the study of the destiny of life. It thus includes the question of the origins of life on Earth and elsewhere, as well as the search for extraterrestrial life, but also the search for organic compounds and the study of organic chemistry and in particular prebiotic-like chemistry in extraterrestrial environments. It is generally considered that life arose on Earth from a long chemical evolution, implying three main ingredients: liquid water, carbonaceous matter, and energy. Extraterrestrial bodies where these ingredients are or have been present are thus of astrobiological interest. They can be classified into two main categories.

There are planetary bodies where (extinct or extant) life may be present and there are bodies where a complex organic chemistry is taking place. Titan falls in the second category and is unique in the Solar System with its extensive atmosphere made mostly of N₂ (~97% in mixing ratio), with a column density 10 times that of Earth's (Fig. 1), and possessing a rich organic



Titan, Fig. 1 Titan's atmosphere – an active place where methane molecules are being broken apart by solar ultraviolet light and the by-products combine to form complex organic compounds. Titan's upper atmosphere observed with the Cassini spacecraft wide-angle camera using red, green, and blue spectral filters which were combined to create this natural color view. The images were obtained at a distance of approximately 9,500 km from Titan on March 31, 2005. The image scale is approximately 400 m per pixel. The haze preferentially scatters blue and ultraviolet wavelengths of light, making its complex layered structure more easily visible at the shorter wavelengths used in this image. (Credit: NASA/JPL/Space Science Institute.). Upper right insert: The glow of Titan's extensive atmosphere shines in false colors in this view acquired by the Cassini VIMS during the July 2, 2004, flyby. While flying over the terminator, where Titan's day and night meet, both the dayside and nightsides are seen at various wavelengths. In these views of the crescent moon, the sunlit side is on the left and the nightside on the right. The blue image shows the sunlit crescent as observed at a wavelength that pierces

through the thick atmosphere to show only the surface. This image is much smaller than the other three images to the right, because it does not show any atmospheric affects. In contrast, the green image (taken at $3.3\ \mu\text{m}$) shows the immense size of Titan's atmosphere manifested in the fluorescent glow of methane gas, which extends over 700 km above the surface. The red image shows that Titan also glows at night, the moon glowing out to more than 200 km in altitude, indicating carbon monoxide emission at the $4.7\ \mu\text{m}$ produced in Titan's relatively warm stratosphere. The multicolor image on the far right combines the three previous images into one composite. Here it is seen that the carbon monoxide glow extends over the dayside as well, producing the yellow layer observed on the left. This is because the two glows, one from methane (green) and carbon monoxide (red), mix together to form yellow in this multicolor composite. Titan's surface is indicated by the circle. Titan's surface appears purple due to the mixing of the blue and red surface images. (Courtesy: NASA/JPL/University of Arizona)

chemistry thanks to the second most abundant constituent, methane (about 1.4% in the stratosphere, 5% on the surface).

Discovered in 1655 by Christiaan Huygens, Titan is the largest satellite of Saturn and the second in the solar system by the size of its solid body (5150 km in diameter). The period of rotation of Titan around the Sun is that of Saturn, 29.5 years. Titan, like Saturn, with an obliquity of 27° , has seasons, each of which lasts

more than 7 terrestrial years. Moreover, Titan revolves around Saturn within 16 Earth-days, with an almost synchronous rotation. Thus Titan's solid surface rotates very slowly. However, due to strong zonal winds (Bird et al. 2005; Lorenz et al. 2008a), Titan's atmosphere presents a super-rotation. Titan's mean distance to the Sun is that of Saturn – about 9.5 astronomical units (AU). This corresponds to a received solar flux at the top of its atmosphere just

slightly higher than 1% of the flux at the Earth. In addition, Titan is far enough from the giant planet (about 20 saturnian radii) to avoid interactions with the rings. However, Titan is close enough to Saturn to allow its atmosphere to interact with the electrons of the magnetosphere of Saturn. This plays a key role, together with the solar photons, in Titan's chemical evolution.

As said above, Titan's atmosphere is mainly composed of dinitrogen and methane. Their dissociation and further chemical evolution, produces a whole host of organic molecules (hydrocarbons like ethane, acetylene, and propane, and nitriles like hydrogen cyanide, acetonitrile, cyanoacetylene, etc.), some of which are of prebiotic interest (like HCN). On the surface, morphological features very similar to the Earth's can be found but made of different materials than on our own planet. With an environment very rich in organics, Titan, along with comets, is thus often considered as one of the best targets to search for prebiotic chemistry at a full planetary scale and is even considered as a possible habitat for extraterrestrial life. More importantly, our understanding of the origin of life on Earth could greatly benefit from studying Titan, where the low solar influx, the composition of the atmosphere, and the possible presence of an internal water ocean, give us the opportunity to study on a planetary scale the conditions prevailing in a primitive Earth.

After 6 years of close observations by remote sensing and in situ instruments on board the Cassini-Huygens mission (see entry "[► Cassini-Huygens Space Mission](#)"), Titan does not appear anymore solely like a frozen primitive Earth, but like an evolving planet, geologically active, with cryovolcanism, aeolian erosion, clouds and precipitations, and a methane cycle very similar to the water cycle on Earth (Coustenis and Taylor 2008; Lorenz and Mitton 2008; Brown et al. 2010; Lebreton et al. 2008; Raulin et al. 2008; and the papers in Nature, 2005). The organic chemistry is found on Titan all the way from the upper atmosphere to the surface and possibly the interior, indicating close exchanges between the different elements.

Cassini and Huygens observations have confirmed the structure of the low atmosphere,

determined by Voyager, provided more precise vertical profiles in stratosphere and troposphere, and obtained information in the higher atmospheric zones. The equatorial surface temperature and pressure measured by HASI (Fulchignoni et al. 2005) are respectively 93.65 ± 0.25 K and 1.467 ± 1 hPa. Due to its low surface temperature, Titan's atmosphere near the surface is about 4.5 times denser than the Earth. Moreover, surface temperatures measurements by the Composite Infrared Spectrometer (CIRS, Jennings et al. 2009) show temperatures 3 or 4 degrees lower at the poles relative to that at the equator, where Huygens landed.

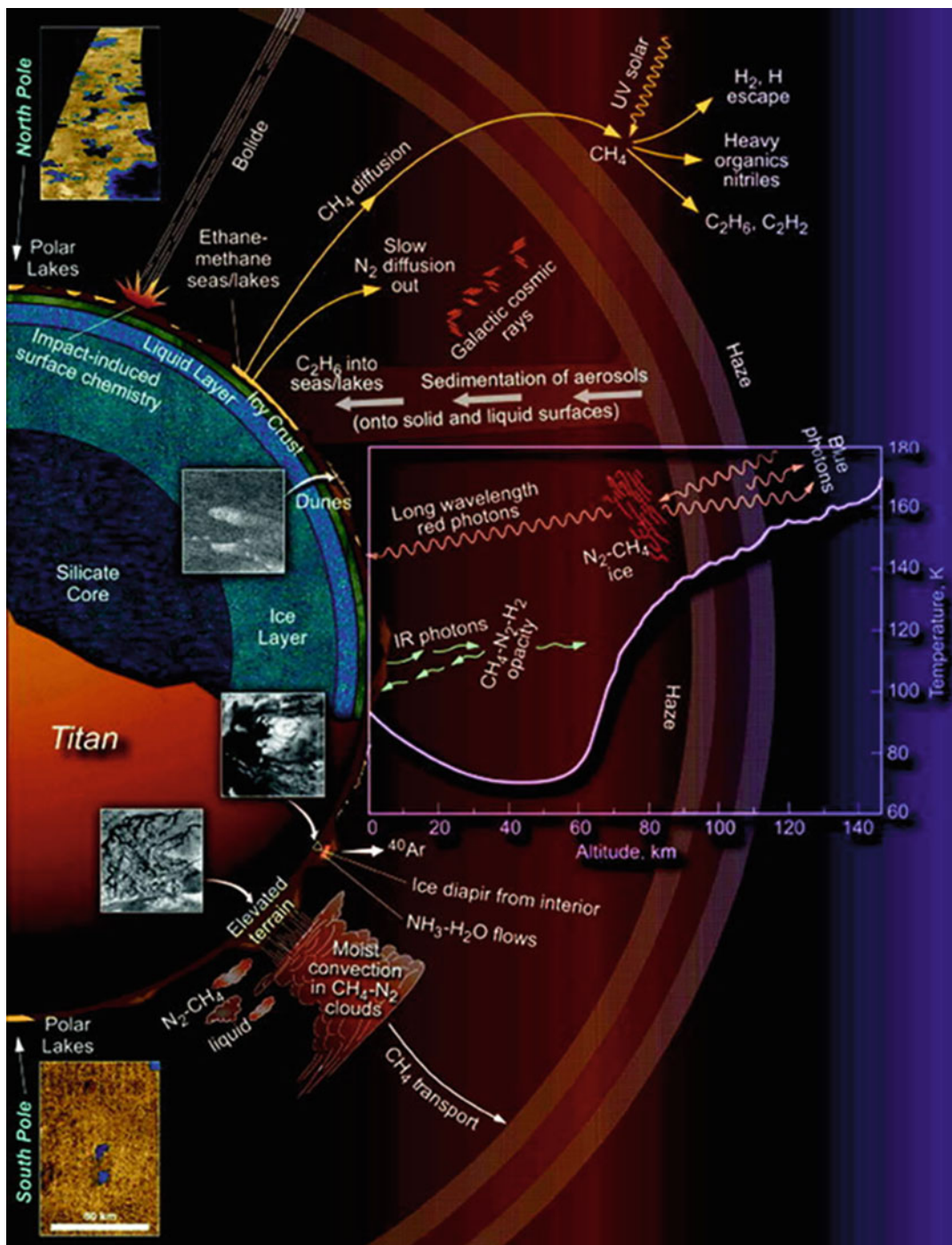
Another discovery of tremendous importance for astrobiology by the Cassini-Huygens mission are the large plumes ejected from Enceladus (see entry "[► Enceladus](#)"), mainly made of water vapor and ice and which include organic compounds (Dougherty et al. 2009; McKay et al. 2014). This strongly suggests the potential presence of a complex organic chemistry going in the interior of this small satellite, in the presence of liquid water.

What is the level of complexity which has been reached by the organic chemistry in Titan and Enceladus? What are the habitability potentialities in the Kronian environment, in particular for Titan? Such are the questions that further exploration of Titan (and Enceladus) will need to answer in the future (Brown et al. 2009).

An Astrobiological Environment

Retracing the processes which allowed for the emergence of life on Earth around 4 billion years ago is a difficult challenge. Our planet has drastically evolved since that time and most of the traces of what were the environmental conditions at that time have been erased. It is thus crucial for astrobiologists to find extraterrestrial locales with similarities to our planet. This will provide a way to study some of the processes which occurred on the primitive Earth, when prebiotic chemistry was active, in the present time.

Titan is an indeed a very complex world much as our own planet (Fig. 2). It is the only one we



Titan, Fig. 2 Schematic illustration of the connections between Titan's interior, surface, atmosphere, and cosmic environment. Images show lakes at north and south poles, mid-latitude terrains with dunes, and fluvial features

carved in the ice crust. Based on data from Cassini VIMS, Radar and Huygens DISR. (Features not presented to scale.) (From Reh et al. (2009))

know of today, beyond our own planet, not only to possess a thick nitrogen-based atmosphere but also a geologically complex active surface including lakes with organic deposits (Raulin 2008) and quite likely a subsurface ocean (Lorenz et al. 2008b; Béghin et al. 2009). The physical processes within this world beg for further close-up investigation in order to better understand the processes also on Earth. The Cassini-Huygens mission has indeed revealed the essential details of the organic and methane hydrologic cycles that we see today on Titan (Brown et al. 2009; Lebreton et al. 2008; Raulin et al. 2008).

Titan's Atmosphere and Surface Hosting a Complex Prebiotic Chemistry

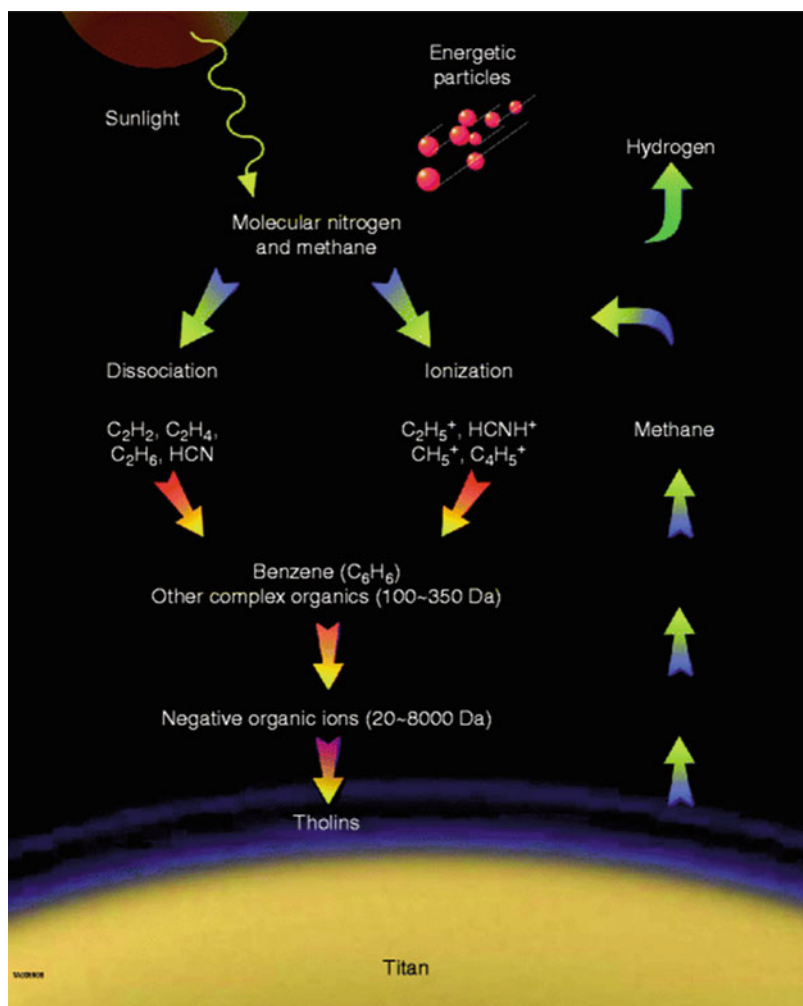
As first shown from ground-based, Voyager and Infrared Space Observatory (ISO) observations, Titan's atmosphere is a chemical factory initiating the formation of complex positive and negative ions in the high thermosphere as a consequence of magnetospheric-ionospheric-atmospheric interactions involving solar EUV, UV radiation, energetic ions, and electrons. In the neutral atmosphere, CH_4 chemistry is coupled with N_2 chemistry producing the formation of many organics in gas and particulate phase: hydrocarbons, nitriles and complex refractory organics. Several photochemical models describing the chemical and physical pathways involved in the chemical evolution of the atmosphere of Titan and estimating the resulting vertical concentration profiles of the different involved molecules have been published for the last 30 years. Based on these models, the cycling of volatile chemicals starts with the dissociation of N_2 and CH_4 through electron, photon impacts, and cosmic rays deeper in Titan's atmosphere. The primary processes allow the formation of C_2H_2 and HCN in the high atmosphere (Figs. 2, 3). These molecules play a key role in the general chemical scheme; once they are formed, they diffuse down to the lower levels where they allow the formation of higher hydrocarbons and nitriles. Additional CH_4 dissociation probably also occurs in the low stratosphere through photocatalytic processes

involving C_2H_2 and polyynes. The end products of the chemical evolution of the methane in the atmosphere are complex refractory organic compounds and ethane (Raulin et al. 2012).

The origin of Titan's atmosphere as such is still a mystery in many aspects; both the Cassini INMS and the Huygens GCMS measured argon in the atmosphere, with the latter obtaining values for both primordial ^{36}Ar and radiogenic ^{40}Ar (Fig. 8). The low value of the former relative to atmospheric N_2 is indirect evidence that Titan acquired its nitrogen originally in the form of ammonia, while the presence of the latter suggests Titan has experienced substantial outgassing over its history (Niemann et al. 2005, 2010). Neon has been tentatively identified by Huygens GCMS, but krypton and xenon have not yet been detected on Titan (Niemann et al. 2010). The presence or absence of krypton and xenon is crucial to constraining the origin of methane as either a primordial gas or one manufactured from carbon dioxide deep in Titan's interior (Atreya et al. 2006). The latter question is not solved today.

The direct analysis of the ionosphere by the Ion and Neutral Mass Spectrometer (INSM) instrument during the low altitude Cassini flybys of Titan shows the presence of many organic species at detectable levels, in spite of the very high altitude (1100–1300 km). Extrapolation of the INMS measurements (limited to mass up to 100 Daltons) and of CAPS data strongly suggests that high molecular weight species (up to several 1000 Daltons) may be present in the ionosphere (Waite et al. 2007). These observations open a fully new vision of the organic processes occurring in Titan's atmosphere, with a strong implication of the ionospheric chemistry in the formation of complex organic compounds in Titan's environment (Fig. 2), which was not envisaged before. These compounds are detectable in solar and stellar UV occultations and initiate the process of haze formation (Waite et al. 2007) to finally condense out starting at ~950 km (Fig. 3). As the haze particles fall through the atmosphere and grow, they become detectable with imaging systems such as the Cassini/Imaging SubSystem (ISS) at ~500 km altitude and are ubiquitous throughout the stratosphere (Porco et al. 2005).

Titan, Fig. 3 The process of tholin formation in Titan's upper atmosphere (Waite et al. 2007). (Credit: H. Waite/Southwest Research Institute)



They are strong absorbers of solar UV and visible radiation and play a fundamental role in heating Titan's stratosphere and driving wind systems in the middle atmosphere, much as ozone does in the Earth's middle atmosphere.

Experiments that simulate the reactions taking place in Titan's atmosphere produce refractory organics, usually named tholins. Tholins represent laboratory analogues of Titan's aerosols and are useful to interpret many observational data which require information on the aerosols. As laboratory analogues of Titan's atmospheric particles, they also allow the study of the aerosols behavior in Titan's condition with the tools available in the laboratory (see for instance, Cable et al. 2012). Several organic compounds

have already been detected in Titan's stratosphere (Waite et al. 2007; Coustenis et al. 2010). The list includes hydrocarbons (both with saturated and unsaturated chains) and nitrogen-containing organic compounds, exclusively nitriles, as expected from laboratory simulation experiments. Since the Cassini arrival in the Saturn system, the presence of water vapor and benzene has been unambiguously confirmed by the CIRS instrument.

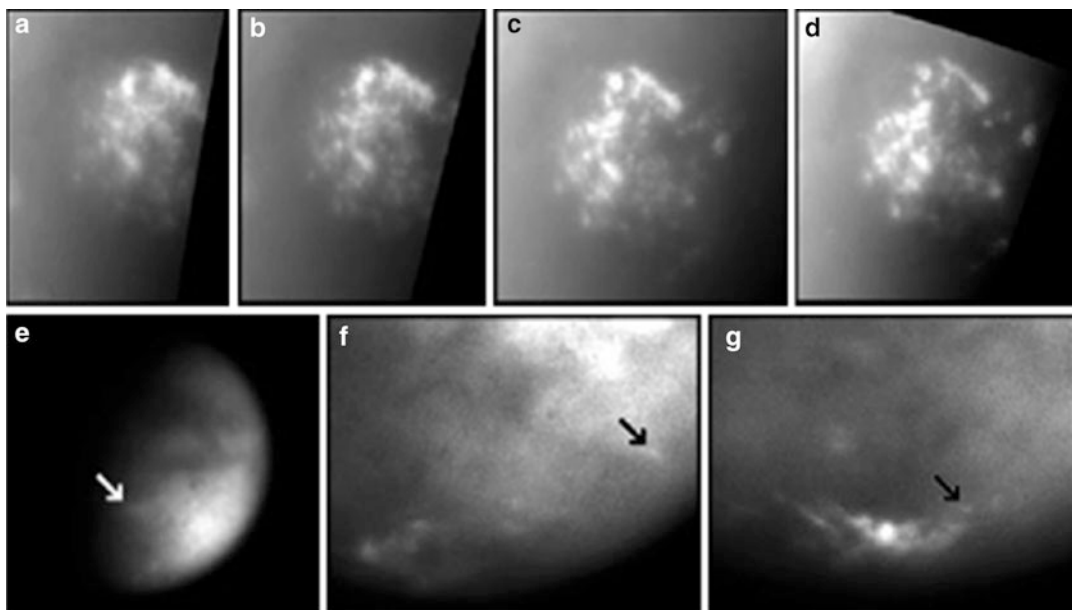
On Titan, methane can exist as a gas, liquid, and solid. Methane is dissociated irreversibly to produce a host of various gases such as hydrocarbons (e.g., C_2H_6 and C_2H_2) and nitriles (e.g., HCN and HC_3N), from the coupled nitrogen chemistry, that are detected in the stratosphere

(between 70 and 500 km in altitude) by CIRS for instance (Coustenis et al. 2010). Playing a role similar to that of water on the Earth, methane is cycled between the atmosphere, surface, and the interior. Cloud systems, the size of terrestrial hurricanes (~up to 1000 km across), appear occasionally, while smaller transient systems form on a daily basis (Porco et al. 2005). The smaller clouds dissipate quickly suggesting the presence of precipitation, carving out the fluvial features that cover much of the equatorial landscape and are common also in the vicinity of lakes seen in the northern polar regions (Lorenz et al. 2008b). Titan's atmospheric methane may be supplemented by high latitude lakes and seas of methane and ethane, which over time cycle methane back into the atmosphere where it rains out, creating fluvial erosion over a wide range of latitudes, as suggested by the many observed clouds (Fig. 4).

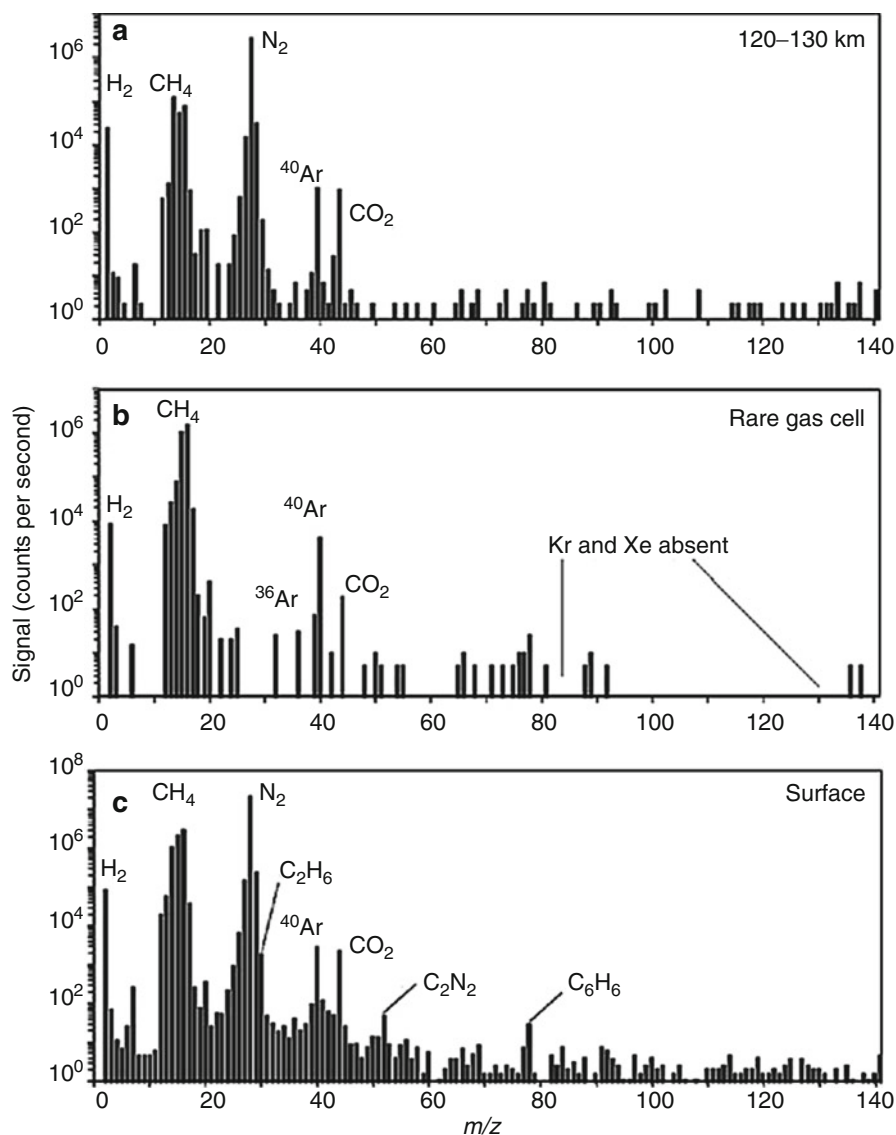
Eventually, these complex organic molecules are deposited on Titan's surface in large quantities, where data from instruments on board Cassini and Huygens hint at their existence. Hence the upper thermosphere is linked

intimately with the surface and the intervening atmosphere. In spite of the low surface temperature, the organics reaching the surface are probably evolving once in contact with water ice and may form organic molecules of biological interest.

Surprisingly, the Huygens Gas Chromatograph Mass Spectrometer (GCMS) on board Huygens has not detected a large variety of organic compounds in the low atmosphere. The mass spectra collected during the descent show that the medium and low stratosphere and the troposphere are poor in volatile organic species, with the exception of methane (Niemann et al. 2005, 2010, Fig. 5). Condensation of these species on the aerosol particles is a probable explanation for these atmospheric characteristics. These particles, for which no direct data on the chemical composition were available before, have been analyzed by the Aerosol Collector Pyrolyzer (ACP) instrument. ACP results show that the aerosol particles are made of refractory organics which release HCN and NH_3 during pyrolysis (Israël et al. 2005). This supports the tholin hypothesis (Coll et al. 2013). It supposes that the



Titan, Fig. 4 Titan clouds as observed with the Cassini cameras (Porco et al. 2005). (Credit: NASA/JPL/Space Science Institute)



Titan, Fig. 5 Mass spectra from Huygens/GCMS at various altitudes (Niemann et al. 2005). These sample-averaged spectra show the ion count rates per second as a function of unit charge (m/z), either at 120–130 km (upper panel) or at 75–77 km in the rare gas cell (middle panel) or at the surface (bottom panel). In the latter case, a surge of methane and ethane was detected shortly after the probe

impact, indicating an evaporation of volatiles from the surface that was being heated by the probe itself. Furthermore, the very presence of Argon may indicate some geological activity on Titan that would transport Ar from the interior through liquid then solids layers, another clue toward the explanation of the methane replenishment in the atmosphere

complex organics made of C, H and N, atoms, formed when simulating Titan's atmosphere chemistry, and called Titan's tholins, are analogues of the material constituting Titan's aerosols. From these new and first in situ measurement data, it seems very likely that the aerosol particles

are made of a refractory organic nucleus, covered with condensed volatile compounds.

However, the nature and abundances of the condensates have not been measured. Even more important for astrobiology, neither the elemental composition nor the molecular structure of the

refractory part of the aerosols has been determined. The potential chirality of its complex organic part is unknown.

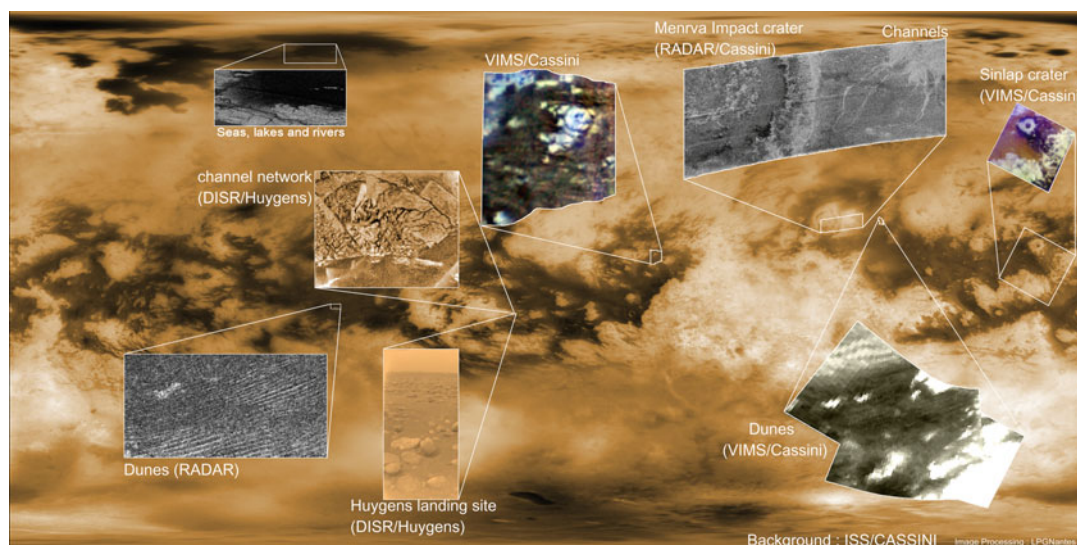
Since 2004, the Cassini-Huygens mission has been providing essential information on Titan. The Cassini orbiter offers global-scale mapping of Titan at moderate spatial resolution (hundreds of meters to kilometers) with potential temporal and spatial variations. The Huygens probe provides very detailed information of one particular location of Titan. The Cassini mission ended in September 2017 with the plunge of the spacecraft into Saturn, after several orbits between the planet and the rings which provided a whole new set of data so that the analysis of the Cassini observations will continue for many years. Those already exploited have revealed a new vision of Titan. The first images of Titan taken by the Cassini instruments have shown a very diversified surface (Fig. 6), with bright and darks zones, and terrains of various morphologies (Porco et al. 2005; Elachi et al. 2005; McCord et al. 2009; Lunine et al. 2008). At higher resolution fluvial, lacustrine, and aeolian processes appear to have shaped the surface as they have on our own planet.

Radar-bright channels (probably methane-wet riverbeds strewn with water ice cobbles like what

was seen at the Huygens landing site) have been observed at low and mid-latitudes, while channels incised to depths of several hundred meters are seen elsewhere, and at high latitudes radar-dark, meandering channels are seen that suggest a lower-energy environment where deposition of fine-grained sediment occurs (Soderblom et al. 2007a; Lorenz et al. 2008b). Radar and near-infrared imagery has revealed channels on much larger scales than those seen by Huygens (Soderblom et al. 2007b; Lorenz et al. 2008b).

Furthermore, since July 2006, we have proof of the existence of exposed open liquid bodies (hydrocarbon lakes or seas) near Titan's north pole (Stofan et al. 2007). Other small lakes exist more to the South, like the Ontario Lacus. The Cassini data have allowed a detailed description of these lakes and their properties, including their main composition –methane and ethane – and surprising transient features (Hofgartner et al. 2016; Le Gall et al. 2016; Hayes et al. 2017; Mastrogiuseppe et al. 2018).

The liquid bodies are one of the main astrobiological aspects of Titan. Cassini's cameras (ISS) have allowed scientists to compile a nearly global surface map and to monitor the surface and atmosphere for activity. Since the detection



Titan, Fig. 6 Titan's surface as observed by Cassini-Huygens, with zooms into surface areas of particular interest, showing possible cryovolcanoes, mountain ranges,

dunes, craters, the fluvial systems, and riverbeds at the Huygens landing site and the lakes in the North. (Credit: NASA/ESA/JPL/LPGN/CICLOPS)

of hydrocarbon lakes similar to those later detected at Titan's North Pole. Intriguingly, repeated south-polar imaging by ISS revealed differences consistent with ponding of hydrocarbon liquids on the surface due to precipitation from a large storm. ISS images of high northern latitudes illustrate the full extents ($>500,000 \text{ km}^2$) of hydrocarbon seas, also observed by Cassini's RADAR. These observations demonstrate dynamic processes at work on Titan and indicate that the poles harbor liquid-hydrocarbon reservoirs, the extents of which differ from pole to pole and which may be coupled to seasonally varying circulation (Turtle et al. 2009).

Other astrobiological aspects are related to the presence of a complex organic chemistry in the environments of the satellite and the question of potential habitability. We also need to consider the addition of water and oxygen ions into Titan's atmosphere from magnetospheric sources which can be traced to Enceladus' observed plumes. The oxygen will primarily be locked up in CO and CO_2 and water will freeze out. Could this water-oxygen compounds then be locked up into aerosols where they form which could be the ionosphere and/or the ionization layers at $\sim 80 \text{ km}$ where the cosmic rays deposit most of their energy.

Potential Habitat

All the ingredients which are supposed to be necessary for life to appear and even develop – liquid water, organic matter, and energy – seem present on Titan at different levels, the atmosphere, the surface, and the interior with opportunities for exchanges and interactions between them.

With the current picture of Titan's organic chemistry, the chemical evolution of the main atmospheric constituents – dinitrogen and methane – produces mainly ethane which accumulates on the surface or the near subsurface, eventually dissolved in methane-ethane lakes and seas, and complex refractory organics which accumulates on the surface, together with condensed volatile organic compounds such as HCN and benzene (Fig. 2).

Simulations of Titan's atmosphere in the laboratory indicated that complex organic chemicals (even larger than the ones found today) could be produced on Titan from reactions taking place in the upper atmosphere where scientists working with Cassini data identified the presence of carbon chain anions (Desai et al. 2017), similar to those existing in the interstellar medium, thus providing clues as to the formation and distribution of organic material throughout the universe. Furthermore, it has been shown in experimental work simulating Titan's atmosphere and without liquid water, that in the presence of energy sources, many prebiotic compounds and even five nucleotide bases, the building blocks of DNA and RNA, were formed along with amino acids, all of which elements are the building blocks of living organisms on Earth. Observations with ALMA showed the presence in Titan's atmosphere of acrylonitrile or vinyl cyanide (Palmer et al. 2017), a molecule which is involved in the formation of azotozomes proposed as membrane alternative without oxygen, at low temperature (Stevenson et al. 2015). In spite of the low temperature, contrary to what was often said, Titan is not a congealed Earth: the chemical system is not frozen. Titan is an evolving planetary body and so is its exciting chemistry.

Once sedimented on Titan's surface, the aerosols and their complex organic content may follow a chemical evolution of astrobiological interest. Laboratory experiments show that Titan tholins can release many compounds of biological interest, such as amino acids, once in contact with liquid water. This seems even possible with water ice. Those processes could be particularly favorable in zones of Titan's surface where cryovolcanism is occurring. Thus one can envision the possible presence of such compounds on Titan's surface or near subsurface. Long-term chemical evolution is impossible to study in the laboratory: in situ measurements of Titan's surface thus offer a unique opportunity to study by a ground-truth approach some of the many processes which could be involved in prebiotic chemistry, including isotopic and enantiomeric fractionation. The Huygens Descent Imager showed that the reflectance spectra of Titan's

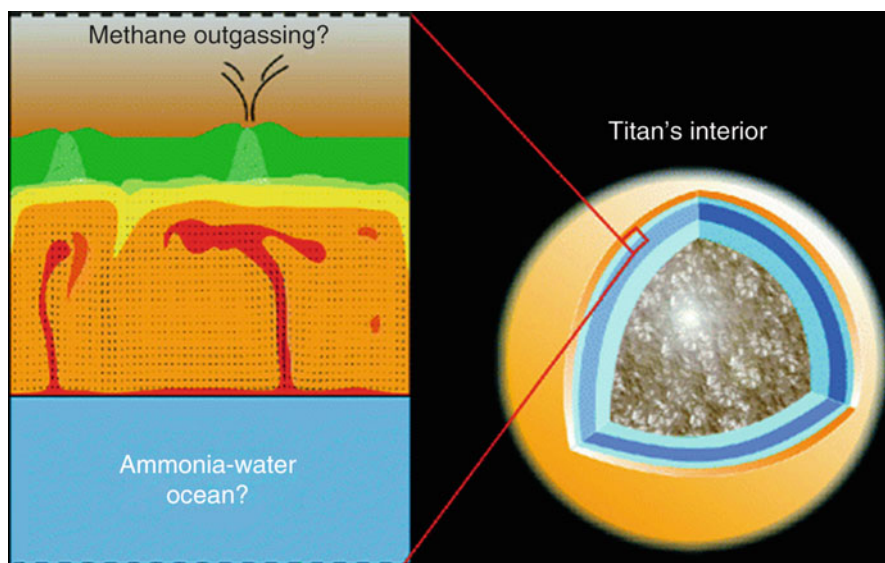
surface was different than any other surface in the solar system (Tomasko et al. 2005). Some of the characteristics of these spectra can be explained by the presence of tholins-like material on the surface. The Cassini Visual Infrared and Mapping Spectrometer (VIMS) has also identified in a global sense the surface properties of Titan with tholins, color properties, as means of categorizing the various surface properties. The source of these inhomogeneities is currently unknown.

However, besides the well-know earth-like life, other forms of living organisms have been speculated to exist in Titan's lakes. McKay and Smith (2005) suggested that some of the methane currently present in Titan's atmosphere could be coming from methanogens, or methane-producing microbes. The microbes would breathe hydrogen rather than oxygen, and eat organic molecules drifting down from the upper atmosphere that they would then metabolize with acetylene instead of glucose, and exhale it in the form of methane instead of carbon dioxide. McKay et al. considered three available substances: acetylene, ethane, as well as tholins, with acetylene, yielding six times as much energy per mole as either ethane or tholins, being the most probable provider. In agreement with this theory, Darrell Strobel found in 2010 larger amounts of molecular hydrogen in the upper atmosphere of Titan as compared to the lower parts, suggesting that the disappearance of hydrogen near Titan's surface could be due to methanogenic life forms if present. Similarly to hydrogen, acetylene was observed to have lower abundance on Titan's surface, again consistent with the hypothesis of organisms consuming hydrocarbons. However, other possible explanations for the decrease of hydrogen and acetylene near the surface exist in possible physical or chemical processes such as a surface catalyst accepting hydrocarbons or hydrogen that remains to be identified or possibly errors in the observations and the models (in particular for the material flow). Stevenson et al. (2015) proposed a model for an "azotosome," a membrane composed of nitrogen, carbon, hydrogen, but no oxygen or phosphorus, which would be capable

of surviving in Titan's liquid methane lakes. But this is still a long way from a new exotic life form that has not yet been detected on Titan (or elsewhere).

Another possible location to look for life on Titan would be in an undersurface liquid water ocean. Indeed, if the models of internal structure are correct, Titan, as Europa, Ganymede, and Callisto, has an internal ocean of liquid water (probably mixed with some ammonia). The presence of an internal ocean is supported by internal models, spin, radar and gravity Cassini measurements (Lorenz et al. 2008b, Iess et al. 2012), and the HASI experiment on Huygens (Béghin et al. 2009), where the extremely low frequency electric signal recorded by HASI was interpreted as a Schumann resonance between the ionosphere and a modestly conducting ocean (since the ice is not conductive) roughly 50 km below the surface. Cassini's measurement of a small but significant asynchronicity in Titan's rotation is most straightforwardly interpreted as a result of decoupling the crust from the deeper interior by a liquid layer. There are now several evidences from the Cassini data confirming the presence of such an internal ocean of crucial astrobiological importance.

Thermal evolution models suggest that Titan may have an ice crust between 50 and 150 km thick, lying atop a liquid water ocean a couple of hundred kilometers deep, with some amount (a few to 30%, most likely ~5%) of ammonia dissolved in it, acting as an antifreeze (Lorenz et al. 2008a). Beneath would lie a layer of high pressure ice (Fig. 7). It has been suggested in a different model by Fortes (2000) that ammonia mixed with liquid water could exist in an undersurface ocean 200 km underneath a water-ice crust. The presence of ammonia, from which Titan's nitrogen atmosphere was presumably derived, distinguishes Titan's thermal evolution from that of Ganymede and Callisto. At the beginning of Titan's history, this hypothetical ocean may have been in direct contact with the atmosphere and with the internal bedrock, offering interesting analogies with the primitive Earth, and the potential implication of hydrothermal



Titan, Fig. 7 Titan's interior and multiple layers. (Credit: NASA/LPGN)

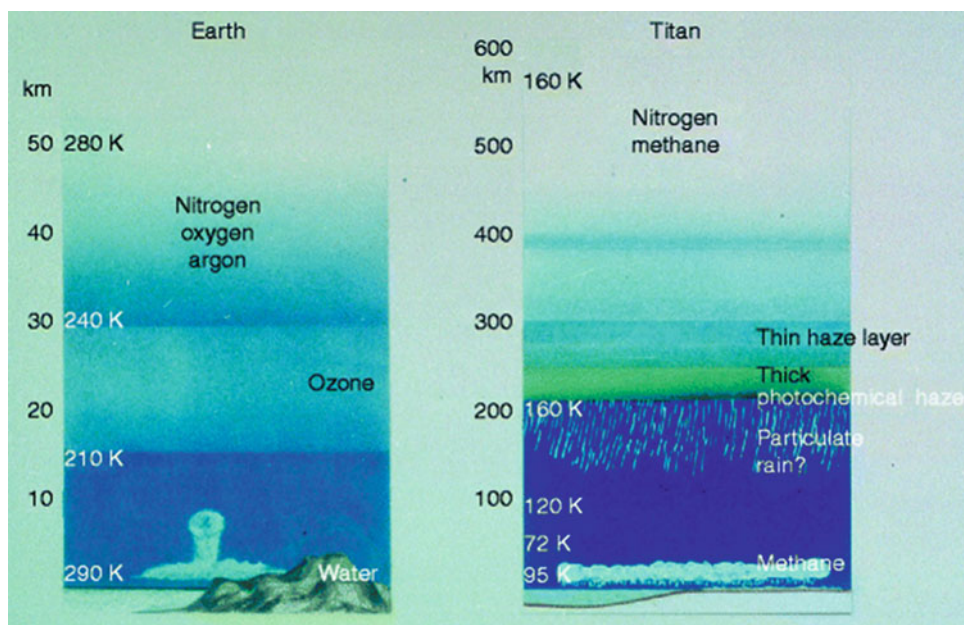
vents in terrestrial prebiotic chemistry. Titan's overall density requires it to have roughly equal proportions of rock and ice. The extent of its differentiation (ice from rock, rock from metal) constrains temperatures in the early Saturnian nebula; Titan was almost certainly warm enough to allow some differentiation – at least partially – into a rocky core with a water/ice envelope but whether an iron or iron–sulfur core formed is not known. Consequently, it cannot be excluded that life may have emerged on or in Titan. In spite of the extreme conditions in this environment, life may have been able to adapt and to persist. Even the possible current oceanic conditions (pH, temperature, pressure, salt concentrations) are not incompatible with life as we know it on Earth. Grasset et al. (2000) suggested that heat transfer between the interior and upper layers on Titan would be essential for sustaining any alien life in the subsurface oceans where biogenic effects in the atmospheric methane and nitrogen might be indicative of microbial life on Titan. However, the detection of a potential biological activity in the current internal Titan's water ocean seems very challenging with current space and ground-based exploration capabilities.

Titan and the Earth

Despite the aforementioned biological possibilities on Titan, there are substantial barriers to the formation and sustainability of life on Titan and hasty analogies with our own planet can prove erroneous. At a vast distance from the Sun, Titan is located at 10 AU at which distance, the temperature and insolation conditions are extremely low. Its atmosphere lacks consequent amounts of oxygen in any form. At the surface, water cannot exist as liquid but only as ice. As a consequence, and although Titan may well harbor a high potential for habitability, it is probably not a good analogue for current or past conditions on Earth.

Similarities with the Early Earth

The direct similarities between Titan and the Earth have been pointed out since the Voyager days: a molecular nitrogen atmosphere like the Earth's, with a surface pressure just 40% larger than that of the Earth. Titan's seasons are longer by a factor of seven than the Earth's (Fig. 8).

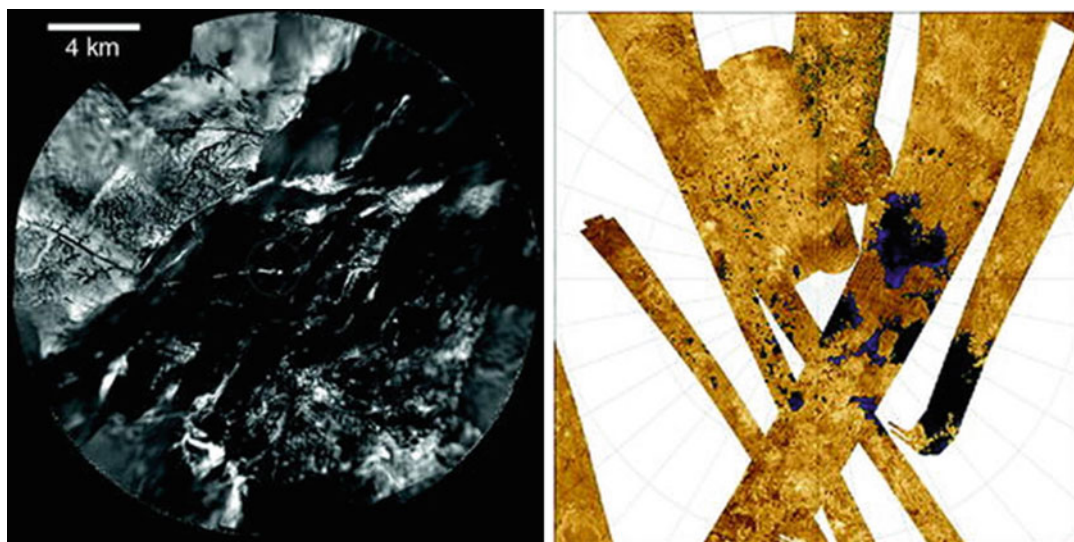


Titan, Fig. 8 Titan and the Earth: comparison of their atmosphere composition and processes. (Credit: NASA)

Although Titan is much colder than the Earth, it does present many similarities with our planet, at different levels. Titan's atmosphere is made of the same main constituent, dinitrogen, has a similar complex structure from the troposphere to the ionosphere, and a surface pressure of 1.5 bar, only case of extraterrestrial planetary atmosphere close to the Earth value. Similarities are obvious between the organic chemistry which is very active now on Titan and the prebiotic chemistry which was active on the primitive Earth. In spite of the absence of permanent bodies of liquid water on Titan's surface, both chemistries are similar. Several of the organic processes which are occurring today on Titan imply some of the organic compounds which are considered as key molecules in the terrestrial prebiotic chemistry, such as hydrogen cyanide (HCN), cyanoacetylene (HC_3N), and cyanogen (C_2N_2). In fact, with several percent of methane in dinitrogen, the atmosphere of Titan is one of the most favorable atmospheres for prebiotic synthesis. Until recently, such atmosphere composition was supposed to be far from that of the primitive Earth. However, new modelling of the hydrogen escape

in the primitive atmosphere of the Earth indicates that it may have been much richer in hydrogen and methane than previously thought.

Many analogies can also be made, as already mentioned, between the role of methane on Titan and that of water on the Earth. The greenhouse properties of both constituents and their potential condensation in the conditions of Titan for methane and the Earth for water are part of the similarities. Clouds, precipitation, liquid bodies on the surface, with lakes, seas, and river beds (Fig. 9), are some of the common features. Methane on Titan seems to play the role of water on the Earth, with a complex cycle, which presents several analogies with that of water on Earth (Atreya et al. 2006) but also many differences. It still has to be understood. Indeed on Earth, water is recycled into the interior at subduction zones (sink), and released at mid-ocean ridges and volcanoes (source), which provides the long-term cycle (one to a few hundred million years), see Fig. 2. On Titan, methane is photo-dissociated and forms ethane and other organic products in the atmosphere at similar although shorter timescales (tens of million years) which do not recycle



Titan, Fig. 9 Left: Dendritic structures on the surface of Titan as seen by the DISR instrument on Huygens in a panorama taken from 6.5 km altitude. (Credit: ESA/NASA/JPL/University of Arizona). Right: Cassini

Radar image of Titan's surface at high latitude regions, showing the presence of several large lakes. (Credit: NASA/JPL)

methane. The sink of methane on Titan is relatively well understood, but the source of methane is still very model-dependent. Cassini ISS has detected surface features near the South Pole, having the shape of large lake (Porco et al. 2005). The VIMS instrument has identified the presence of liquid ethane in Ontario Lacus confirming it is liquid (Brown et al. 2008). The Cassini radar has discovered the presence of hundreds of lakes and three large seas in the north polar regions (Stofan et al. 2007), also likely to be of liquid methane and ethane (Fig. 9).

The pictures of Titan's surface provided by the Descent Imager/Spectral Radiometer (DISR) instrument on the Huygens probe show dendritic structures (Tomasko et al. 2005) similar to fluvial networks seen on Earth (Fig. 9). Analogous but larger structures are also observed at coarser resolution on Cassini Orbiter radar images (Lorenz et al. 2008b; Burr et al. 2013 and refs included). These structures are located in relatively young terrains and produced by a recently flowing liquid. Moreover, the Huygens GC-MS (Niemann et al. 2005, 2010) has measured the atmospheric CH_4 abundance from 150 km altitude down to the surface and the data show that above the landing

site, methane reaches the saturation level at an altitude of approximately 8 km, compatible with clouds formation (Fig. 3), although they have not been observed at those latitudes. Such clouds could produce rain which could be the origin of the observed fluvial-like networks. In addition, the gas chromatography measurements after the probe has landed strongly suggest the presence of condensed methane on the landing site (Niemann et al. 2005, 2010).

Many observations of Titan's surface from the Cassini instruments show features evidently derived from diverse geological processes analogous to the terrestrial ones. There are mountains on Titan of several hundred meters high (Radebaugh et al. 2007), sign of the presence of tectonic activity, fluvial and wind-driven features (Fig. 4). A wide variety of Cassini data support the presence of cryovolcanism on Titan. Indeed, at least two regions have been observed to change reflectance on Titan's surface and one of them in RADAR images exhibits lobate "flow" forms, consistent with the morphology of volcanic terrain, supporting the hypothesis of cryovolcanic eruptions (Lopes et al. 2007, 2013). If so, then Titan is presently geologically

active on the surface (Solomonidou et al. 2016) and in its interior. However, on Titan fluid water mobilized and made buoyant by ammonia and other materials replaces terrestrial melted silicates. If Titan is currently active then the questions arise: What is the full extent of current geologic activity? What are the ongoing processes? Are Titan's chemical processes today supporting a prebiotic chemistry similar to that under which life evolved on Earth?

The surface of Titan shows also the presence of sedimentological and meteorological processes, as we see on Earth: there are many large dunes areas (Lorenz et al. 2006, Radebaugh et al. 2008), (Fig. 4) where the terrestrial silica sand is probably replaced, once more, by water ice particles, mixed with the organic material of the aerosols. There are many features that look like terrestrial dry lakebeds, as seen on the pictures of Titan's surface (Fig. 9) taken by DISR (Tomasko et al. 2005). But again on Titan, the terrestrial silica pebbles are replaced by water ice pebbles. Moreover, the lakes and seas (Fig. 9) observed on Titan in the polar regions (Stofan et al. 2007; Mitri et al. 2007) make Titan the only body in the solar system having permanent large liquid bodies on its surface. These very dark features at the high northern latitudes of Titan were finally shown to be liquid-filled (most probably with ethane rich mixtures, Brown et al. 2008) basins—"lakes." The features range in size from less than 10 km² to at least 100,000 km². They are confined to the region poleward of 55°N. To date, some 655 such features have been identified and mapped (Fig. 9).

All of this suggests that Titan maybe even more similar to the primitive Earth than we thought. However, the degree of complexity which can be reached from such an organic chemistry in absence of permanent liquid water bodies on Titan's surface is still unknown, although it could be quite high.

Titan and the Future of Our Planet

Titan is also an analogue, albeit with different working materials, of the future state of the Earth when surface conditions preclude stable equatorial/mid-latitude oceans. If we are to focus

on the Earth and its climate, as well as on its organic chemistry, we need in the future to concentrate on another object in the solar system that sustains an active hydrologic cycle with surface liquids, meteorology, and climate change. The Cassini-Huygens mission has firmly established that Titan is such a body, in which the active working fluid of the hydrologic cycle is methane. The cycle is active but different from the Earth because Titan lacks a surface methane ocean. It possesses, however, methane lakes and seas, fluvial erosion, rounded pebbles, and liquid methane in the soil at the Huygens site.

With Titan, we are observing an active hydrologic cycle subjected to seasonal, annual, and longer term changes, as on the Earth. Moreover, the future increase in the solar luminosity make it almost inevitable that eventually water on the Earth will no longer be trapped in our ocean and troposphere but will escape rapidly in a process we see today for methane on Titan. The late stages of this evolution – an Earth with liquid water in the polar regions, in the crust, but no longer in an ocean – may be echoed by the configuration we see today in Titan's methane hydrologic cycle (Fig. 2).

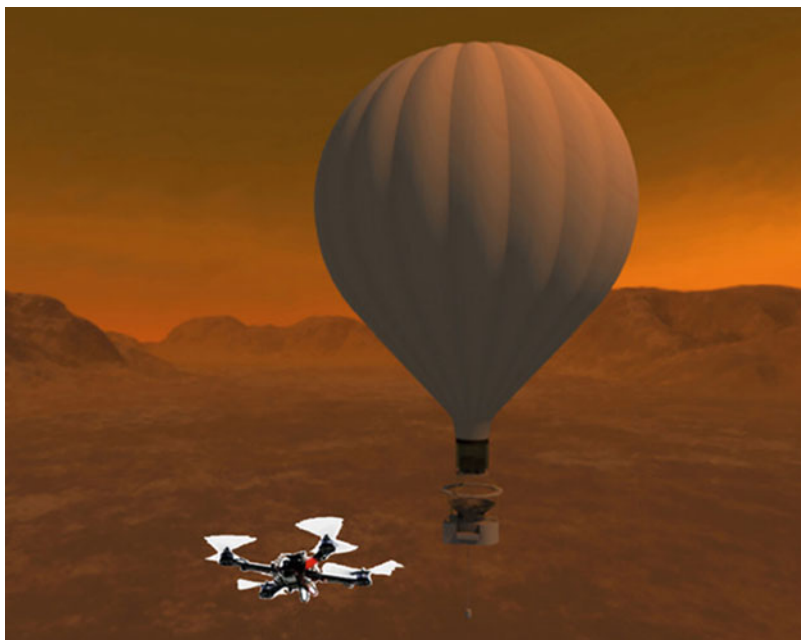
Future Directions

Lessons from Huygens will be used in the future to go back to Titan and explore in detail and in situ its surface, in many locations. This was already envisaged (Coustenis et al. 2008) with an international mission such as TSSM (Titan/Saturn System Mission). TSSM, jointly studied by NASA and ESA, planned to send a lander to explore one of the Titan's lake, and a Montgolfière to study for several months Titan's atmosphere and surface (Fig. 10). More recently, Dragonfly has been pre-selected as a New Frontier mission to explore Titan in several surface locations with a drone.

Such missions could bring some answers to important astrobiological questions with precise measurements as follows:

- What degree of complexity is achieved by Titan's organic chemistry in the different parts of the geological system?

Titan, Fig. 10 Artist's concepts for future exploration of Titan, either with several drones, like the Dragonfly mission proposed to NASA (left) or by a Montgolfière (hot-air balloon) element of a mission proposed to ESA and NASA. (From L. Matthies, NIAC 2014 Phase I Titan Aerial Daughtercraft Final Report, 2017). (Credit: NASA/STMD)



- Is Titan a habitable world? Does it have an undersurface liquid water ocean or episodic liquid water bodies on the surface?
- Is there currently, has there been or will there be biological activity on Titan?

To answer these questions, new missions dedicated to the detailed exploration of Titan are now needed, such as the Dragonfly mission to be launched, if finally selected, around 2025. Space and ground-based observations along with models and experimental work is needed for us to better understand this complex world. Although life itself may not exist there, our understanding of habitable conditions in the outer solar system and in particular of prebiotic aspects on Titan with its unique organic chemistry remain of great interest in understanding the emergence of life on our own planet and the formation of habitats.

Cross-References

- ▶ [Albedo](#)
- ▶ [Amino Acid](#)
- ▶ [Atmosphere, Structure](#)
- ▶ [Atmosphere, Organic Synthesis](#)
- ▶ [Cassini Mission](#)
- ▶ [Chromatography](#)
- ▶ [Complex Organic Molecules](#)
- ▶ [Cryovolcanism](#)
- ▶ [Cyanoacetylene](#)
- ▶ [Cyanogen](#)
- ▶ [Deuterium/Hydrogen Ratio](#)
- ▶ [Enceladus](#)
- ▶ [ESA](#)
- ▶ [Europa](#)
- ▶ [Flux, Radiative](#)
- ▶ [Gas Chromatography](#)
- ▶ [GC/MS](#)
- ▶ [Giant Planets](#)
- ▶ [Habitability on Mars](#)
- ▶ [Habitable Zone](#)
- ▶ [Habitat](#)
- ▶ [Hubble Space Telescope](#)
- ▶ [Huygens Probe](#)
- ▶ [Hydrocarbons](#)
- ▶ [Hydrogen](#)
- ▶ [Hydrogen Cyanide](#)
- ▶ [Imaging](#)
- ▶ [Abiotic](#)
- ▶ [Abundances](#)
- ▶ [Acetonitrile](#)
- ▶ [Aerosols](#)

- [Infrared Space Observatory](#)
- [Infrared Spectroscopy](#)
- [Isotopic Ratio](#)
- [JPL](#)
- [Landing Site](#)
- [Life](#)
- [Life in the Solar System \(History\)](#)
- [Magnetosphere](#)
- [Mass Spectrometry](#)
- [Methane](#)
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- [Modelling Terrestrial Planetary Atmospheres](#)
- [NASA](#)
- [Nitrile](#)
- [Nitrogen](#)
- [Noble Gases](#)
- [Organic Material Inventory](#)
- [Organic Molecule](#)
- [Origin of Life](#)
- [Photochemical Hazes](#)
- [Photochemistry, Atmospheric](#)
- [Photolysis](#)
- [Prebiotic Chemistry](#)
- [Radiative Transfer \(Atmospheres\)](#)
- [Refractory Molecule](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Spectroscopy](#)
- [Stratosphere](#)
- [Terrestrial Analog](#)
- [Tholins](#)
- [Visible](#)
- [Water](#)

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Titan as an Earth Analog

- [Titan](#)

Titan Bioastronomy

- [Titan](#)

Titan Exobiology

- [Titan](#)

Titan Organic Chemistry

- [Titan](#)

Titan's Atmosphere Module

- [Huygens Probe](#)

Titan's Atmosphere Probe

- [Huygens Probe](#)

Titania

Therese Encrenaz

LESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Definition

Titania is the fourth of the five biggest satellites of ► [Uranus](#), in terms of increasing distance to Uranus; it is the biggest in terms of mass. It was discovered by Herschel in 1787. It orbits at a distance of 436,300 km (or 17 planetary radii) from Uranus. Its diameter is 1,580 km. The part of the satellite imaged by Voyager 2 in 1981 shows a smooth surface with large canyons and faults. The longest one is Messina Chasmata with an overall length of about 1,500 km. The only large crater, Gertrude, is 326 km in diameter. Titania probably consists of a rocky core and an icy mantle; it orbits inside Uranus' ► [magnetosphere](#).

Cross-References

- [Giant Planets](#)
- [Titanium Dioxide \(TiO₂\)](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)

Titanium Dioxide

- [Titanium Dioxide \(TiO₂\)](#)

Titanium Dioxide (TiO₂)

William M. Irvine

Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Titania](#); [Titanium dioxide](#)

Definition

Titanium dioxide, TiO₂, is on Earth the naturally occurring oxide of titanium, forming minerals such as rutile, anatase, and brookite. TiO₂ molecules have recently been identified by radio astronomers in the circumstellar envelope of the evolved star VY Canis Majoris (see ► [Molecules in Space](#)). Rutile traveling-wave ► [masers](#) have been used in very sensitive receivers for ► [radio astronomy](#) (e.g., Yngvesson and Kollberg 1965).

History

The principal isotope of titanium is ⁴⁸Ti, but four other stable isotopes are known – ⁴⁶Ti, ⁴⁷Ti, ⁴⁹Ti, and ⁵⁰Ti. Titanium isotopic anomalies (differences from typical solar system values for the relative abundances of Ti isotopes; see Bernatowicz and Zinner 1997) have been found in ► [meteorites](#) and interpreted as possible evidence for the survival of pre-solar material, possibly interstellar dust grains or material from a nearby ► [supernova](#) explosion. The related molecule, titanium monoxide, ► [TiO](#), has long been known to be present in the atmospheres of some cool stars, and it has also recently been detected by radio astronomers in the circumstellar envelope of the evolved star VY Canis Majoris.

Cross-References

- [Circumstellar Chemistry](#)
- [Interstellar Dust](#)

- [Molecules in Space](#)
- [Titanium Monoxide \(TiO\)](#)

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Titanium Monoxide

- [Titanium Monoxide \(TiO\)](#)

Titanium Monoxide (TiO)

William M. Irvine

Department of Astronomy, University of
Massachusetts, Amherst, MA, USA

Synonyms

[Titanium Monoxide](#)

Definition

Titanium monoxide, TiO, has been known to be present in the atmospheres of cool stars for more than 100 years. We do not in general list or discuss molecular constituents of stellar atmospheres in this Encyclopedia; however, more recent observations show that TiO is also be present in the circumstellar envelopes of some cool stars (Kaminski et al. 2013; see ► [Molecules in Space](#)).

History

Isotopic anomalies for titanium (differences from typical solar system values for the relative

abundances of Ti isotopes) have been found in ► [meteorites](#) and interpreted as possible evidence for the survival of presolar material, possibly interstellar grains or material from a near-by ► [supernova](#) explosion.

The related molecule, titanium dioxide, ► [TiO₂](#), has been identified by radio astronomers in the circumstellar envelope of the evolved star VY Canis Majoris.

Cross-References

- [Circumstellar Chemistry](#)
- [Interstellar Dust](#)
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- [Titanium Dioxide \(TiO₂\)](#)

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Titius-Bode Law

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The Titius-Bode law is the statement that the ► [semimajor axes](#) of planetary ► [orbits](#) in the solar system follow approximately a geometric progression when going from the innermost to the outermost planets. There is no real physical explanation for this law, which stems from observation only and was first introduced by the German astronomers Johann Daniel Titius and Johann Elert Bode around 1770.

The formula for the ► [semimajor axis](#) a reads: $a = (0.4 + 0.3 \times 2^n)$ with $n = -\infty, 0, 1, 2, 3, \dots$ and a in astronomical units.

The formula is fairly correct for the planets that were known when it was proposed, and it correctly predicted the approximate orbit of objects in the asteroid belt (assumed to be a failed planet) and Uranus. However, it failed for Neptune's orbit. Note also that for Mercury $n = -\infty$ which breaks the logics of the law.

Cross-References

- [Orbit](#)
- [Semimajor Axis](#)

TMC-1 Molecular Cloud

Marcelino Agúndez
Instituto de Física Fundamental, CSIC, Madrid,
Spain

Keywords

Molecular cloud · Star formation ·
Cyanopolyne · Molecules in space

Synonyms

[Taurus Molecular Cloud 1](#)

Definition

TMC-1 (Taurus Molecular Cloud 1) is a ridge-shaped dark cloud located in the Taurus Molecular Cloud, a complex of dark clouds located at a distance of only 140 parsec, which makes it one of the nearest sites of star formation. The north-western part of TMC-1 contains an infrared source (IRAS 04381+2540), coincident with a peak in the intensity of NH₃, which suggests that it is more evolved than the south-eastern part, where there is a peak in the emission of cyanopolyynes. The cyanopolyne peak hosts a very rich chemical composition and has been a prominent source for the discovery of new molecules in space.

Overview

The Taurus Molecular Cloud is a dark nebula located in the constellation of Taurus that was discovered in 1852 by J. R. Hind. This nebula is considered to be a stellar nursery, as it contains hundreds of dense molecular cores (Qian et al. 2012), the sites of future star formation, and hundreds of newly formed stars with ages below 2×10^6 year (Kenyon and Hartmann 1995; Luhman et al. 2010). It lies at a distance of 140 parsec (Elias 1978), making it an ideal target to study star formation from the earliest stages (starless and pre-stellar cores) to the later ones (protoplanetary disks and young planetary systems).

Belonging to the Taurus Molecular cloud complex, TMC-1 stands out as a ridge-shaped dark cloud extending $5' \times 15'$ along the southeast to northwest direction. The physical conditions in TMC-1 are those of a cold, dark, dense, and molecular gas. The gas kinetic temperature is very low, around 10 K, and the volume density is a few 10^4 particles (mostly H_2 molecules) per cubic centimeter (Pratap et al. 1997). The densest regions have visual extinctions above 10 magnitudes (Fuente et al. 2019), which implies that the gas is well protected against external visible and ultraviolet radiation from nearby hot stars. Apart from the presence of the infrared source IRAS 04381+2540, located in the north-western part and thought to be a protostellar system (Apai et al. 2005), there is no sign of ongoing star formation activity, which makes TMC-1 an ideal region on which to study the earliest stages of star formation.

TMC-1 has been widely observed in molecular lines. These observations show that the south-eastern region is particularly rich in carbon chain molecules such as C_2S , C_4H , and HC_3N , while in the north-western region, NH_3 is particularly abundant. This fact has led to the identification of two prominent positions in TMC-1, called the cyanopolyne peak, located in the south-eastern part with coordinates $RA(J2000) = 4^h 41^m 41.9^s$ and $Dec(J2000) = +25^\circ 41' 27.0''$, and the ammonia peak, located in the north-western region, close to the IRAS source. The marked chemical differentiation between these two positions has

been an active subject of debate. It has been suggested that the south-eastern part, where the cyanopolyne peak resides, is physically and chemically less evolved than the north-western part, where the NH_3 peak and the infrared source are located (Hirahara et al. 1992). This explanation continues to be the most widely accepted.

The cyanopolyne peak of TMC-1 is not merely a source where carbon chain molecules are abundant, but it is one of the objects of the sky with the largest inventory of molecules detected. This fact has made this source the template on which to confront the results of the majority of chemical models of cold dark clouds (e.g., Agúndez and Wakelam 2013). In recent years, the cyanopolyne peak of TMC-1 has been the scenario of many discoveries of new molecules, with profound implications for our understanding of interstellar chemistry. Families of molecules other than carbon chains have been found to be quite abundant there. Among them, O-bearing complex organic molecules like methyl formate and dimethyl ether (Agúndez et al. 2021), moderately large hydrocarbons like vinyl and allenyl acetylene (Cernicharo et al. 2021a, b), and aromatic cycles such as benzonitrile (McGuire et al. 2018), cyanonaphthalene (McGuire et al. 2021), indene (Cernicharo et al. 2021c), and benzyne (Cernicharo et al. 2021d). The discovery of polycyclic aromatic hydrocarbons (PAHs), either pure or substituted with CN, at the cyanopolyne peak of TMC-1 is the first secure detection of PAHs in space and strongly suggests that PAHs are formed in situ in cold dark clouds through a bottom-up process starting from smaller hydrocarbons.

Cross-References

- [Cyanopolyne](#)
- [Dense Cloud](#)
- [Dense Core](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Cloud](#)
- [Interstellar Molecule](#)
- [Molecular Cloud](#)
- [Molecules in Space](#)
- [Polycyclic Aromatic Hydrocarbon](#)

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TNO

► Trans-Neptunian Object

Todd, David

William M. Irvine

University of Massachusetts, Amherst, MA, USA

History

David Peck Todd (1855–1939), Professor of Astronomy and Director of the Observatory at Amherst College (Massachusetts, USA) from 1881 to 1920, led 12 solar eclipse expeditions between 1878 and 1914 to all parts of the world; in 1882 the new Lick Observatory chose him to lead the observations of the transit of Venus. He has also been credited with “the first successful astronomical observation from an artificial platform above the Earth’s surface” by sketching Halley’s Comet from a balloon (Sagan and Druyan 1985) and with promoting the Chilean high deserts as excellent astronomical sites (Todd 1908).

He may be considered an early astrobiologist and SETI pioneer from his interest in the possibility of intelligent life on Mars. In 1907 Percival Lowell chose him to lead an expedition to South America to observe a favorable opposition of Mars, with the hope of verifying the “canals” that Lowell and others had reported and ascribed to a technical civilization. This involved dismantling and shipping to Chile Amherst’s new large refracting telescope. Although the expedition’s photographs and drawings left the origin of the Martian surface features ambiguous, Todd was sufficiently intrigued by the results and by Marconi’s recent successful transatlantic radio transmissions to propose as early as 1909 sending signals to and listening for transmissions from Mars. He did persuade the US Army and Navy to observe a period of radio silence during the 1924 opposition of Mars; although unusual

signals were reportedly received, they could not be ascribed to Martians! (Dick 1996).

Cross-References

► SETI

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Tonalite-Trondhjemite-Granodiorite

Hervé Martin¹ and Nicholas Arndt²

¹Laboratoire Magmas et Volcans, Université Clermont Auvergne, Aubière Cedex, France

²Maison des Géosciences, LGCA, Université J. Fourier, St-Martin d'Hères, France

Keywords

Archean Eon

Synonyms

TTG

Definition

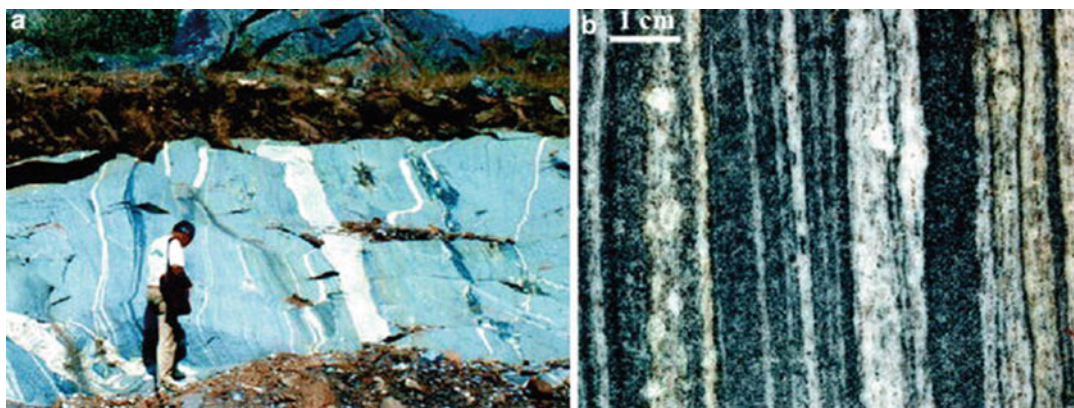
Tonalite-trondhjemite-granodiorite (or TTG suite, a term coined by Jahn et al. 1981) is an association of rocks that compose a large part of Archean continental crust. It is widely accepted that this rock suite formed by melting of hydrous

metabasalts at high pressure, yet the geodynamic setting in which this melting took place is discussed. Two main sources of melt are proposed: (1) basaltic material that was previously underplated beneath thickened crust (e.g., Smithies 2000) and (2) basaltic rocks in subducting oceanic slabs that melted in a hotter Archean mantle (e.g., Martin et al. 2005).

Overview

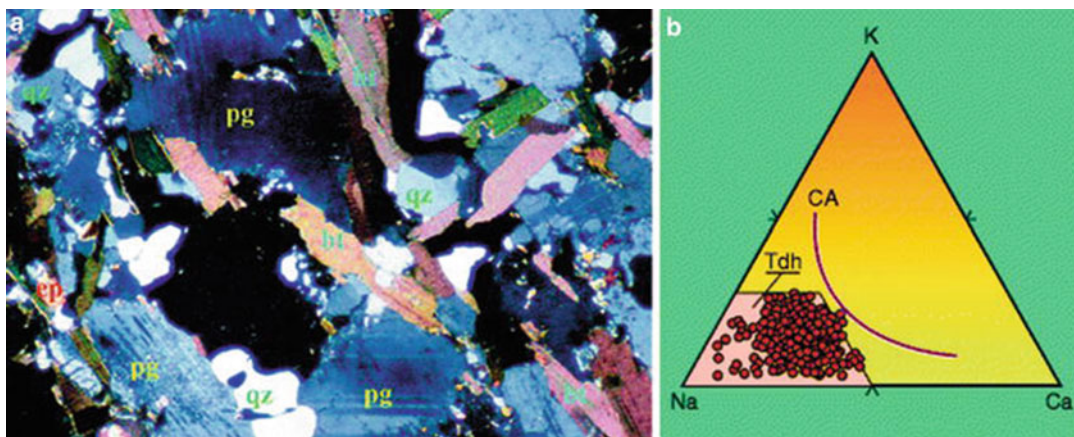
About 90% of the juvenile continental crust generated between 4.0 and 2.5 Ga belongs to the “TTG suite” (tonalite, trondhjemite, and granodiorite) (Jahn et al. 1981; Moyen and Martin 2012), although in some ► cratons (e.g., Yilgarn Craton, Australia; Champion and Sheraton 1997), high-K monzodioritic and syenogranitic rocks can also be abundant. Most of these rocks are gray orthogneisses (metamorphosed granitic rocks) displaying well-developed foliation and/or banding (Fig. 1a). Typically, the banding consists of an alternation of pale-colored quartz-plagioclase layers with darker biotite and amphibole-rich gray layers (Fig. 1b). From the mineralogical point of view, TTGs are equigranular quartz + plagioclase + biotite-bearing plutonic rocks; K-feldspar, where present, appears in subordinate proportions. The more primitive members of the suites can be hornblende rich. Accessory phases are allanite, epidote, apatite, zircon, sphene, and titanomagnetite (Fig. 2a).

TTGs are silica rich ($\text{SiO}_2 > 64$ wt.%; commonly 70 wt.% or greater) with high Na_2O contents ($3.0 \text{ wt.\%} \leq \text{Na}_2\text{O} \leq 7.0 \text{ wt.\%}$) and correspondingly low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (< 0.5). They exhibit no K-enrichment during magmatic differentiation (Fig. 2b). They are Al rich and poor in ferromagnesian elements ($\text{Fe}_2\text{O}_3^* + \text{MgO} + \text{MnO} + \text{TiO}_2 \leq 5 \text{ wt.\%}$). Their rare-earth-element (REE) patterns (Fig. 3a) show that they are La-rich and Yb-poor, resulting in strongly fractionated patterns (high La/Yb, up to 150), when compared with the present-day juvenile continental crust that has high Yb contents and poorly fractionated patterns (low La/Yb; Fig. 3b). These features are interpreted as reflecting the presence of garnet and amphibole and



Tonalite-Trondhjemite-Granodiorite, Fig. 1 (a) 3.3-Ga-old Gurur TTG gneiss (Karnataka, India). (b) Detail of the 3.6-Ga-old Ancient Gneiss Complex (Swaziland).

(Both photographs show the characteristic gray color of TTGs as well as their foliation and banding (Photos H. Martin))



Tonalite-Trondhjemite-Granodiorite, Fig. 2 (a) Thin section of typical TTG showing its mineralogical composition (*pg* sodic plagioclase, *qz* quartz, *bt* biotite, *ep* epidote). Biotite crystals are roughly parallel, defining the gneissic foliation. (b) K-Na-Ca diagram, showing the

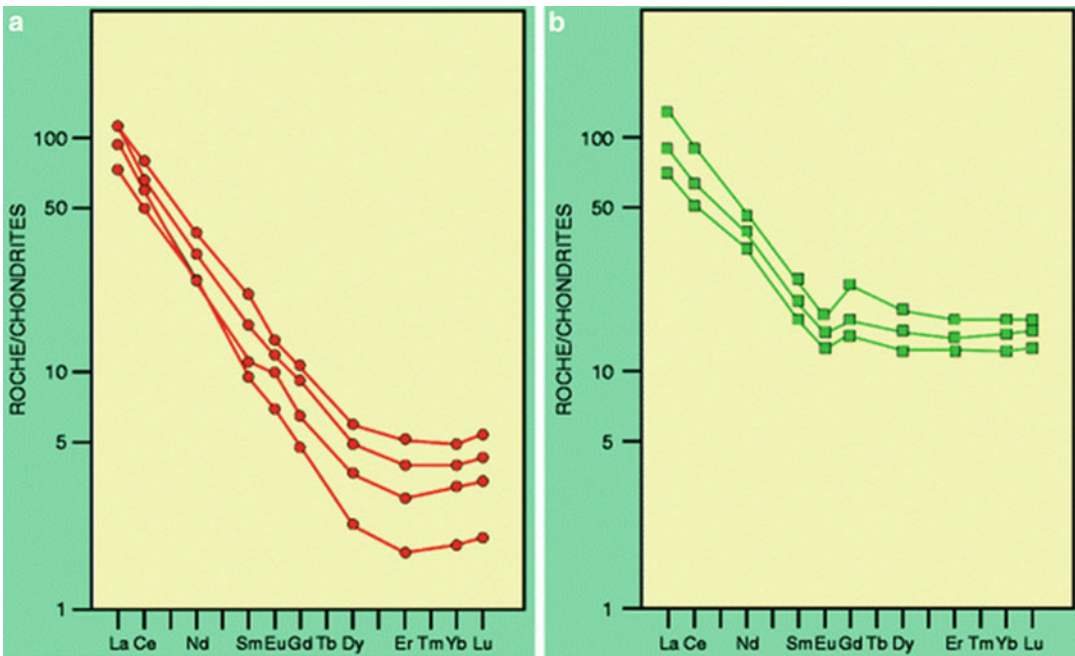
sodic character of Archean TTG (*red dots*). All fall in the field of trondhjemites (*Tdh*) and strongly differ from the average composition of the modern continental crust (*CA trend*)

a lack of plagioclase, both as residual or fractionating phases (Martin et al. 2005). The presence of garnet indicates that TTG genesis took place at high pressure (≥ 12 kbars) such that, as pointed out by Champion and Smithies (2003), a high-pressure origin has become implicit in the term “Archean TTG.”

Petrogenetic Models

Consideration of the geochemical characteristics of Archean TTG and the results of experimental high-pressure melts of hydrous basalt have led to

the conclusion that TTG formed via low- to moderate-degree partial melting of hydrated basaltic crust at pressures high enough to stabilize garnet $\pm$ amphibole (i.e., eclogite or garnet amphibolite) (Martin 1987; Rapp and Watson 1995; Moyen and Martin 2012). The lack of mafic endmembers to the TTG suites indicates that partial melting, rather than fractional crystallization, was the dominant process. More recently, Foley et al. (2002) argued that only a garnet-bearing amphibolitic source is able to account for the typically low Nb/Ta and high Zr/Sm ratios



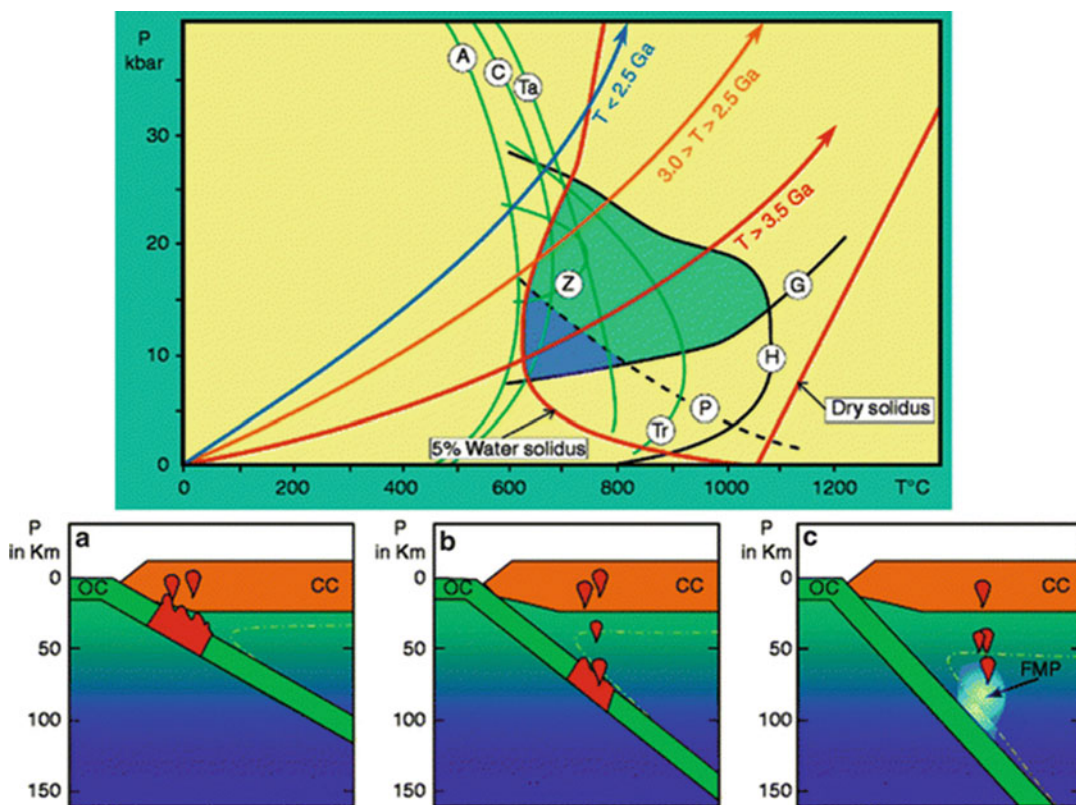
Tonalite-Trondhjemite-Granodiorite, Fig. 3 (a) Chondrite-normalized REE patterns for typical Archean TTG showing their richness in La and their poorness in Yb, which results in high La/Yb ratios, indicating that garnet was stable in the residue of their source. This implies that

their genesis took place at high pressure. (b) Chondrite-normalized REE patterns for modern juvenile continental crust. The relatively high Yb contents point to the absence of residual garnet during their genesis

of TTG. However, Rapp et al. (2003) show that similar ratios can also result from partial melting of hydrous basalt, leaving an eclogitic residue.

In some rare modern subduction environments where a young and hot ► [oceanic crust](#) is subducted, small volumes of TTG-like magmas (Na rich, high La/Yb), called adakites, are generated (Defant and Drummond 1990). The high pressures required for TTG genesis and the compositional similarities with adakites have led to the conclusion that TTG also formed via melting of subducted oceanic slabs (Martin 1986; Martin et al. 2005; Fig. 4). Archean heat production was two to four times greater than today (Brown 1986); consequently, Archean geotherms were significantly greater than typical modern ► [geotherms](#). During the Archean, the “normal” thermal regime was probably quite similar to that observed in modern zones of “hot” subduction, where adakitic magmas are typically produced. Such comparisons clearly support a subducted-slab-melt model for TTG. However, the idea that

adakite is invariably a petrogenetic analogue for all TTGs has recently been challenged. Based on secular changes in TTG compositions, Smithies (2000) and Smithies and Champion (2000) proposed that alternative processes, such as melting of tectonically or magmatically thickened hydrous mafic crust, might be more appropriate for the early Archean TTG. Bédard (2006) has suggested that delaminated hydrous basaltic lower crust sinks into the mantle where it partially melts to produce TTG. More recently, it has been proposed that melting of oceanic plateaus in a subduction environment better accounts for LILE budget in TTG (Martin et al. 2014). On the other hand, Laurent et al. (2020) consider that the composition of TTG plutons of South Africa rather reflects the combined accumulation of plagioclase phenocrysts and loss of interstitial liquid that erupted as silicic volcanic rocks. They conclude that the entire compositional diversity of TTGs could derive from the upper crustal differentiation of a single, tonalitic magma formed by basalt melting.



Tonalite-Trondhjemite-Granodiorite, Fig. 4 Pressure-temperature (P-T) diagram and schematic cross-section of a subduction zone illustrating a possible interpretation of the formation of TTG. In the early Archean ($t > 3.5$ Ga), the geothermal gradient along the Benioff plane was very high; subducted slab melted at shallow depth with plagioclase as residual phase. Because of the small thickness and low temperature of the wedge, mantle-melt interactions were limited or absent (red arrow and inset (a)). At the end of Archean ($3.0 < t < 2.5$ Ga), Earth was cooler and the geothermal gradient along Benioff plane was lower;

slab melting occurred at greater depth without residual plagioclase. The overlying mantle wedge was thick and hot, and interactions may have occurred between slab melts and the mantle (orange arrow and inset (b)). After 2.5 Ga, Earth had cooled further and the geothermal gradient along the Benioff plane was still lower (blue arrow and inset (c)) such that slab dehydration generally occurred before its melting could begin. The expelled volatiles (mainly water) ascended through the mantle wedge, thus lowering its solidus temperature, which induced its melting

The P-T diagram shows the solidus of tholeiite with 5% water as well as main dehydration reactions of oceanic lithosphere. H is hornblende, A is anthophyllite, C is chlorite, Ta is talc, Tr is tremolite, and Z is zoisite. G and P outline stability fields of garnet and plagioclase, respectively. The gray field is P-T domain where slab melts can coexist with hornblende- and garnet-bearing residue. OC is oceanic crust; CC is continental crust; and ms is solidus of hydrated mantle. Areas in red indicate magma; light blue indicates dehydration volatiles

Change in TTG Composition Through Time

Recently, Smithies (2000), Smithies and Champion (2000), and Martin and Moyen (2002) showed that the chemical composition of TTGs changed through the Archean. Throughout that eon, the most remarkable change was a decrease in average SiO_2 and an increase in average MgO content. According to Martin and Moyen (2002), the Mg# of the more primitive TTG magmas increased from maximum values of 0.45 at 4.0 Ga to 0.65 at 2.5 Ga. These authors also pointed out that over the same time interval, the

maximum concentrations of Ni increased from ~30 to ~70 ppm, Cr from ~50 to ~200 ppm, Sr from ~550 to ~1,200 ppm, and (Na₂O + CaO) from 9 to 11 wt.%. They interpret the high Mg# and the high Ni, Cr, and Sr contents in TTG parental magmas as due to the deep melting of the subducted basalt, which interacts with a thick slice of the mantle wedge peridotite. Recently, Smithies et al. (2019) considered that, during the Archaean, basalt melting depth never exceeds 50 km.

However, considering elements other than Sr, Ni, Cr, and Mg, the close similarities in the compositional range for TTG are independent of age and suggest a common petrogenetic relationship that is also age independent. In the younger TTG, the high Mg# and high Ni are thought to arise as magma derived by great-depth melting of subducting oceanic crust, which interacts with peridotite of the mantle wedge (Smithies et al. 2019). The lower Mg# and low Ni, Cr, and Sr contents in the older TTG indicate the lower efficiency of such interaction, perhaps because melting took place at shallower depth, under a thinner (or even with no) mantle wedge.

Cross-References

- ▶ [Archaean Eon](#)
- ▶ [Archaean Tectonics](#)
- ▶ [Barberton Greenstone Belt](#)
- ▶ [Craton](#)
- ▶ [Greenstone Belt](#)
- ▶ [Isua Supracrustal Belt](#)
- ▶ [Pilbara Craton](#)
- ▶ [Proterozoic Eon](#)
- ▶ [Rare Earth Elements](#)
- ▶ [Silicate Minerals](#)

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Total Solar Irradiance

► [Solar Constant](#)

4179 Toutatis

► [Toutatis](#)

Toutatis

Line Drube
DLR Institute of Planetary Research, German
Aerospace Center (DLR), Berlin, Germany

Synonyms

[1934 CT](#); [1989 AC](#); [4179 Toutatis](#)

Definition

Toutatis is a near-Earth asteroid of the Apollo class, with an orbit that crosses Earth's orbit so that it is classified as a potentially hazardous asteroid. With its 1:4 resonance with Earth's orbit, it has been observed carefully since 1992

with astronomical telescopes and radar during its close flybys every 4 years. In 2012 it passed by the Earth within just 18 lunar distances, which will be the closest flyby for more than a century. During this flyby the Chinese spacecraft Chang'e 2 observed Toutatis from a distance of less than 1 km and could see details down to a size of a couple of meters.

Toutatis is a stony type asteroid (S (IV)) with a density of about 2.5 g/cm³; it has an elongated shape (4.75 × 1.95 km) and seems to consist primarily of two large pieces, leading to speculation that the asteroid has a rubble-pile structure resulting from a large impact. Toutatis has a slow tumbling rotation with just one rotation per 5.4 days on the long axis and a long-axis precession of 7.4 days.

History

Astronomer Christian Pollas discovered Toutatis on January 4, 1989.

Cross-References

► [Near-Earth Objects](#)

TPF/Darwin

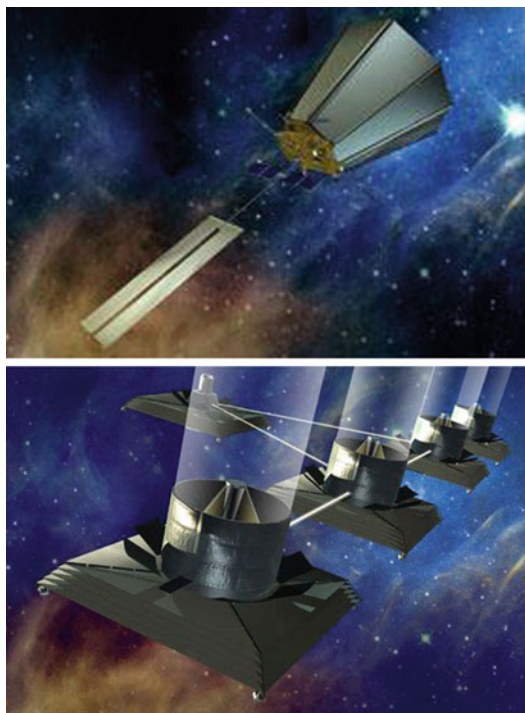
Marc Kuchner
NASA Goddard Space Flight Center, Exoplanets
and Stellar Astrophysics Laboratory, Greenbelt,
MD, USA

Synonyms

[New Worlds Observer](#)

Definition

TPF/Darwin refers to two canceled space missions that were dedicated to finding and



TPF/Darwin, Fig. 1 TPF coronagraph (*top*) and interferometer (*bottom*)

characterizing extrasolar Earthlike planets by directly imaging them, with the ultimate goal of detecting evidence of life. This broad concept and its variations have borne many names. “Terrestrial Planet Finder” (TPF) was a mission from NASA whereas “Darwin” was a phase-A study performed by the European Space Agency. The proposed instrument was either several formation-flying telescopes (Fig. 1, bottom) linked to form an infrared interferometer or a single large telescope collecting visible light and manipulating it with a coronagraph (Fig. 1, top). The spacecraft was to carry an associated ► [spectrometer](#) capable of identifying atmospheric ► [biomarkers](#) such as O₂, O₃, CO₂, and H₂O.

History

The concept of a planet-finding space-interferometer dates back to a paper by Ron Bracewell in 1978. In 1980, NASA’s Project

Orion considered a space mission using a coronagraph to directly image extrasolar planets.

Cross-References

- [Coronagraphy](#)
- [Direct-Imaging, Planets](#)
- [Exoplanets, Discovery](#)
- [Nulling Interferometry](#)

Trace Elements

Nicholas Arndt
ISterre, University Grenoble Alpes, Grenoble, France

Definition

On Earth a trace element is an element present in low concentrations in rocks, in waters, or in biological materials. A concentration of 100 parts per million (ppm) is commonly accepted as an upper limit. In geochemistry, trace elements are distinguished from major elements. The importance of trace elements is their lack of mutual interaction, which is the basis of Henry’s law of dilute solution. Major elements are the essential constituents of the crystal framework of minerals and rocks; trace elements substitute for or replace major elements. The concentrations of trace elements in rocks and minerals vary from several thousands of parts per million (e.g., strontium or nickel) to a few parts per billion for elements like platinum.

► [Rare Earth elements](#) are trace elements belonging to the family of lanthanides. In biology, a trace element is defined as an element that is present in low concentrations but is essential for the growth, development, and physiology of an organism. Trace elements are useful for monitoring the evolution of the core, mantle, and crust of the Earth and other planets; the appearance and evolution of life through geological time, as well as climate change in the past and at present; and the impact of industry on the environment.

Cross-References

- [Micronutrients](#)
- [Rare Earth Elements](#)

Trace Metals

Leslie J. Robbins^{1,2}, Kaarel Mänd¹,
Noah J. Planavsky², Daniel S. Alessi¹ and
Kurt O. Konhauser¹

¹University of Alberta, Edmonton, AB, Canada

²Yale University, New Haven, CT, USA

Keywords

Metalloenzymes · Biosignatures ·
Oxygenation · Redox reactions · Trace metals

Synonyms

[Transition metals](#)

Definition

Trace metals are metallic elements on the periodic table that are found in low concentrations in both aqueous environments (seawater, freshwater, mine waters) and geologic samples (minerals, rocks, and mine tailings). In aqueous environments, trace metals include any metal element present at concentrations between 10^{-15} mol/L (1 fM) and 10^{-5} mol/L (10 μ M). In geological samples, trace metals are present in abundances of <0.1% by weight and typically quantified in either ppm (mg/kg) or ppb (μ g/kg). With regard to trace metals in astrobiology and geobiology, there is an increased focus on transition metals in columns 3–12 of the periodic table.

Overview

Trace metals are ubiquitous components of aqueous environments, geological samples, and

biological processes. In biological systems, trace metals play critical roles as reaction centers and structural components in metalloenzymes or can even be used as terminal electron acceptors in redox-driven metabolisms such as manganese reduction. Within metalloenzymes, trace metals act either as reaction centers or as a structural component that enhances the integrity of enzymes. This is especially true of the first-row transition metals (V, Mn, Fe, Co, Ni, Cu, and Zn) as well as Mo. While essential for life at low concentrations, at elevated concentrations many trace metals (Fe, Cu, Zn, etc.) prove toxic. Thus, trace metals offer the potential to trace biological processes in modern and ancient environments and from an astrobiological perspective may be useful as a paleoenvironmental or biotic tracer.

Trace Metals in Seawater

In aqueous environments, such as seawater, trace metals tend to display one of the four profile types: (i) conservative, (ii) nutrient-like, (iii) particle-scavenged, or (iv) a hybrid distribution (Bruland et al. 2014). Trace metals with conservative profiles (e.g., Mo, W, Re) are those that have high concentrations relative to the efficiency of their sinks, and they tend to display little variation in concentration. In nutrient-like profiles, trace metals (e.g., Zn, Cd, Ag) are heavily depleted in the shallow surface water because of incorporation by phytoplankton communities through either surface adsorption or assimilation. Both processes are a function of microbial surface reactivity and microbial metal binding. These trace metals are then replenished at depth, as cellular biomass decays, and eventually return to the photic zone via upwelling. Conversely, particle-scavenged trace metals (e.g., Co) exhibit peak concentrations in the ocean's surface and become depleted at depth. This may be due to settling following their adsorption onto reactive particles or biological surfaces or through their incorporation into authigenic marine precipitates (i.e., chemical sediments formed in marine systems). Ultimately, this results in the export of trace metals to seafloor sediments. Certain elements may be defined by a hybrid distribution, a notable example being Fe (Bruland et al. 2014). Elements

that display a hybrid distribution are dependent on the geographical location and basin characteristics, which ultimately dictate whether they display nutrient-like or particle-scavenged features. Notably, the profile type of a given trace metal can be dependent on the prevalent biological and redox conditions in the oceans and can change on geological timescales.

In modern oceans, trace metals are strongly bound by microbial ligands, in some cases exceeding 97% of their total concentration. Chelation by microbial ligands is especially prevalent for Fe, Zn, Ni, Co, Cd, and Cu (Vraspir and Butler 2009; Bruland et al. 2014). Perhaps the best-known examples are the Fe-specific ► [ligands](#), siderophores, which act to keep insoluble Fe(III) in solution, thereby increasing Fe bioavailability for planktonic microbial species. Conversely, other ligands may act to decrease the free concentrations of trace metals, such as Cu, keeping them below toxic levels for microbial communities (Bruland et al. 2014). Today, Fe is a co-limiting nutrient over large areas of the oceans, depressing nitrogen fixation and primary productivity (e.g., Falkowski et al. 1998; Mills et al. 2004). Yet, despite the potential for Fe co-limitation in the modern ocean, on geological timescales, phosphorous is considered to be the ultimate limiting nutrient (Tyrrell 1999).

Trace Metals as Drivers of Ecosystem Change

Changes in the bioavailability of these trace elements have long been recognized to have the potential to drive biological evolution or control ecosystem structure over geological time (e.g., Frausto da Silva and Williams 2001). It has been suggested that the timing of the proliferation of specific metalloenzymes should broadly track changes in the environmental availability of the requisite trace metals (Dupont et al. 2010). Further, it has been debated if environmental trace metal availability limited the size and scope of the biosphere for much of Earth's early history (e.g., Anbar and Knoll 2002). For example, methanogens have a high requirement for Ni, due to its incorporation into enzymes needed to carry out methanogenesis (Ragsdale and Kumar 1996). It follows that methanogens would be

sensitive to environmental fluctuations in Ni availability (see discussion below).

Sedimentary Trace Metal Archives

Trace metal concentrations in the oceans in deep time, and by extension first-order trends in their bioavailability, are primarily unlocked by examining trace metal abundances in marine chemical sediments. These archives include black shales (e.g., Scott et al. 2008, 2013; Chi Fru et al. 2016), banded iron formations (e.g., Konhauser et al. 2009, 2011; Robbins et al. 2013), sedimentary to early diagenetic pyrite (e.g., Large et al. 2014; Mukherjee et al. 2018), and carbonates (Liu et al. 2016). Reconstructions of trace metal inventories of these records have been variously related to the ► [oxygenation of Earth's atmosphere](#) (Mo, V, Zn), the marginalization of methanogens (Ni), the onset of aerobic oxidation of terrestrial minerals (Cr), and the role that intrinsic biological processes may play in the evolution of complex life (Zn, Cu). Additional trace metal compilations produced temporal records for V (Sahoo et al. 2012), U (Partin et al. 2013a, b), Co (Swanner et al. 2014), and Re (Sheen et al. 2018). While these records are variably susceptible to overprinting during ► [diagenesis](#) and metamorphism, it is telling that many of the temporal trends are reproducible across multiple chemical sedimentary records, suggesting that these sedimentary archives are tracking first-order trends in global trace metal concentrations in seawater.

Basic Methodology

Today, the most common methods for measuring trace metal concentrations involve the use of inductively coupled plasma mass spectrometry (ICP-MS) or optical emission spectroscopy (ICP-OES). These methodologies can be used to directly analyze aqueous samples and, via laser ablation, geological samples. Additionally, both anodic and cathodic voltammetric stripping have been used in measurements of shipborne seawater samples and have proven critical in assessing the degree of organic ligand complexation of trace

metals such as Fe, Zn, Cu, and Cd (Bruland et al. 2014).

Aqueous Samples

Generally speaking, for aqueous samples including seawater and freshwater, a sample is collected and then filtered and acidified prior to analysis. Filter size is generally in the range of 0.22 μm such that microbial, particulate, and colloidal material is removed and the dissolved concentration of trace metals is measured; although, ultrafiltration is common and provides a true dissolved concentration. Following collection, samples may be diluted in a weak acid and introduced into an ICP-OES or ICP-MS or measured directly depending on instrument sensitivity and initial metal concentration. Analyses are generally calibrated against internal matrix-matched standards prepared with certified, commercial standards.

Geological Samples

Geological samples (e.g., banded iron formations, black shales, carbonates, pyrite) may be completely digested using various concentrated acids (such as a combined HNO_3 -HCl-HF attack). This involves several steps of acid addition, heating the sample, and evaporating the sample to a residue. The residue is then dissolved into a dilute acid matrix, typically 1–2% HNO_3 , and analyzed by ICP-MS. Alternatively, samples may be subjected to a series of sequential extractions designed to leach the authigenic and typically more reactive phases. Analyses are typically calibrated against internal standards and compared to well-characterized geological standards. Alternatively, trace metals may be measured by coupled laser ablation ICP-MS. In LA-ICP-MS analysis, a geological sample (thin section, small rock or mineral) is ablated in an airtight chamber with a laser, and the liberated fine particles are then carried to the ICP-MS by an inert gas line. Similar to solution analyses, LA-ICP-MS measurements are calibrated against well-known geological standards. Stable isotope measurements of trace metals are becoming commonplace by multi-collector ICP-MS (MC-ICP-MS), which often require additional sample processing and purification.

Key Research Findings

While the fact that >97% of certain trace metals are organically complexed in seawater is a profound observation in of itself (Vraspir and Butler 2009; Bruland et al. 2014), some of the most powerful inferences regarding trace element chemistry and their relation to Earth systems evolution have been garnered from the geological record. For instance, the enrichments of several transition metals in black shales, including Mo, V, Cr, U, and Re (Scott et al. 2008; Sahoo et al. 2012; Partin et al. 2013b; Reinhard et al. 2013; Sheen et al. 2018), are known to track the two-stage oxygenation of the ocean-atmosphere system (see Lyons et al. 2014 for a review).

A late-Archean secular decline in Ni/Fe ratios in banded iron formations indicates a decrease in Ni bioavailability (Konhauser et al. 2009, 2015) that is critical for methanogens (Ragsdale and Kumar 1996). This secular decline is the result of decreasing komatiite weathering and may have led to the marginalization of ancient methanogens, allowing for oxygenic cyanobacteria to expand into previously occupied environmental niches. These events, in turn, led to the first permanent rise in atmospheric oxygen ~2.48–2.3 Ga, a period known as the Great Oxidation Event (GOE) (e.g., Konhauser et al. 2011).

While Mo, V, U, Cr, Re, and Ni show stark temporal trends that track the rise and fall of oxygen, several trace metals show records that are considerably more static in both banded iron formations and black shales. Static records for trace metals, such as Zn and Cu (Robbins et al. 2013; Scott et al. 2013; Chi Fru et al. 2016), hint at the possibility of pervasive microbial ligand complexation in deep time, which would have stabilized trace metal concentrations against changes in bulk ocean chemistry or atmospheric conditions. These static records stand in stark contrast to the assertion that evolving trace metal abundances should be trackable by the proliferation of corresponding trace metal complexes in biological systems (e.g., Dupont et al. 2010). For example, despite geological evidence that points toward an attenuated marine reservoir for Mo in the Archean to Proterozoic (Anbar and Knoll

2002; Scott et al. 2008), isotopic evidence points to an Archean appearance of Mo nitrogenase (Stüeken et al. 2015). This questions the idea that an organism's elemental stoichiometry always reflects the fundamental chemistry of the environments in which they evolved.

Future Directions

Transition metals and their isotopes are increasingly measured in both modern and ancient settings. The advent of MC-ICP-MS has led to a rapid proliferation of trace and transition metal isotope data. Studies that utilize this new avenue of data collection are primed to explore the response of the ancient biosphere to changes in environmental conditions or shifts in community structure. For instance, recent examinations of zinc isotopes have shown shifts in their signature that coincide with the rise of eukaryotes to dominance at ~800 Ma (Isson et al. 2018) and may indicate the recovery of biosphere primary productivity or changes in zinc cycling following the Cryogenian glaciations at ~635 Ma (Kunzmann et al. 2013; John et al. 2017). Copper isotopes measured in black shales (Chi Fru et al. 2016) show a distinct shift around the GOE and are attributed to changes in oxidative weathering and a decline in banded iron formations, whereas changes in Mo isotope ratios through the Paleoproterozoic point to major fluctuations in redox balance in the oceans (Asael et al. 2018). Studies such as these highlight the utility of non-traditional stable isotopes of trace metals in extracting information about changes in ancient environmental conditions and offer a clear avenue for future studies that can be focused on shifts recorded in a given basin or over geological time.

Cross-References

- Banded Iron Formation
- Copper Isotopes
- Diagenesis
- Ligand
- Manganese Reduction

- Methanogenesis
- Oxygenation of the Earth's Atmosphere
- Phytoplankton
- Zinc Isotopes

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Trace of Life

- Biomarkers
- Biomarkers, Morphological

Traces of Life in Basaltic Crust

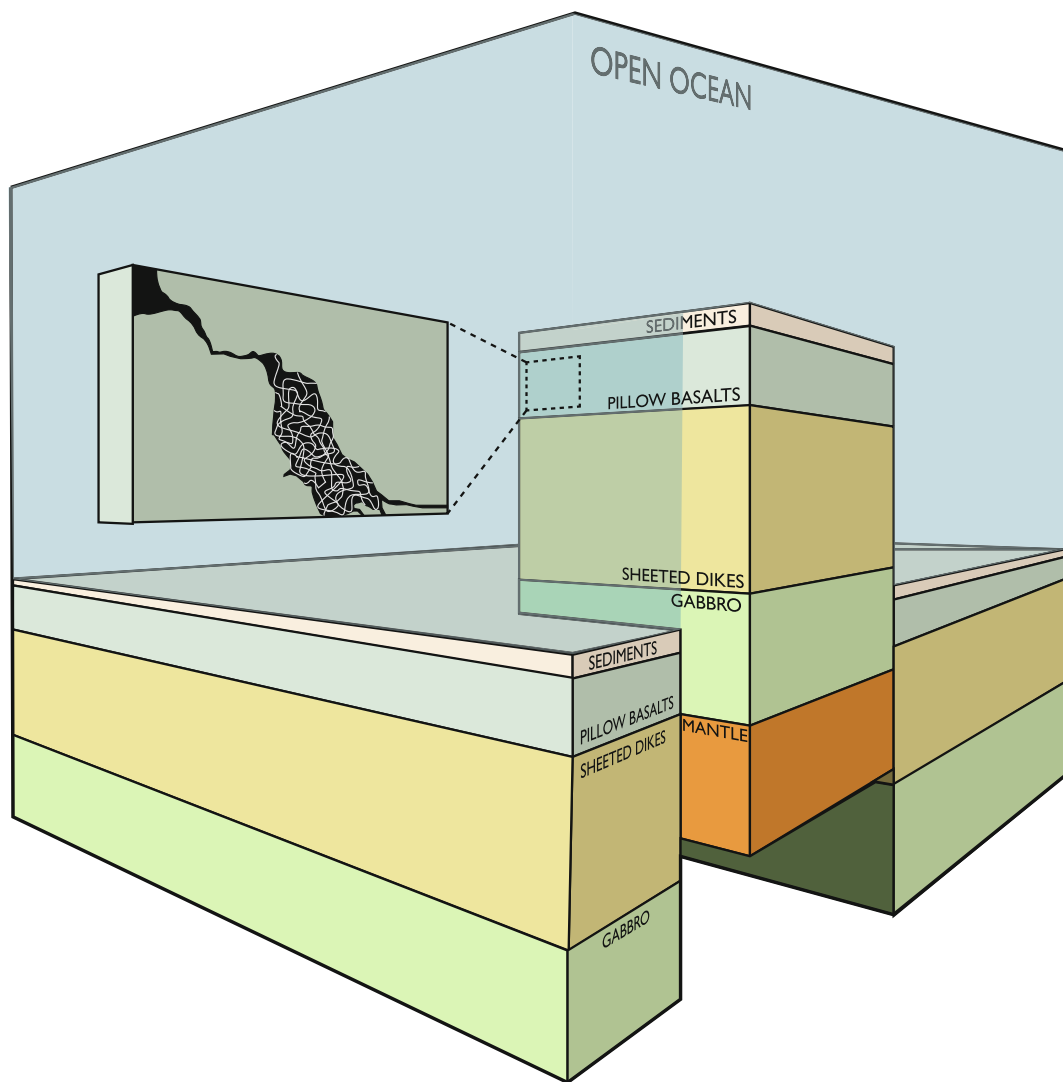
Magnus Ivarsson
Department of Paleobiology, Swedish Museum of Natural History, Stockholm, Sweden

Keywords

Deep biosphere · Igneous crust · Fossilized microorganisms

Definition

Traces of life in basaltic crust refer to signs of past life, including fossilized microorganisms and ichnofossils that reflect microbial activity, in mafic rock. The organisms were once engaged in an endolithic, that is, rock-dwelling lifestyle colonizing open pore space, such as fractures or vesicles, and preserved in situ upon their death. A majority of the fossil remains have been found in subseafloor basalts or ancient oceanic crust (Fig. 1), and only rarely in continental settings. Body fossils are found throughout the basaltic



Traces of Life in Basaltic Crust, Fig. 1 Image showing the oceanic crust and endolithic habitat

formations, while ichnofossils are almost exclusively found in volcanic glass of pillow lavas.

History

Studies date back to Ross and Fisher (1986), who reported etched grooves in glass shards from a Miocene tephra (an air bourn volcanic deposit). They compared the etch marks with fungal borings in carbonate grains and suggested that fungi

were responsible for the production of the ichnofossils. In the early and mid-1990s, several observations were made of granular and tubular microstructures in volcanic glass from drilled and dredged samples from the ocean floor (Thorseth et al. 1992, 2003). A prokaryotic affinity was assigned to these findings even though a fungal origin of tubular ichnofossils has also been inferred (Staudigel et al. 2008). In the 2000s, fossilized microorganisms were described from various deep seafloor settings, (Schumann

et al. 2004; Ivarsson et al. 2008a, b; Peckmann et al. 2008) and during the last decade a more comprehensive fossil record of the deep basaltic crust has been established (Ivarsson et al. 2012, 2013, 2020; Bengtson et al. 2014, 2017). The concept of a diverse deep biota of prokaryotes and eukaryotes as well as symbiotic-like relationships between the two is now emerging based on the fossil evidence and microbiological studies. This is a significant change of view, considering that the deep igneous oceanic crust was considered barren of life prior to the 1990s.

Overview

Traces of life in basaltic crust comprise three different types: (1) body fossils, (2) ichnofossils, and (3) chemofossils (Ivarsson et al. 2020). The first category constitutes fossil remains of mineralized or encrusted microbial cells. A majority of the body fossils consist of purported fungal fossils such as hyphae, yeast-like structures, sporophores, and resting structures. The fungal interpretation of the fossils has been based on specific fungal morphologies such as septa, anastomoses, reproduction structures, or the presence of chitin (Ivarsson et al. 2012, 2020). The fossils are usually mineralized by montmorillonite clays or occasionally iron oxides. Encrusted and mineralized cells of inferred prokaryotic origin have also been reported, and usually interpreted as the remains of iron- or manganese-oxidizing prokaryotes (Thorseth et al. 2003). Laminated micro-stromatolitic structures are believed to be the products of cyclic biofilm formation of iron- and manganese-oxidizing bacteria, even though an abiogenic influence cannot entirely be ruled out. Complex, branching microstromatolites are referred to as *Frutexit* (Bengtson et al. 2014).

The second category is ichnofossils, described in the literature as traces of microbial activity in volcanic glass, and occasionally olivine. They constitute etch marks with conspicuous granular and tubular morphologies (Staudigel et al. 2008; McLoughlin et al. 2009, 2010). The granular type consists of micrometer-sized, near-

spherical voids etched into the fresh glass, and subsequently filled with authigenic minerals like clays and Fe oxides/hydroxides. They commonly occur in irregularly distributed clusters. The tubular type consists of smoothly curved, sometimes segmented tubes with branched or spiraling morphologies. They usually occur in assemblages and are commonly associated with the granular morphology. The two morphologies are formalized in the ichnogenera: *Granulohyalichnus* and *Tubulohyalichnus* (McLoughlin et al. 2009), which are further subdivided into five ichnospecies on the basis of morphological variations. Fisk and McLoughlin (2013) further produced a comprehensive photographic atlas of ichnofossils and other structures in volcanic glass. Recently, the biogenicity of the oldest Archean trace fossils has been questioned and debated (Grosch and McLoughlin 2014).

The third category is chemofossils: the remains of chemical signatures specific for life, such as biomarkers or isotopic signatures. The preservation of chemofossils is rare in basaltic crust, but $\delta^{34}\text{S}$ values in pyrite corresponding to microbial sulfur cycling and $\delta^{13}\text{C}$ values in organic material as well as vein carbonates consistent with methane cycling (Lever et al. 2013) have been reported. Fluorescent staining has also been used to detect nucleic acids and DNA associated with ichno- and body-fossils, as well as specific stains that detected chitin in fungal fossils (Ivarsson et al. 2008b, 2012).

All traces of life in basaltic crust represent endolithic life forms (including chasmo-, crypto-, and euendoliths) and are thus found at the interface between host rock and pore space, open, or filled with secondary minerals. Body fossils are the remains of microorganisms that used the vein or fracture walls as substrate for growth and therefore have a perpendicular growth direction with respect to the host rock. Ichnofossils in volcanic glass occur conversely to that: still perpendicular to the surface of the glass, but stretching inwards forming negative cavities.

A majority of the fossil remains are found in deep drill cores and are thus considered to represent the deep biosphere. The deep biosphere represents one-tenth to one-third of all living biomass

today, but it has been put forward that prior to the colonization of land in the Ordovician most of Earth's biomass (~80%) was to be found in the deep biosphere (McMahon and Parnell 2018). This suggests that deep environments have played a crucial role in life's history and that fossils of the deep biosphere hold a key to our understanding of early evolution of both prokaryotes and eukaryotes. The fossil record of basaltic crust range from the present back to Devonian ages in ophiolites. Rare reports of much older deep biosphere fossils suggest life to be present in igneous oceanic crust already at 2.4 Ga (Bengtson et al. 2017), and sulfur isotope signatures in pyrite indicate life in subseafloor basalt already at 3.45 Ga (Aoyama and Ueno 2018).

In an astrobiological context, traces of life in mafic crust (e.g., Fisk and Giovannoni 1999) are important because all terrestrial planets in the solar system, except Earth, consist almost exclusively of basalts. Thus, traces of life in basalts have been targeted for upcoming missions designated for the search for signs of life on other planets.

Cross-References

- Basalt
- Deep Biosphere
- Deep Subsurface Microbiology
- Microfossils

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Transatlantic Exoplanet Survey

► [TrES](#)

Trans-Neptunian Object

Therese Encrenaz
LESIA, Observatoire de Paris, PSL Université,
CNRS, Sorbonne Université, Université de Paris,
Meudon, France

Synonyms

[Kuiper belt object](#); [TNO](#)

Definition

The name “trans-Neptunian object” (TNO) has been given to the small solar-system bodies that constitute the Kuiper belt, beyond the orbit of Neptune. The existence of this population was first proposed by Kenneth Edgeworth and Gerard Kuiper on the basis of dynamical considerations. Over 4100 trans-Neptunian objects are known by the end of 2021. The first discovery of a TNO was made in 1992 by David Jewitt and Jane Luu. Trans-neptunian objects are classified in different categories: the “classical” objects, at 42–47 AU from the Sun, have a low inclination and a low ► [eccentricity](#); the “plutinos” are in resonance with Pluto and have the same semimajor axis as Pluto; and the “scattered” objects are more distant and have larger eccentricities.

Cross-References

► [Kuiper Belt](#)
► [Orbit](#)
► [Quaoar](#)
► [Sedna](#)

Transcription

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València, Spain

Synonyms

[RNA synthesis](#)

Definition

Transcription is the synthesis of an ► [RNA](#) chain by copying a complementary ► [DNA](#) strand of a particular ► [gene](#) (or cluster of genes in bacterial operons). Both in prokaryotic and eukaryotic cells, a DNA template is required for transcription as well as the four ribonucleoside triphosphates (ATP, GTP, CTP, and UTP) acting as substrates and the enzyme RNA polymerase. As a result, a molecule of RNA (mRNA, tRNA, or rRNA) is produced. The initiation of transcription usually requires the presence of an upstream promoter sequence – i.e., a specific sequence to which RNA polymerase binds tightly and that indicates where to start the transcription and which strand of DNA to transcribe. Some RNA viruses (e.g., human immunodeficiency virus, HIV) make a DNA copy of their genome, i.e., synthesize a DNA molecule using RNA as template in a process called reverse transcription (these viruses are known as retrovirus).

Cross-References

► [DNA](#)
► [Gene](#)
► [Genetics](#)
► [RNA](#)

Transcription Networks

► [Biological Networks](#)

Transcription Unit

► [Gene](#)

Transduction

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia Evolutiva, Universitat de València, València, Spain

Definition

1. Genetics sense. Transduction is a ► [virus](#)-mediated transfer of DNA from one cell to another. Although transduction was first observed in bacteriophages and bacteria, it has also been observed in retroviruses and eukaryotic cells.
2. Bioenergetics sense. Transduction refers to any of the diverse mechanisms of conversion between different types of energy, for example, from chemical to mechanical (cell motility), from electromagnetic to chemical (► [Photosynthesis](#)), or from chemical to osmotic (ion pumps).
3. Cell regulation sense. Transduction refers to any of the diverse processes of conversion of information based on the use of chemical signals, for example, the hormone-mediated generation of a second messenger and its effects on metabolic flux regulation.

Cross-References

- [ATP Synthase](#)
- [Energy Conservation](#)
- [Photosynthesis](#)
- [Transformation](#)
- [Virus](#)

Transferase

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Definition

In biochemistry, a transferase is an ► [enzyme](#) or ► [ribozyme](#) that catalyzes the transfer of a chemical group (e.g., acetyl, methyl, amino, or phosphate group) from one molecule, the donor, to another, the acceptor. There are more than 450 known protein enzyme classes that catalyze the transfer of various chemical groups from one compound to another. For example, transaminases catalyze the transfer of an amino group from an amino acid to an α -keto acid.

Cross-References

► [Enzyme](#)

Transformation

Juli Peretó

Institut Cavanilles de Biodiversitat i Biologia

Evolutiva, Universitat de València, València, Spain

Definition

Transformation is a process in which a cell takes up and functionally integrates exogenous ► [DNA](#). There are many examples of natural transformation between bacteria, virus and bacteria, bacteria and plants, or virus and eukaryotic cells. Genetic engineering techniques are artificial adaptations of cases of natural transforming systems.

History

The process of transformation was initially described by Fred Griffith (1877–1941) in 1928 (Griffith 1928). The experiments on the transformation of pneumococcal bacteria, published in 1944 by T. Oswald Avery (1877–1955), Colin MacLeod (1909–1972), and Maclyn McCarty (1911–2005), established that the genetic information is chemically written in DNA (Avery et al. 1944).

Cross-References

- [Cloning](#)
- [DNA](#)
- [Lateral Gene Transfer](#)

References and Further Reading

- Avery OT, MacLeod CM, McCarty M (1944) Studies on the chemical nature of the substance inducing transformation of pneumococcal types. Induction of transformation by a desoxyribonucleic acid fraction isolated from pneumococcus type III. *J Exp Med* 79:137–158
- Griffith F (1928) The significance of pneumococcal types. *J Hyg* 27:113–159

Transit

David W. Latham¹ and Nader Haghighipour²
¹Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
²Institute for Astronomy, University of Hawaii-Manoa, Honolulu, Hawaii, HI, USA

Definition

In astronomy, a transit is the occurrence, as seen by an external observer, of a partial ► [eclipse](#) of a body (star, planet) by another body (star, planet) orbiting the first one. The transit refers to the entire duration of the phenomenon. Historically, the observations of the transit of Venus in front of the Sun as seen from Earth, and especially the ones in 1761 and 1769, have been the occasion

to measure the Sun–Earth distance with a fair accuracy. The last transit of Venus across the Sun was in 2012.

The transit phenomenon presents a powerful method for detecting extrasolar planets. Thanks to the *Kepler* space telescope and now the TESS and CHEOPS satellites and many ground-based instruments (e.g., HATNet, MEarth, SPECULOOS), this method has been able to detect close to 2400 extrasolar planets. The transit of an extrasolar planet in front of its host star is also used to determine several of the planet's parameters such as its radius, period, and eccentricity. It is also the most promising technique for characterizing exoplanets atmosphere.

Cross-References

- [Eclipse](#)
- [HATNet](#)
- [Kepler](#)
- [MEarth](#)
- [Occultation](#)
- [SPECULOOS](#)
- [TESS](#)
- [Transiting Planets](#)

Transiting Exoplanet Survey Satellite

- [TESS](#)

Transiting Planets

Nader Haghighipour¹ and Emeline Bolmont²
¹Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA
²Department of Astronomy, Université de Genève, Versoix, Switzerland

Keywords

Exoplanets · Spectroscopic orbit · Transit

Definition

Transiting planets are those that orbit stars beyond the solar system and are observed to ► [transit](#) across the disk of their host star.

History

The 1995 discovery of a Jupiter-mass planet orbiting the solar-type star 51 Pegasi with a remarkably short period of 4.2 days opened the eyes of astronomers to a promising new way to detect and study exoplanets. If planets in such tight orbits were common, then the chances that some of them would transit their host stars could be as high as one in ten, because the probability that a planet's orbital plane is properly aligned to cross the disk of its star is roughly R_S/a , where R_S is the radius of the star and a is the distance from the planet to the star. By 1999, enough close-in planets had been detected by the ► [radial velocity](#) method that the odds for one to be transiting its host star were very good. As often happens in science, the actual discovery was made almost simultaneously by two different teams, and the two papers announcing that a giant planet transited HD 209458 were published back to back in the *Astrophysical Journal Letters* in 2000.

Several teams realized that an effective way to discover transiting planets would be to monitor the light of a large number of stars, looking for the slight dimming due to a planet passing in front of the star and blocking some of its light. For a planet the size of Jupiter passing in front of a star like the Sun, the dimming would be about 1% and would last just a few hours. If close-in ► [giant planets](#) were as common as 1 in 100 and the chances were that 1 in 10 would transit, then the yield should be about one transiting planet per 1000 stars. Projects to monitor the light of many thousands of stars looking for microlensing events had a head start, and the OGLE team identified several dozen candidates transiting planets. Eventually, a handful of these candidates were confirmed as planets based on spectroscopic orbits. However, the OGLE candidates were all quite faint and difficult to confirm and characterize. The job of discovering brighter candidates fell to wide-angle surveys that covered

much larger areas of the sky using ► [CCD](#) cameras mounted on telephoto lenses, typically with apertures of 100 mm. The Trans-Atlantic Exoplanet Survey (► [TrES](#)) was the first of the wide-angle photometric surveys to confirm a transiting planet, followed soon by the Hungarian-made Automated Telescope Network (► [HATNet](#)), the Wide-Angle Search for Planets (► [WASP](#)), and the XO Project.

In the meantime, radial velocity surveys were undertaken specifically aimed at finding short-period planets that might then be shown to transit. Two of the planets found this way, ► [HD 189733b](#) and HD 149026b, proved to be among the best targets for follow-up studies of giant planets, primarily because their host stars are nearby and bright, much brighter than the typical transiting systems found by even the wide-angle surveys.

The photometric precision that can be achieved from the ground with small telescopes is limited by the Earth's atmosphere, both by rapid variations due to scintillation and by slower variations in atmospheric extinction (transmission) and seeing (image quality). This motivated the development of photometric space missions to search for transiting planets, first the French-led CoRoT mission, launched in December 2006, and then NASA's ► [Kepler mission](#), launched in March 2009. CoRoT was scoped to have the ability to detect planets as small as super-Earths, and its discovery of CoRoT-7b, a rocky planet in a 0.85-day orbit around an 11th magnitude K dwarf, is the most important planet discovered by CoRoT so far. The design of *Kepler* was much more ambitious, with the goal of detecting true Earth twins, namely Earth-sized planets in 1-year orbits around stars like the Sun. This led to a strategy of monitoring 150,000 solar-type stars in a single field of 100 square degrees in Cygnus and Lyra for nearly 4 years. During the course of its primary mission, *Kepler* identified more than 900 transiting planets (and close to 3000 planetary candidates) with most of them smaller than Neptune. For both CoRoT and *Kepler*, the challenge is now to sort out which candidates are actually transiting planets and which ones are systems of stars that show light curves that mimic transiting planets. The CoRoT and *Kepler* (and its follow-up, K2)

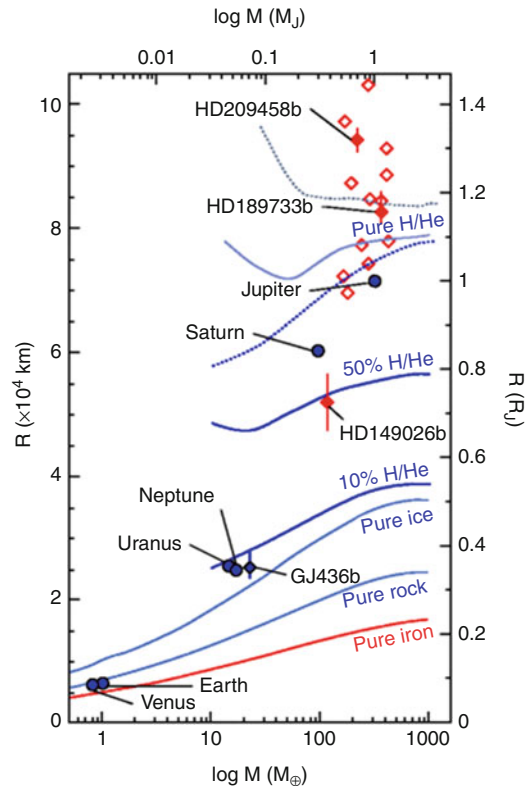
satellites are no longer functioning. However, other space missions are now on sky, detecting and characterizing new planets: TESS (a NASA mission, which began observations in 2018) and CHEOPS (a Swiss-led mission, which began observations in 2020). Both are designed to observe planetary transits around bright stars to detect new planets and to improve the radius estimates. These planets can then be observed from the ground to obtain radial velocities.

In recent years, there has been a growing interest in searches for planets orbiting M dwarfs. This is because it may be easier to discover and characterize rocky planets orbiting M dwarfs in the ► [Habitable Zone](#), where water might be liquid on the surface and life as we know it could potentially develop. M dwarfs offer two main advantages compared to the Sun. They are much cooler, so the Habitable Zone is much closer in, corresponding to periods as short as a few weeks or even days. The tighter orbits and shorter periods in the Habitable Zone imply that it is more likely for a habitable planet's orbit to be aligned so that transits are observed. In addition, the reflex motion of the host star is much larger, both because the mass of an M dwarf is smaller than that of the Sun and because the orbital period in the Habitable Zone is shorter. This has led to photometric surveys looking for planets transiting M dwarfs. The first major initiative is the MEarth project, which has discovered several small planets, like GJ 1214b and more recently LHS-1140b, a 1.7 Earth radius planet in the Habitable Zone of its star (Dittmann et al. 2017). Later, SPECULOOS, another photometric survey joined the game. Its prototype, TRAPPIST, allowed to detect the amazing TRAPPIST-1 system (e.g., Gillon et al. 2017).

Overview

Transiting planets are important because they have enabled studies of whole new areas in the astrophysics of exoplanets, such as the structure of planetary interiors, the temperatures and compositions of their atmospheres, and the formation and evolution of planetary systems.

If a ► [spectroscopic orbit](#) is available for the star hosting a transiting planet, then both the radius and the mass of the planet can be determined. Combining the mass and radius yields the bulk density of the planet, which can be compared with theoretical models of planetary interiors to constrain the composition and structure of the planet. This is illustrated by Fig. 1, which shows a mass versus radius diagram for the planets in the Solar System together with a subset of the transiting planets known in 2007. The lines in Fig. 1 illustrate the masses and radii predicted by models for planets with different compositions, ranging from gas giants dominated by hydrogen and helium at the large end to water worlds and rocky planets at the small end.



Transiting Planets, Fig. 1 The mass versus radius diagram for the planets in the Solar System and a subset of the transiting planets known in 2007. The lines illustrate the masses and radii predicted by models of planets with different compositions. The horizontal axes are plotted in Earth masses (bottom) and Jupiter masses (top); the vertical axes are plotted in km (left) and Jupiter radii (right)

A spectacular application for transiting planets has been the detection and even spectroscopy of planetary atmospheres during transits and secondary eclipses. Spectral features due to molecules such as water, methane, and carbon dioxide have been identified in the atmospheres of the transiting planets plotted as filled diamonds on Fig. 1. In the case of HD 189733b, the thermal emission from the planet has been tracked for more than half an orbit, as the view marched around from the night-side to the dayside. This allowed a map of the temperature of the atmosphere to be constructed as a function of longitude on the planet.

By tracking the radial velocities during transit events, it has been possible to deduce the amount of misalignment between the spin axis of the host star and the normal of the orbital plane, using the so-called ► [Rossiter-McLaughlin effect](#) (see also Fig. 3). In some cases, the plane of the orbit is closely aligned with the star's equator, but the misalignment is often observed to be large and even retrograde. This leads naturally to the interpretation that at least two mechanisms have been responsible for the migration of giant planets from the outer regions of the protoplanetary disks where they formed to the inner regions where they are now observed: Gradual migration in a disk versus violent gravitational scattering followed by tidal dissipation of the orbits that pass close to the star (see “► [Planetary Migration](#)”). The interpretation that gentle migration in a disk can sometimes dominate is supported by the independent result from NASA's *Kepler* mission that some systems show transits for two or more planets in orbits that must be nearly coplanar.

Variations in the observed times of transits can indicate the presence of additional planets in a system. This approach is especially powerful for systems with multiple transiting planets. With rich data sets covering full cycles of transit time variations, it is possible to derive masses of the planets involved without the need for radial velocity observations, even the masses of planets for which the radial velocity variations would be too small to measure with present techniques.

In principle, if the photometric precision is good enough, it should be possible to use the

detailed shapes and timings of transit light curves to deduce the presence of moons orbiting the planets and even the shape of the planet, such as oblateness due to rapid rotation.

Basic Methodology

A planet and its host star orbit a common center of mass. An orbital solution based on the spectroscopically observed radial velocities of the host star is traditionally called a spectroscopic orbit by astronomers. Although the orbital period and eccentricity are determined unambiguously by a spectroscopic orbit, the observed velocity amplitude of the orbital solution is only the component projected along the line of sight. From radial velocities alone, it is not possible to determine the inclination of the orbital plane to the line of sight, and thus the true orbital amplitude, and therefore the true mass of the companion are ambiguous. In order for planets to transit, the orbit must be oriented nearly edge on to the observer; the actual inclination can be determined accurately from the shape and duration of the transit events. This allows the actual mass of the planet relative to the host star to be determined if a spectroscopic orbit is also available. Moreover, the transits also yield the radius of the planet relative to the star, because the depth of the dip in the light curve depends on the fraction of the area of the stellar disk that is blocked.

In many cases, the accuracy with which the mass and radius of a transiting planet can be determined is limited by uncertainties in the mass and radius of the host star. This problem is worse for stars where the distance is not known and the characteristics of the host star have to be estimated using stellar models and spectroscopic classification of the stellar parameters. If accurate distances are available, the host star characteristics can be constrained more accurately. Recently, the precision of the stellar parameters for the *Kepler* planets was improved using parallaxes data from the Gaia satellite. This allowed to discover a new feature of the super-Earth/mini-Neptune exoplanet population: the Fulton gap (Fulton and Petigura 2018) separating a population of small

radii (more rocky planets) and a population of larger radii (more gaseous planets). Asteroseismology promises to provide very accurate stellar densities, and from that the masses, radii, and even ages can be derived quite accurately with the help of stellar models. But asteroseismology requires essentially continuous highly precise photometric monitoring over many days. NASA's *Kepler* mission has demonstrated that this approach is feasible for solar-type dwarfs brighter than about 11th or 12th magnitude (see “► [Dwarf Star](#),” e.g., Huber et al. 2013). Recently, Kayhan et al. (2019) revisited the parameters of 20 planetary systems for which there was asteroseismology data (mostly from *Kepler*) to find that including these constraints could lead to differences in planetary radii up to 25% (for Kepler-444b-f).

There are two opportunities for isolating the light from a transiting planet, and both rely on separating the light of the planet from the host star in time rather than in space. The two situations are illustrated in Fig. 2. During the secondary eclipse, when the planet is occulted by the star, only the light of the star is observed. This can be compared with the light observed just before and just after the secondary eclipse, when the combined light of the star and the dayside of the planet are observed. The difference gives the light from the planet, which can be mostly thermal emission from the planetary atmosphere at long wavelengths. During the transits, when the planet passes in front of the star, the amount of light

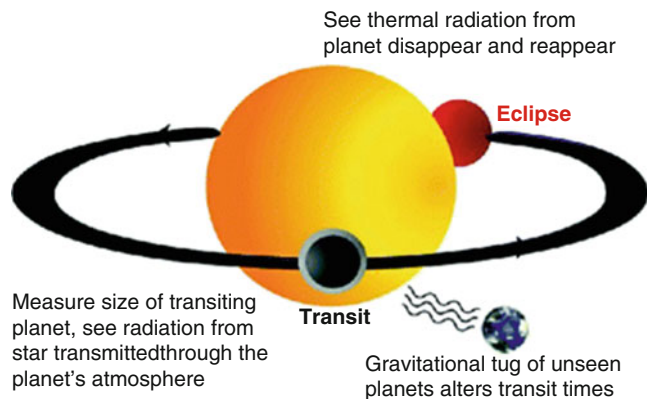
blocked by the planetary atmosphere depends on its opacity. Thus, any variation in the depth of the transits as a function of wavelength follows the variation of absorption in the atmosphere as a function of wavelength. This can reveal the presence of different molecules in the atmosphere, such as water and methane.

If a star is rotating, then there is a systematic variation of the spectrum across the disk of the star due to Doppler shifts, to the blue for the approaching limb (edge) and to the red for the receding limb. As a transiting planet crosses the stellar disk, it blocks some of the light and introduces a subtle variation in the apparent radial velocity. The shape of the velocity curve during transit depends on the apparent angle, λ , of the trajectory of the planet across the stellar disk compared to the axis of rotation and also on the impact parameter, b , as illustrated in Fig. 3. This distortion on top of the orbital velocity is called the Rossiter-McLaughlin effect.

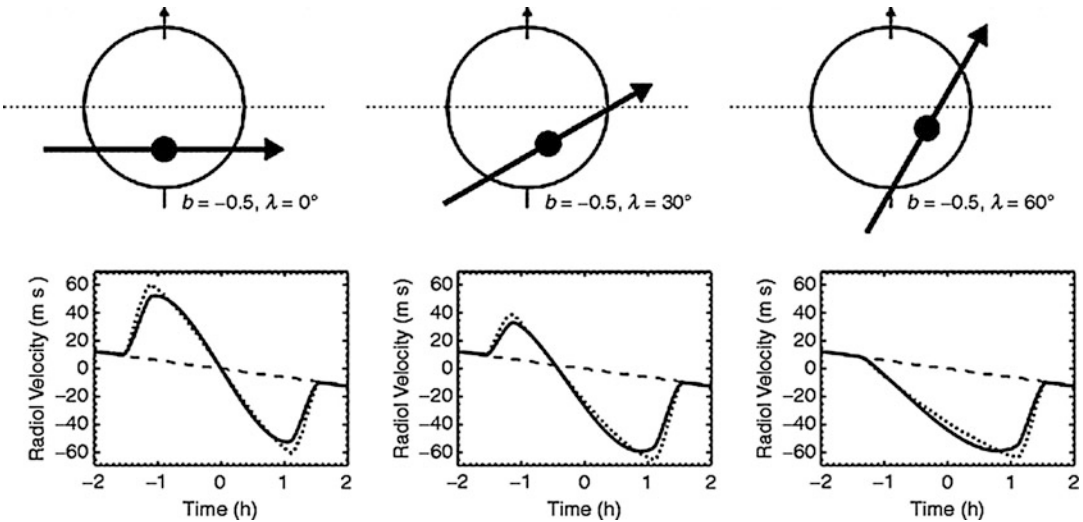
Stellar systems can mimic the shallow light-curve dips produced by transiting planets. For a planet the size of Jupiter transiting a star the size of the Sun, the dip is about 1% deep. Stellar binaries with cool M dwarfs eclipsing stars similar to the Sun (and larger) can produce light curves that are indistinguishable from transiting giant planets. This is because electron degeneracy sets in near the bottom of the main sequence, and the smallest stars have more or less the same size as substellar objects all the way down to giant planets, 100 times less massive. Fortunately,

Transiting Planets,

Fig. 2 Secondary eclipses, when the planet is occulted by its host star, and transit events, when the planet passes in front of the star, both offer opportunities to study the spectra of the planetary atmospheres, as described in the text



TRA0009



Transiting Planets, Fig. 3 The Rossiter-McLaughlin effect for three different trajectories of a transiting planet across the disk of a rotating star. The apparent angle of the trajectory relative to the spin axis is λ , while the impact parameter that measures the displacement of the trajectory

from the center of the stellar disk is b . When the orbit is retrograde, with the orbital motion in the opposite direction to the stellar spin, the velocity distortions are nominally mirror images of the examples shown

eclipsing binaries are easy to distinguish from transiting planets, because the amplitude of the orbital velocity is much larger and therefore easy to detect spectroscopically. If the photometric precision is good enough, it is also possible to detect brown dwarf and massive planets by the ellipsoidal variations that they induce due to gravitational distortions of the stellar shapes combined with Doppler boosting (also known as relativistic beaming) in the light curves outside of eclipses.

Another source of astrophysical false-positives that mimic transiting planets is grazing eclipsing binaries where the dips in the light curves are shallow because only a tiny fraction of the area of each star is blocked. These imposters are also easy to identify with spectroscopy, especially when the spectra of both stars are visible in the first observation.

Astrophysical false positives composed of fainter eclipsing binary systems contaminating the light of separate stars are more difficult to identify. The contamination by background eclipsing binaries is worse for surveys with poorer spatial resolution and larger pixels. Follow-up observations with high spatial resolution can often pinpoint the offending neighbor. The most

difficult cases are hierarchical systems where the eclipsing binary is physically associated with the target and therefore is too close to be resolved spatially.

Wide-angle ground-based surveys for transiting planets are magnitude limited; every star in the field of view is analyzed. Giant stars can amount to as much as half of the observed sample, despite the fact that they are relatively short-lived and therefore rare in the solar neighborhood, because they are more luminous and can be seen at much larger distances than dwarfs. When follow-up observations show that a transiting planet candidate is a giant star, it is usually assumed that it must be a blend with an eclipsing binary.

The initial enthusiasm for detecting transiting planets with wide-angle ground-based photometric surveys was quickly tempered by the very high rate of astrophysical false positives, typically more than 90%, that required major campaigns of follow-up spectroscopy and photometry to sort out the true planets. In contrast, the M_{Earth} survey targets individual M dwarfs, one by one. M dwarfs are already among the smallest stars, so imposters involving eclipses by smaller stars are

not a problem. Hierarchical blends are unlikely as false positives, because there are so few intrinsically fainter eclipsing binaries. The rate of false positives for the CoRoT and *Kepler* missions is somewhere in between that of MEarth and the wide-angle ground-based surveys, mostly because these two space missions observe lists of targets that have been cleaned of giants. This requires extensive ground-based work to prepare the necessary target catalogs. In the case of the *Kepler* mission, the ability to measure displacements of image centroids during transits with a precision as small as a tenth of a millipixel has made it possible to identify most of the background eclipsing binaries using centroid motion (or lack thereof).

For a long time, the ability to measure radial velocities with a precision sufficient to determine masses of small planets in long-period orbits was the main limitation to the confirmation and characterization of potentially habitable rocky planets that transit. However, that recently changed with the arrival of new spectrographs like ESPRESSO. The reflex motion induced on the Sun by the Earth is less than 10 cm/s, and ESPRESSO has already shown its capacity to reach ~ 20 cm/s precisions (e.g., Kunovac Hodžić et al. 2021).

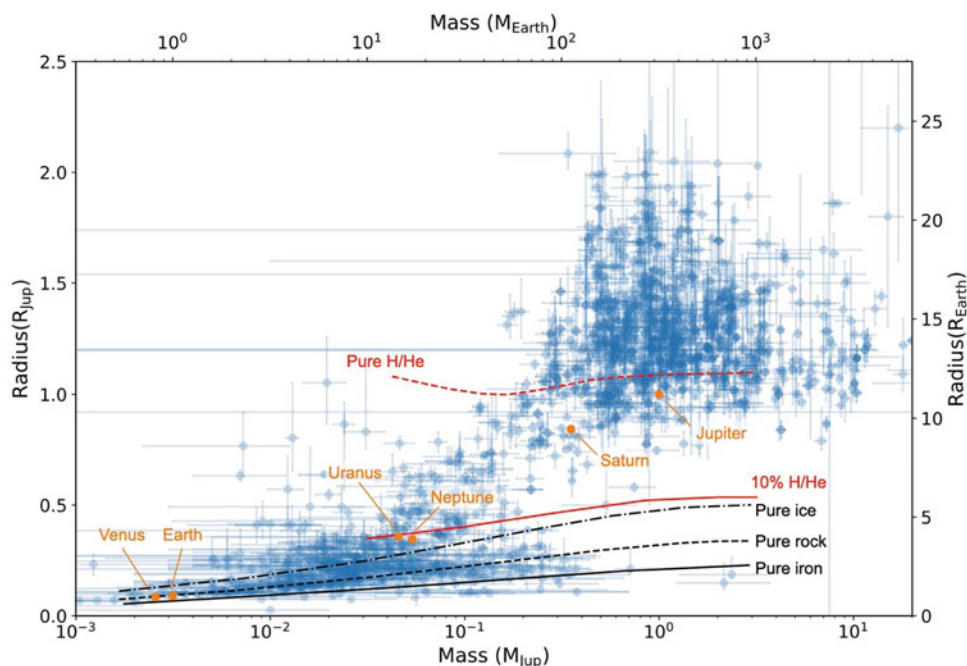
Key Research Findings

Figure 4 plots the masses and radii for the transiting planets published by mid-2021, nearly 1900 in all (it was about a 100, 10 years ago, this figure can also be compared to Fig. 1 to see the progress the field has done), along with the planets in the Solar System. The large population of points in the upper right quadrant of Fig. 4 illustrates the domain of the gas-giant planets, where the planetary radius is expected to be almost independent of mass because of electron degeneracy in the interiors (see the discussion in “► Brown Dwarf”). The actual observed range of radii is larger than expected and is not yet well understood. Three transiting planets similar to Uranus and Neptune have been discovered, with radii quite similar to their counterparts in our Solar System, despite the fact that they are much hotter. The parameter

space of mass and radius between Uranus and Neptune on the one hand and the Earth and Venus on the other is not populated in the Solar System, but is of great interest because planets with masses in the range 1–10 Earth masses (often called super-Earths) may be enough Earth-like to be potential abodes for life, if there is liquid water on the surface and the primordial atmosphere of hydrogen and helium has been replaced by a secondary atmosphere containing molecules such as carbon dioxide, nitrogen, methane, and water. This region of the parameter space, almost empty 10 years ago is now widely populated, thanks to NASA’s *Kepler* mission. The first two examples of transiting planets confirmed in this region were CoRoT-7b and GJ 1214b. The smaller one, CoRoT-7b, appears to be a very hot rocky planet, while the slightly larger one, GJ 1214b, appears to have a substantial atmosphere of hydrogen and helium and thus is more like a mini-Neptune than a super-Earth. One of the major outcomes of NASA’s *Kepler* mission has been to highlight that this population of Super-Earths/Mini-Neptunes is very common (e.g., Hsu et al. 2019).

Although the atmospheres of several giant, mini-Neptune, and even Super-Earth transiting planets have been detected, HD 189733b is still the poster child for atmospheric studies, initially using both the *Hubble Space Telescope* and the *Spitzer Space Telescope* and also using ground-based observations. Spectral features due to water, methane, carbon dioxide, and carbon monoxide have been reported, and the temperature profile from the nightside to the dayside of the planet has been mapped. These results are described in more detail in the entry on HD 189733.

Observations of the Rossiter-McLaughlin effect have now been reported for more than 250 transiting planets (see review by Triaud (2018) and the catalog <https://www.astro.keele.ac.uk/jkt/tepcat/obliquity.html>). These planets are almost all gas giants though thanks to new spectrophotographs (like ESPRESSO), it is now possible to obtain Rossiter-McLaughlin detections for lower mass planets (e.g., recently a super-Earth, see Kunovac Hodžić et al. 2021). Curiously, the first nine systems all showed pretty close alignment between the



Transiting Planets, Fig. 4 Masses and radii for the transiting planets published as of 2021 (<https://exo-planetarchive.ipac.caltech.edu/>), along with the planets in the Solar System (Venus, Earth, Uranus, Neptune, Saturn, and Jupiter). Comparing this figure with Fig. 1 illustrates the progress made from 2007: many more planets were

discovered, in particular in the bottom left part of the diagram: where the small possibly rocky planets lie. Most of these new planets were discovered by *Kepler*. The horizontal axis is mass in Jupiter masses (bottom) and Earth masses (top). The vertical axis is radius in Jupiter radii (left) and Earth radii (right)

orbital plane of the planet and the equator of the star as defined by its rotation. The following systems showed a range of misalignments, including some retrograde orbits (e.g., Triaud 2018). The distribution of alignments may be consistent with an evolutionary scenario in which planetary systems form in a disk and thus are initially coplanar, but subsequently the orbits are disrupted by gravitational encounters between planets. The planets that are scattered into orbits that pass close to the star experience tidal forces that tend to circularize the orbit by pulling in the apastron (see “► [Periastron](#)”). The planets that survive in wider orbits are less affected by tidal forces and can retain the eccentricities and inclinations that they received during the scattering era. However, this may not be the only mechanism responsible for the migration of giant planets from the cold outer regions where they formed into the inner regions where they are observed. The *Kepler* mission and more recently the TESS mission have announced several

systems that show multiple transiting planets where all the orbits are within about a degree of being coplanar. Furthermore, a small number of these multi-planet systems have been found to be in mean motion resonance (the ratio of the orbital periods of adjacent planets is a ratio of integers), like the Kepler-223 system (Mills et al. 2016) and the TRAPPIST-1 system. Presumably, these systems have not been disturbed from their initial flat geometry dictated by the protoplanetary disk from which they formed, and the migration process must have been gentle. The resonance configuration of some of these systems is also thought to be an outcome of a smooth migration within the disk. To reproduce the ratio of observed resonant systems over all the multi-planet systems, 95% of resonant chains have to be disrupted by the end of the disk phase (Izidoro et al. 2017). On a related note, the *Kepler* data also showed that there is an excess of period ratios that are just slightly larger than some resonances, as though the systems were

formed in these resonances and slightly departed from them over time (e.g., Fabrycky et al. 2014). This feature occurs naturally when resonant planets undergo dissipation (like tides) which damps the eccentricities. Instabilities occurring when the protoplanetary disk dissipates and dissipative processes can therefore disturb the resonant chains naturally formed by migration in the disk. Another remarkable characteristic of the multi-planet systems discovered by *Kepler* is that all the planets within each system appear to be similar in sizes and regularly spaced (like peas in a pod, Weiss et al. 2018). Planetary formation and evolution models help understanding these trends (e.g., Mishra et al. 2021), although there are still open questions. *Kepler* 9 is the first system of planets to show convincing evidence for transit time variations. The two outer planets are very close to a 2:1 mean motion resonance, with periods of 19.2 and 38.9 days. The observed variations in transit times are sufficient by themselves to confirm the planetary nature of the transits. This discovery illustrates the potential for confirming small planets enabled by continuous photometric monitoring over many months and even years.

Future Directions

The *Kepler* mission monitored a field of view that covered only 100 square degrees, just one part in 400 of the entire sky, and CoRoT covered even less area of the sky. To identify the best transiting systems for the confirmation and characterization of small planets, especially ones in their Habitable Zones, it is necessary to survey the entire sky for the nearest and brightest examples. This is what the Transiting Exoplanet Survey Satellite (TESS) has been doing since 2018. By the end of June 2021, TESS has confirmed 131 planets (around 70 new ones) and counts more than 4000 planetary candidates. Since the beginning of 2020, the Swiss satellite CHEOPS has also contributed to better characterizing planets around bright stars. These two missions are ongoing and will contribute significantly to the deeper understanding of

planetary systems. Another example of such missions is PLATO, which has been selected as an ESA M-Class mission to be launched in 2026. In particular, PLATO will determine the radii of the planets with extreme precision and astero-seismology measurements will allow to put exquisite constraints on the age of the system. PLATO has also been designed to find Earth-size planets orbiting at 1 AU from a Sun-like star. Planets smaller than Neptune can have a wide range of compositions and structures and atmospheres, and using just the observable mass and radius to distinguish between different possibilities remains a challenge. However, with the spectrograph ESPRESSO which can measure or refine the masses of the new TESS or CHEOPS planets, the characterization of the population of exoplanets will improve in the years to come. Furthermore, the James Webb Space Telescope (to be launched on December 2021) will allow to probe the atmosphere of some transiting Habitable Zone planets (see “► [TRAPPIST-1 System](#)” and “► [Planet Characterization: Transmitted](#)”), which is going to mark the beginning of an exciting era.

Cross-References

- [51 Pegasi B](#)
- [CoRoT Satellite](#)
- [Dwarf Star](#)
- [ESPRESSO](#)
- [Exoplanets, Discovery](#)
- [Giant Planets](#)
- [Habitable Zone](#)
- [HARPS](#)
- [HATNet](#)
- [HD 189733B](#)
- [HD 209458B](#)
- [Kepler](#)
- [LHS-1140b](#)
- [MEARTH](#)
- [Optical Gravitational Lensing Experiment](#)
- [Planet Characterization: Transmitted](#)
- [Planet Detection: Transit Timing Variation](#)
- [Planetary Migration](#)

- [Radial-Velocity Planets](#)
- [Spectroscopic Orbit](#)
- [SPECULOOS](#)
- [Super-Earths](#)
- [Transit](#)
- [TRAPPIST-1 System](#)
- [TrES](#)
- [WASP](#)

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Transition Metals

- [Trace Metals](#)

Translation

Juli Peretó
Institut Cavanilles de Biodiversitat i
Biologia Evolutiva, Universitat de València,
València, Spain

Synonyms

[Protein synthesis](#)

Definition

Translation is the biosynthetic process by which a nucleotide sequence in an mRNA is decoded into an amino acid sequence of a ► [protein](#), following the equivalences dictated by the ► [genetic code](#). As a metabolic process, it consists of a complex set of reactions, with a high-energy demand and limiting cell growth. The essential steps occur inside the ► [ribosome](#) where the catalytic ability to form the peptide bond is performed by a ► [ribozyme](#) (the large subunit rRNA).

Cross-References

- [Gene](#)
- [Genetic Code](#)
- [Genetics](#)
- [Protein](#)
- [Ribosome](#)
- [Ribozyme](#)
- [RNA](#)

Translation Machinery

- [Ribosome](#)

Translucent Interstellar Clouds

Steven B. Charnley
Solar System Exploration Division,
Astrochemistry Laboratory, Greenbelt, MD, USA

Definition

A translucent interstellar cloud is one that has visual extinction intermediate between that of a ► [diffuse cloud](#) and that of a dense ► [molecular cloud](#). Despite the importance of photochemical processes over much of their extent, translucent clouds contain significant molecular column densities. Translucent clouds can be studied both in molecular absorption and emission lines. This term is also used to describe lines of sight through the diffuse edges of dense clouds.

Cross-References

- [Column Density](#)
- [Dense Cloud](#)
- [Diffuse Cloud](#)
- [Molecular Cloud](#)
- [Photochemistry](#)

Transmission Spectroscopy

- [Planet Characterization: Transmitted](#)

Transport, Biological

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

Transport refers to the exchange of molecules across cell membranes. There are two types of biological

transport, passive and active. Diffusion or passive transport is a kind of transport by which ions or molecules move along a concentration gradient, from an area of higher concentration to an area of lower concentration. In moving substances across a biological membrane, a passive transport may or may not need the assistance of a membrane protein (carrier). Carrier-mediated transport shows a characteristic saturation effect. Passive transport does not require energy. In contrast, active transport is responsible for the movement of ions and molecules in and out of a cell across a selective semipermeable cell membrane against a concentration gradient. In this case, chemical energy is required because osmotic work has to be performed. Transport and ► [energy conservation](#) are intimately related (see ► [“Bioenergetics”](#)).

Cross-References

- [Bioenergetics](#)
- [Cytoplasmic Membrane](#)
- [Energy Conservation](#)
- [Proton Motive Force](#)

Transvaal Supergroup, South Africa

Axel Hofmann
Department of Geology, University of
Johannesburg, Johannesburg, South Africa

Definition

The Transvaal Supergroup is best known for excellent exposures of a mixed siliciclastic-carbonate ramp grading upward into an extensive carbonate platform overlain by banded-iron formation. Deposited on the Kaapvaal ► [Craton](#) between 2,670 and 2,050 Ma, the Transvaal Supergroup is best preserved in the Transvaal and Griqualand West structural basins in South Africa and extends into Botswana as the Kanye basin. The Transvaal Supergroup rests on

the ≥ 2.70 Ga Ventersdorp Supergroup or older rocks with an angular unconformity and is intruded by the 2.05 Ga Bushveld Complex. In the Transvaal subbasin, it comprises two unconformity-bounded sequences:

1. Quartz arenites of the Black Reef Formation overlain by predominantly chemical ► [sedimentary rocks](#) (dolomite and ► [banded-iron formation](#)) of the Chuniespoort Group (including rock sequences of the well-developed ► [Campbellrand-Malmani](#) platform)
2. Sandstones, mudrocks, carbonates, glacial diamictites, and minor basalt-andesite flows of the Pretoria Group

The Transvaal Supergroup has been studied by astrobiologists for its banded iron formation deposits, abundant ► [stromatolites](#), and its record of the Great Oxygenation Event.

Cross-References

- [Banded Iron Formation](#)
- [Campbellrand-Malmani Platform, South Africa](#)
- [Great Oxidation Event](#)
- [Sedimentary Rock](#)
- [Stromatolites](#)

Trapped Fluids

- [Fluid Inclusions](#)

TRAPPIST-1 System

Emeline Bolmont and Martin Turbet
Department of Astronomy, Université de Genève,
Versoix, Switzerland

Keywords

Exoplanets · Transit · Habitable zone ·
Habitability · Atmospheres · Characterization

Definition

TRAPPIST-1 is an extraordinary planetary system whose discovery was announced in 2016–2017. The system hosts at least seven transiting planets, which orbit very close to a nearby very small star (only 9% the mass of the sun). Among these seven planets, three of them are in the classical Habitable Zone, defined as the region around a star where a planet with the right atmosphere can sustain surface liquid water. This system is known to have an exquisite precision in terms of the radii and masses of the planets, which makes it the system with the best constraints after our own solar system. Finally, the planets of this system are excellent targets for atmospheric characterization, for instance with the James Webb Space Telescope and ELT instruments.

Overview

TRAPPIST-1 is a remarkable planetary system, with at least seven planets in a compact configuration orbiting a small star. The farthest detected planet is at a distance of about 6% the Earth-sun distance. This system is being and will be intensively studied due to its richness for the following reasons: (Gillon et al. 2017) it hosts planets which could harbor surface liquid water, (Gillon et al. 2016) it has an interesting dynamical configuration, shaped by its history and its interactions with the host star, (Agol et al. 2021) the densities of the planets are now known to have an exquisite precision and were found to be very Earth-like and to share a very similar interior composition, and (Ducrot et al. 2020) the atmospheres of these planets will be spectroscopically characterized in the near future, with the James Webb Space Telescope (JWST), for instance. Indeed they all frequently transit a very small star, which makes them good targets for transmission spectroscopy.

Basic Methodology

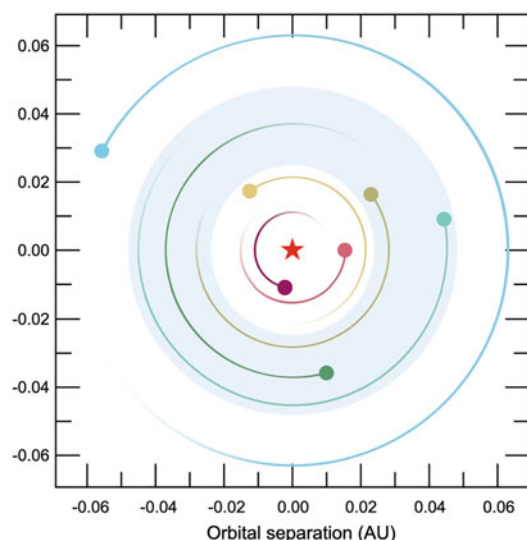
Constraints from Observations

Transits. The system was discovered using the transit method, which monitors the dip in

luminosity coming from the star when a planet passes in front of it. The TRAPPIST-1 system was discovered using a small 60-cm ground-based telescope (TRAPPIST for TRANSiting Planets and Planetesimals Small Telescope) located on the site of La Silla in Chile. In late 2015, this telescope monitored the light coming from a small star and the observed light curves showed some dips. After careful analysis of the signal, Gillon et al. (2016) published the detection of two planets, TRAPPIST-1b and c, with some hints at a third planet in the system.

Motivated by this discovery, subsequent intense monitoring of the system was carried out by the NASA satellite Spitzer in 2016, and the signals which were originally attributed to a potential third planet were actually corresponding to several additional planets in the system (Gillon et al. 2017). The planets were named TRAPPIST-1d, e, f, and g. In the Spitzer data, there was an orphan transit which was attributed to a TRAPPIST-1 h. Using the knowledge of the particular dynamical configurations of the six inner planets, the orbital period of planet h was hypothesized to be around 18 days. And this was later confirmed in Luger et al. (2017), using data from the K2 satellite. Although some orphan transits have been detected in the Spitzer data, they are of low significance and are therefore not attributed to new planets (Ducrot et al. 2020) (Fig. 1).

Transit timing variations. Follow-up observations allowed for better constraining of the properties of the star and its planets, in particular for their radii (e.g., Delrez et al. 2018) and masses (e.g., Grimm et al. 2018; Agol et al. 2021). While the radius of the planet is a natural outcome of the transit method, the masses of the planets were derived using the transit timing variation technique. Transit Timing Variations (TTVs) happen when the orbit of a planet is perturbed from a perfect Keplerian orbit. In the absence of additional planets, the transit of one planet would occur at regular intervals (every orbital period). If there is an additional planet in the system, there will be gravitational interactions which will perturb the orbit, sometimes delaying the transit, sometimes advancing it. These are the transit timing variations. For TRAPPIST-1, the planets are in a very compact configuration and a



TRAPPIST-1 System, Fig. 1 Representation of the orbits of the seven planets. The blue area represents the extent of the Habitable Zone. (Figure adapted from Gillon et al. (2017))

dynamical configuration, which exacerbates the TTVs. Using the TTVs for all the planets, models can be run to infer their masses. Grimm et al. (2018) showed, using this technique, that the planets have a composition somewhat similar to the Earth and that some of them may even have a large reservoir of volatiles (i.e., water). Recently, 447 transit times over 4 years of observations were compiled to derive even more precise masses (Agol et al. 2021). These masses allowed for better constraining of the range of possible compositions of the planets.

Transit spectroscopy. Measuring the transit depths of the planets at different wavelengths can be very instructive. If the instrumental biases are perfectly removed and if there is no contamination from stellar activity, the dependence of the transit depth (or planetary radius) with wavelength is due to the absorption from the planets' atmosphere. This technique is called transit spectroscopy (see also planet characterization: transmitted light). Transit spectra of TRAPPIST-1b to h were measured in the mid-infrared with Spitzer (Delrez et al. 2018; Ducrot et al. 2020) and in the near-infrared with the WFC3 instrument of the Hubble Space Telescope (De Wit et al. 2016, 2018; Lionel Garcia and Michael Gillon, private

communication). The results are discussed in the section “Key Research Findings.”

Constraints from Simulations and Theory

Parallely to the efforts to observationally constrain both the structure and the atmosphere of the planets, many theoretical studies aimed at understanding the system.

Planet formation and dynamics. The formation of the system and the water delivery to the planets was investigated using models that account for N-body dynamics and the effect of the disk. Planets embedded in protoplanetary disks interact with the gas and dust and this can lead to migration (in most cases, an inward migration), which can lead to collisions and ejections. These codes aim at reproducing this migration in order to better understand the system's current dynamical state. Simulations of the tidal N-body dynamics of the system have also been performed to try to constrain today's dynamical state, for instance to understand the particular resonant configuration of the system (e.g., Papaloizou et al. 2018), or to infer the rotation state of the planets and the resulting tidal heat flux (e.g., Turbet et al. 2018).

Water loss. Some other theoretical studies also tried to estimate the amount of water lost by the planets during the long hot pre-main sequence phase of the host star. The evolution of a small star like TRAPPIST-1 is different from the evolution of a sun-like star. The pre-main sequence is the early stellar evolution phase during which the star contracts and its luminosity decreases. When the temperature in the center of the star reaches the temperature allowing for hydrogen fusion, the star enters the main sequence and its luminosity becomes constant. The pre-main sequence phase for a small star like TRAPPIST-1 lasts much longer than for a sun-like star. This means that a planet in the Habitable Zone today initially received levels of insolation that were too high to sustain surface liquid water. During that long pre-main sequence phase, all the water is therefore in gaseous form in the atmosphere and is submitted to the high-energy radiation (X and Extreme UV) coming from the star. These radiations can break up the molecules of water and make the hydrogen and oxygen atoms escape the gravitational pull of the planet (Bolmont et al. 2017).

Atmospheric escape can also be driven by magnetic interactions (e.g., Garraffo et al. 2017).

Climates. Many theoretical studies aim at (Gillon et al. 2017) constraining the planets' atmospheres and (Gillon et al. 2016) assessing the planets' potential to host surface liquid water. These studies are usually done with climate models, either 1D (only one globally averaged vertical column of the atmosphere is modeled) or 3D (altitude, latitude, and longitude are modeled; see Turbet et al. 2020b). These models can also be coupled with photochemical models in order to account for the influence of the stellar radiation on the chemical composition of the planets' atmosphere (e.g., Chen et al. 2021). For different assumptions on the atmospheric composition, one can compute the size of the planet and how it varies with wavelength and rule out certain compositions, for instance, and one can also test the capacity to sustain surface liquid water.

Key Research Findings

Using all the constraining methods detailed in the previous section, many discoveries were made about the system.

Dynamics and Compositions

This system is extraordinary concerning its dynamical configuration: the planets are close to mean motion resonances. Just like the three inner satellites of Jupiter which orbit the planet with period ratios of 4:2:1 (while Io orbits Jupiter 4 times, Europa orbits it twice, and Ganymede once), the planets of TRAPPIST-1 orbit their stars with ratios of 24:15:9:6:4:3 (Luger et al. 2017). Not only are the planets in mean motion resonances, each set of three planets is also in a three-body resonance called a Laplace resonance (another similarity to the Jovian system).

This particular orbital configuration is thought to be an inheritance from the formation stages and the following tidal evolution. One possible formation pathway is migration in the disk from outside the snowline (the radial position in the disk where water condenses from gas to solid). Indeed, while the protoplanets are still embedded in the gas and

dust protoplanetary disk, they can migrate due to the disk interactions. In that scenario, the planets are initially formed far from the star, out of the snowline, and are therefore water-rich. One outcome of several planets migrating in a disk is the creation of these long resonant chains of planets (e.g., Izidoro et al. 2017; Coleman et al. 2019). The majority of these chains destabilize when the disk dissipates, but some of them survive, and TRAPPIST-1 is one of the best examples (e.g., Tamayo et al. 2017). Another formation pathway is in situ formation (MacDonald and Dawson 2018). In that scenario, the planets only migrate a small distance and form close to their present location. Therefore, they do not all originate from outside the snowline and are hence expected to have a drier composition. In situ formation can also reproduce the main characteristics of the system, like the mean motion resonances and the three-body resonances. The main difference between the two pathways is the theoretical amount of water that makes up the bulk of the planet: water-rich for the long-range migration and water-poor for the in situ formation.

For the systems which survive the disk dissipation, tidal dissipation can later play a role by also driving migration. Migration changes the distance between the planets and, in particular, tidally induced migration can also explain the more specific three-body Laplace resonance (e.g., Papaloizou et al. 2018). It was also shown in Turbet et al. (2018) that tides lead to a quick synchronization of the rotation of the planets and a damping of the eccentricities. Just like the Jovian satellites, the small eccentricities are enough to drive significant tidal heating in the close-in planets and Earth-like levels of heating for the Habitable Zone planets (e.g., Barr et al. 2018; Makarov et al. 2018; Bolmont et al. 2020). Although this level of heating should not have a major impact on the climates of the HZ planets, it could influence the surface temperature of the potential cold traps on the nightside of the planet where the gases that make up the atmosphere can condensate or it could also influence the depth of an eventual subsurface ocean (see Turbet et al. 2018).

Thanks to the method of the Transit Timing Variations recently used in the Agol et al. (2021)

study (see section “[Basic Methodology](#)”), the planetary masses are now known with exquisite precision. Contrary to the previous study of Grimm et al. (2018), where some compositional differences have been hypothesized, these new results show that all planets can in fact be described by a single interior composition (see Fig. 2): either an Earth-like composition but slightly depleted in iron (21% vs 32% for the Earth) or an Earth-like composition but with a light-element enhancement (e.g., a surface water layer).

However, the latter scenario is not favored. In fact, using the mass-radius relations for planets with steam atmospheres (Turbet et al. 2020a; Agol et al. 2021; Acuña et al. 2021), these new mass measurements show that the inner planets are most likely to be dry. This is compatible with several theoretical studies (e.g., Bolmont et al. 2017; Bourrier et al. 2017; Garraffo et al. 2017; Dong et al. 2018), which showed that the atmospheric escape for the inner planets of the system is a very efficient process. The outer planets’ masses and radii are compatible with some non-negligible amount of water, which could be a clue that they indeed formed outside the snowline and

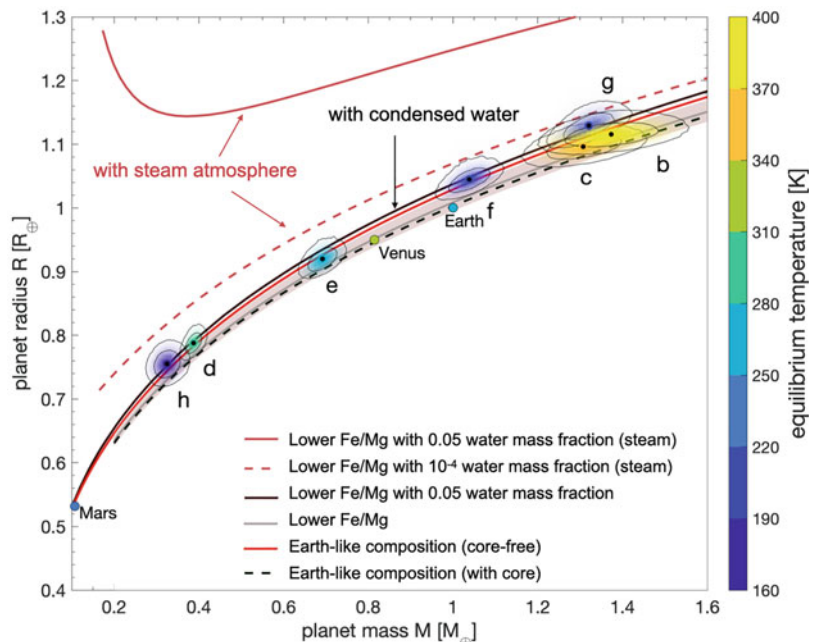
migrated in and that they did not lose their water as the inner planets did.

Atmospheres and Habitability

One of the most fascinating features of the system is that three planets are located inside the Habitable Zone. This system is ideal to deepen the understanding of the concept of habitability with planets both in the Habitable Zone and outside of it. Just as understanding Mars and Venus helped us fathom the specificities of Earth’s climate, investigating all the planets of the system will help us comprehend the potentially habitable planets of TRAPPIST-1.

The investigation on the atmospheres of the TRAPPIST-1 planets has been done observationally and theoretically with climate simulations, whether 1D or 3D. As explained in the “[Basic Methodology](#)” section, the system has now been observed with a large number of astronomical observatories (see Turbet et al. 2020b and references therein). Observations by the **Hubble Space Telescope** (HST) (de Wit et al. 2016, 2018; Wakeford et al. 2019) and Spitzer (Delrez et al. 2018; Ducrot et al. 2020) were used to perform pioneering transit spectroscopy measurements of

TRAPPIST-1 System,
Fig. 2 Mass-radius relationship for the TRAPPIST-1 planets based on TTVs analysis. The contours show the mass and radius of the planets. The full lines represent theoretical mass-radius relations for different assumptions. (Figure adapted from Agol et al. (2021))



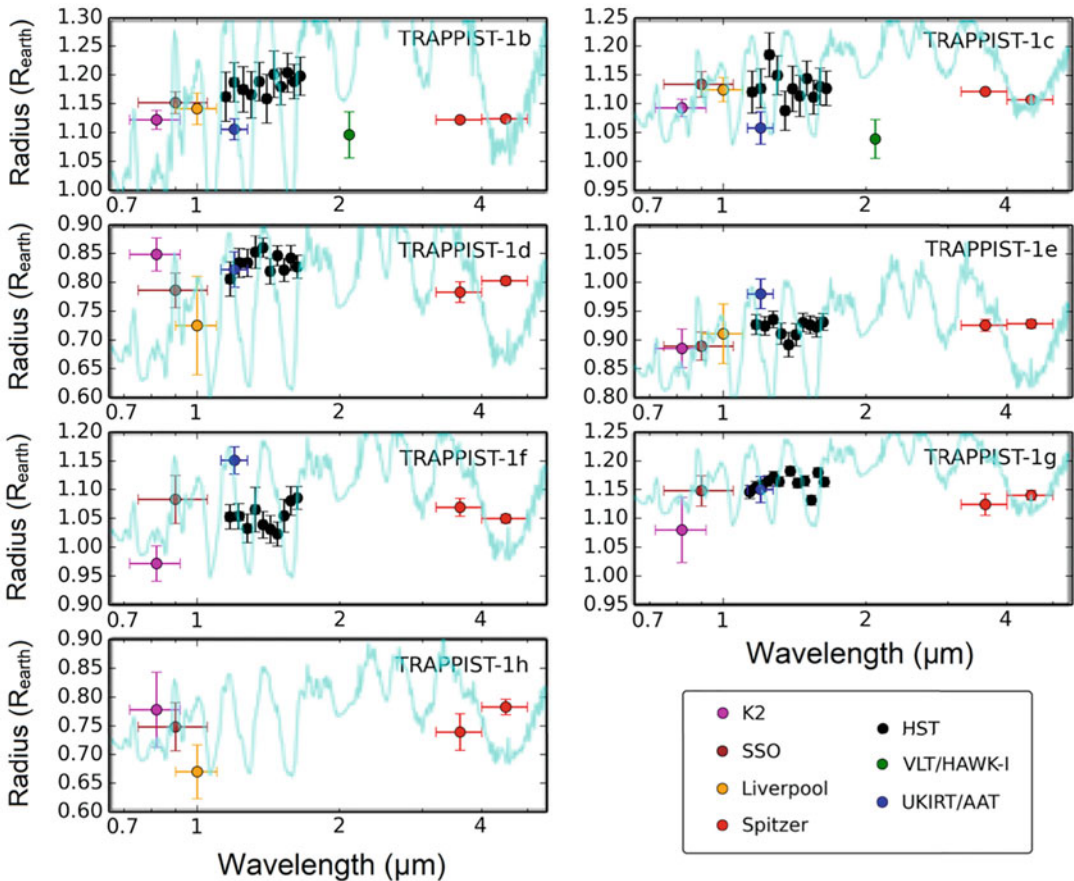
the planets. These observations allowed for the ruling out of the presence of clear light-weight (i.e., low metallicity) hydrogen-dominated atmospheres for all TRAPPIST-1 planets, with a variable degree of certainty depending on the planet. This result is illustrated in Fig. 3, which shows that the expected spectral variations of a cloud-free H_2 -dominated atmosphere (mainly due to absorption by H_2O and CH_4) are much larger than those individually observed by HST (from 1.1 to 1.7 microns) and/or Spitzer (between the two observation channels, at 3.6 and 4.5 microns).

Data could in principle still be in agreement for most planets with a hydrogen-dominated atmosphere with either high-altitude clouds/hazes

and/or with heavy weight (due to a very high metallicity).

However, the presence of hydrogen-rich atmospheres (whether it is cloudy or not; whether it has a low or high metallicity) should produce a large dispersion of the density between the planets (Turbet et al. 2020a) – because small variations in mass, temperature, metallicity, and cloud/haze position of the hydrogen atmosphere should produce large variations in radii – which can now be ruled out using the most accurate density measurements available (Agol et al. 2021).

In sum, this means that the planets of TRAPPIST-1 are not hydrogen-dominated and



TRAPPIST-1 System, Fig. 3 Transit spectra for the TRAPPIST-1 planets: the points correspond to the measurements coming from different space telescopes (Kepler

(K2), Hubble Space Telescope (HST), and Spitzer) and the blue curves correspond to model spectra of (cloud-free) hydrogen-dominated atmospheres

could therefore be composed of heavier molecules like N_2 , CO_2 , H_2O , O_2 , or CH_4 , or not have an atmosphere at all.

Now that a primitive atmosphere has been ruled out, can any of the planets of TRAPPIST-1 sustain liquid water at their surface? This would mean that 1) they have an atmosphere, 2) they have some water, and 3) this water can be liquid at the surface.

The issue with 1) and 2) is that during the long pre-main sequence of the star, the high luminosity and the high energetic radiations could have driven significant atmosphere loss and therefore water loss. The main conclusions of the review of Turbet et al. (2020b) concerning the existence of different atmospheres on the planets are given below:

Hydrogen atmospheres. Given the constraints on the masses and radii of the planets (e.g., from Agol et al. 2021), the constraints based on HST and Spitzer transit spectra (e.g., De Wit et al. 2018; Ducrot et al. 2020), and the constraints coming from atmosphere escape models (e.g., Bourrier et al. 2017), it is unlikely that the planets were able to retain a hydrogen atmosphere (either clear or cloudy/hazy). The detailed justification of this rationale is given in Turbet et al. (2020b).

Water envelopes. From the masses and radii of the planet, it is also possible to infer the content of water of the planet (under certain assumptions on the rocky core): the inner planets of TRAPPIST-1 (b to d) are likely to have a low water content (a water mass fraction below 10^{-3}) and the outer planets (e to h) could have water mass fractions as high as a few % (Agol et al. 2021). A drier inner system and a wetter outer system is compatible with (Gillon et al. 2017) a formation farther away in the disk and therefore a water-rich initial composition and (Gillon et al. 2016) the hydrodynamic water loss calculations of Bourrier et al. (2017). They found that the inner planets lose their water since their formation up to the present day, which can amount to between 25 and 90 Earth oceans lost. However, if the outer planets stop losing water when they reach the Habitable Zone, they lose much less water (less than 3 Earth oceans).

Future Directions

One of the features that makes this system particularly interesting is the future observation prospects of their atmospheres. Indeed, thanks to the proximity of the system to Earth, thanks to the size of the host star and the short orbital periods of the planets, it will be possible to probe the atmospheres of the TRAPPIST-1 planets. For instance, using transit spectroscopy with the James Webb Space Telescope (JWST), it will be possible to put constraints on these atmospheres. The system is the target of two proposals the Guaranteed Time Observations Programs in Cycle 1 and following the call for proposals for the General Observer Programs in Cycle 1, three proposals targeting the system's planets were accepted (<https://www.stsci.edu/jwst/science-execution/approved-programs/cycle-1-go>). The system is the target of two proposals in the Guaranteed Time Observations Programs in Cycle 1 and following the call for proposals for the General Observer Programs in Cycle 1, three proposals targeting the system's planets were accepted.

Cross-References

- ▶ Planet Characterization: Transmitted
- ▶ Planet Detection: Transit Timing Variation
- ▶ Speculoos
- ▶ Synchronous Rotation
- ▶ Transit
- ▶ Transiting Planets

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Trapps

Nicholas Arndt¹ and Daniele L. Pinti²

¹Emeritus Professor, ISTerre, University Grenoble Alpes, Grenoble, France

²GEOTOP Research Center for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

Basaltic flood plains; Continental Flood Basalt Provinces; Flood basalt; Traps

Acronyms

CFB

Definition

Trapps is a Swedish word for “stairs” a reference to the step-like topography of the basaltic sequences. Most flood basalts erupted subaerially, hence the name of Continental Flood Basalt or CFB but they can erupt also as a part of an oceanic plateau, and together forming the group of large igneous provinces (LIP). Flood basalts form thick (500 to more than 3000 m thick) volcanic sequences that cover large areas, up to 1.5 million km² in the case of the largest one, the Siberian Traps. Most authors believe that the trapps formed through the melting of large mantle plumes. The distribution of volcanism is primarily controlled by existing lithospheric and crustal weaknesses (Jerram and Widdowson 2005). The main phase of volcanism consists of repeated episodes of eruption of tholeiitic basalts that generate large tabular flows and flow fields in a relatively short period of time (1–5 Ma). The overall duration of flood volcanism last 5–10 Ma. The volume of igneous rocks erupted by the 16 identified CFB and oceanic plateaus formed in the last 500 Ma on Earth exceeds the total output of present-day mantle plumes and even possibly exceeds over short times the entire crustal production at mid-ocean ridges, making CFB major geodynamic events in the Earth history (Courtilot and Renne 2003). Plausible chronological relations exist between CFB and major biological and geological crisis such as mass extinctions and oceanic anoxia events, suggesting that the large volume of lava flows, associated toxic sulfur gases and CO₂ emission in the atmosphere produced by fires could have played a role in those events (Courtilot and Renne 2003).

Cross-References

- Basalt
- Deccan Trapps
- Igneous Rock
- Mass Extinctions

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Cross-References

- ▶ [Exoplanets, Discovery](#)
- ▶ [HATNet](#)
- ▶ [Kepler](#)
- ▶ [Transiting Planets](#)
- ▶ [WASP](#)

Traps

- ▶ [Trapps](#)

Tree of Life

- ▶ [Phylogenetic Tree](#)

TrES

David W. Latham
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, USA

Synonyms

[Transatlantic Exoplanet Survey](#)

Definition

The Transatlantic Exoplanet Survey (TrES) is a wide-angle ground-based photometric survey for transiting exoplanets. Large areas of the sky are monitored robotically using three small (4 in.) telescopes located at the Palomar Observatory in California, the Lowell Observatory in Arizona, and the Instituto de Astrofísica de Canarias on Tenerife. The first exoplanet found by a ground-based wide-angle survey using small telescopes was named TrES-1, and TrES-2 was the first transiting planet found in the field of view of NASA's Kepler mission.

Tricarboxylic Acid (TCA) Cycle

- ▶ [Citric Acid Cycle](#)

Trihydrogen Nitride

- ▶ [Ammonia](#)

Triple Point

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Meguro-ku, Tokyo,
Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, the triple point of a substance is the point in a pressure/temperature regime under which a compound exists in all three states of matter in thermodynamic equilibrium: gas, liquid, and solid. The triple point of water occurs at 273.16 K (0.01 °C) and a vapor pressure of 611.73 Pa. As the temperature of the triple point of water is an exact defined value and not a measured quantity, the triple point of water can be used to define the Kelvin.

Cross-References

► [Water, Solvent of Life](#)

Tritium

► [Hydrogen Isotopes](#)

Triton

Therese Encrenaz
LESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Keyword

Neptune's satellites

Definition

Triton is Neptune's largest satellite. It was discovered in 1846, a few weeks after ► [Neptune](#). Triton's average distance to Neptune is 354,800 km, or 14 planetary radii. Triton's orbit is nearly circular but shows a very high inclination (157° , with respect to the normal to Neptune's equator, so that it revolves in retrograde motion around Neptune), which suggests that the satellite was captured. Triton's high inclination, together with Neptune's obliquity (29°), leads to very large variations of the latitude of the subsolar point ($\pm 52^\circ$). As a result, Triton exhibits the largest seasonal effects known in the solar system. Triton, as most of the outer satellites, is in synchronous rotation with its planet: it always turns the same face toward Neptune.

Overview

Prior to the encounter of the Neptune system by the Voyager 2 probe, little was known about

Triton's atmospheric and surface properties. Methane and nitrogen ices had been detected from near-infrared ground-based spectroscopy, which suggested the presence of a stable N_2 atmosphere, but the surface pressure was unknown.

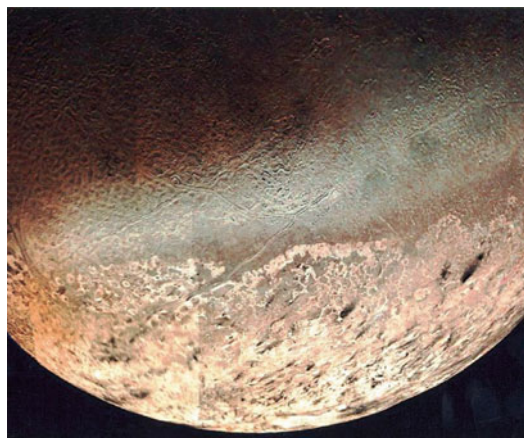
Most of our knowledge about Neptune's largest satellite has come from the Voyager 2 observations. Precise determinations of Triton's diameter (2700 km), density (2.1 g/cm^3), surface temperature (38 K), and surface pressure (14 microbars) were retrieved from Voyager 2 data. With an albedo of 0.76, Triton is among the brightest solar system bodies, and its surface temperature is the lowest ever measured. Nitrogen was found to be the main atmospheric component, with traces of methane at the 0.01% level. The presence of a stable atmosphere, which is unusual on such a small object, can be explained by the low temperature of the satellite, which increases the escape velocity.

Triton's Surface and Internal Structure

Voyager's observations mostly covered the southern hemisphere of Triton. The images revealed a bright, extended polar cap around the South Pole. North of this region, rugged terrain shows a pattern of intercepting ridges, which appear as the remnants of past tectonic activities. There are few craters, which implies that the surface is relatively young. The equatorial region is more cratered and might be 3 billion years old (Fig. 1).

In the bright region around the South Pole, Voyager detected dark trails rising vertically up to an altitude of 8 km and then trailing to the west side over more than 100 km. The most common interpretation of these plumes is active ► [cryovolcanism](#). The outgassed products would be mostly N_2 and CH_4 , which freeze as they reach the surface. Some dust is also present, presumably hydrocarbons, that contributes to the dark color of the plumes. The cryovolcanic activity could be driven by the strong seasonal thermal variations.

In addition to N_2 and CH_4 ices, ground-based near-infrared ► [spectroscopy](#) allowed the detection of a variety of ices: H_2O , CO_2 , CO , and NH_3 . Due to seasonal effects, N_2 and CH_4 are transported alternatively from one polar cap to the



Triton, Fig. 1 The surface of Triton as observed by the Voyager 2 spacecraft in 1989

other. In the atmosphere of Triton, they play a role similar to CO_2 and H_2O on Mars: large-scale dynamical motions are induced by seasonal transfer, as shown by the dynamical motions of the plumes.

Very little is known about the internal structure of Triton. Theoretical models propose a central core of metals and rocks, surrounded by a mantle of water ice, covered by a mixture of various ices.

Triton's Atmosphere

The atmosphere of Triton extends up to an altitude of 800 km. The [troposphere](#) extends up to an altitude of 8 km where the temperature is minimum. The temperature increases again in the thermosphere, to reach a value of 95 K at an altitude of 400 km, where ionization takes place. Hydrocarbon hazes and nitrogen clouds have been identified by Voyager in the southern hemisphere, presently illuminated by the Sun.

In the 1990s, new observations of Triton's surface have been obtained from the ground using the stellar [occultation](#) technique. The atmosphere was found to be more dense than reported by Voyager 2, and the surface temperature increased by 5% between 1989 and 1998. This increase is the sign of an unusually warm summer. A possible reason might be a change in the ice composition of the surface, leading to a lower albedo, or, alternatively, a reddening of the surface due to the geyser activity.

Origin of Triton

What is the origin of Triton? The high inclination of its orbit suggests that it is a captured object. Triton's surface and atmosphere show a striking similarity with [Pluto](#), in terms of physical properties (surface pressure and temperature), atmospheric composition (dominated by N_2 with traces of CH_4), and surface composition (ices of N_2 , CH_4 , CO , CO_2 , H_2O , and NH_3). These similarities strongly suggest that Triton might be a trans-Neptunian object. However, the mechanism of Triton's capture remains unexplained, as the probability of such a capture is quite small.

Cross-References

- [Cryovolcanism](#)
- [Giant Planets](#)
- [Kuiper Belt](#)
- [Neptune](#)
- [Pluto](#)
- [Trans-Neptunian Object](#)
- [Voyager, Spacecraft](#)

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Trojans (Asteroids)

Maria Antonietta Barucci¹ and Sonia Fornasier^{1,2}

¹LESIA, Observatoire de Paris, Université PSL, CNRS, Université Paris Cité, Sorbonne Université, Meudon, France

²Institut Universitaire de France (IUF), Paris Cedex 05, France

Keywords

Asteroids · Jupiter

Synonyms

Lagrangian point objects

Definition

Trojans are all the objects located in the L_4 and L_5 ► [Lagrangian points](#) of the orbit of a planet around the sun or of a large satellite around a planet.

Overview

The objects located in the L_4 and L_5 Lagrangian points of a planet's or large satellite's orbit are called Trojans. The Lagrangian points of stability, L_4 and L_5 , are located at the 1:1 sun-planet (or planet-satellite) resonance and lie 60° of heliocentric (or planetocentric) ecliptic longitude ahead (L_4 , leading point) and 60° behind (L_5 , trailing point) the larger body. The Trojan objects have sufficient dynamical stability to survive over the age of the solar system. The term Trojans originally referred to the ► [asteroids](#) populating the Lagrangian points of Jupiter's orbit, but to date Trojan objects have been also discovered in the orbits of Earth, Mars, Uranus, and Neptune, and Trojan moons are known to orbit at the Lagrangian points of Tethys and Dione, two midsized moons of Saturn.

The numbers of discovered Trojans is close to 10,000 to date, and the vast majority of them populate the L_4 and L_5 swarms of Jupiter. Only 10 Trojans were discovered for the inner planets (1 for the Earth, 9 for Mars), 29 for Neptune, and just one for Uranus. However, the real population of Trojans is expected to be much larger, with millions of objects populating the Jupiter and Neptune L_4 and L_5 swarms. The Neptune Trojan population is expected to be 20 times larger than that of Jupiter, despite the relatively few discovered objects to date.

While the dynamical characteristics are quite well determined, the physical properties of the Mars, Jupiter, and Neptune Trojan populations are not yet well known.

Concerning the Mars Trojans, seven of them form an orbital cluster and share similar olivine-rich composition that may be consistent with an origin from impact ejecta from Mars. However, other Mars Trojans have a different mineralogy, suggesting that they did not form in their current locations.

For the Jupiter Trojans, a number of surveys in the visible and infrared range permitted the casting of light on their physical properties and composition. These asteroids have low albedo and usually a red spectral behavior (the reflectance increasing with the increasing wavelength) consistent with an organic-rich composition. Two models have been proposed for the origin of the Jupiter Trojans. The first classical model considers that the Trojans were planetesimals formed in the vicinity of Jupiter's orbit and captured at the stable points. The other model also invokes the capture of Trojans, but from a more distant disk. This primordial transneptunian disk is also the source of the ► [Kuiper belt](#) or transneptunians objects. This latter dynamical modeling suggests a genetic relation among transneptunian objects and Jupiter and Neptune Trojans. This potential link is strengthened by the fact that both Jupiter and Neptune Trojans have colors and surface composition very similar to part of the transneptunians population in the outer solar system. All these objects are believed to have formed at heliocentric distances in a region rich in frozen volatiles.

Important advances on the knowledge of Jupiter Trojans' physical properties are foreseen in the future, thanks to the ground-based and space new generation telescopes (LSST, ELT, GAIA, JWST) and to the Lucy mission, a NASA discovery mission that will visit six Jovian Trojans between 2025 and 2033.

Cross-References

- [Asteroid](#)
- [Giant planets](#)
- [Jupiter](#)
- [Kuiper belt](#)
- [Lagrange points](#)

Trona

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Tronite](#)

Chemical Formula

$\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$

Definition

Trona is a non-marine evaporitic mineral. It is a hydrated sodium carbonate of the monoclinic crystal system. Trona is the main source of sodium products on Earth. In association with thermonatrite and natron is one of the main minerals precipitating in soda lakes. These particular environments – filled by strong alkaline waters – have been proposed as possible analogues of ancient oceans on Earth. Together with natron, trona has been detected by spectral imagery in silica-rich opaline deposits of the Inner Basin of Columbia Hills at Gusev Crater, Mars.

Cross-References

- [Evaporite](#)
- [Natron](#)
- [Oceans, Origin of](#)
- [Soda Lake](#)
- [Thermonatrite](#)

Tronite

- [Trona](#)

Troposphere

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Definition

The troposphere (from “tropos” = turning) is that portion of the atmosphere of a planet where the dominant means of energy transport is via convection and in which the temperature decreases with height due to adiabatic expansion, above the surface for a ► [terrestrial planet](#) or above an arbitrary level such as the top of the cloud decks for a giant planet like Jupiter. The temperature minimum at the top of the Earth’s troposphere is called the tropopause, above which is the ► [stratosphere](#) (in the case of the Earth, the ► [giant planets](#) and ► [Titan](#)) or the mesosphere (in the case of Mars and Venus).

Cross-References

- [Atmosphere, Structure](#)
- [Atmosphere, Temperature Inversion](#)
- [Giant Planets](#)
- [Mesosphere](#)
- [Radiative transfer \(Atmospheres\)](#)
- [Stratosphere](#)
- [Terrestrial Planet](#)
- [Titan](#)

True Polar Wander, Theory of

Daniele L. Pinti

Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Polar shift](#); [Polar motion](#)

Acronyms

TPW

Definition

True polar wander is the rotation of a planet or moon with respect to its spin axis, causing poles to change position or “wander.” The theory states that the development of an unequal distribution of mass in the interior or on the surface of the planet causes a change in the axis of rotation. Causes of TPW include postglacial crustal rebound, asteroid impacts, change in the core-mantle boundary topography, and mantle avalanches (avalanche of cold, dense crustal slab material into the lower mantle). Earth has undergone several periods of polar wander in the past resulting in cumulative magnitudes of up to 75°. Offset position of paleopolar deposits with respect to Mars poles suggests that the Red Planet has undergone TPW, possibly driven by shift or large-scale volcanism on Tharsis region. TPW might have happened on ► [Enceladus](#) and ► [Europa](#) (up to 80°).

Cross-References

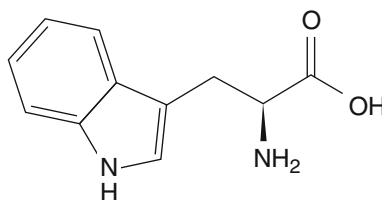
- [Enceladus](#)
- [Europa](#)
- [Mars](#)

Tryptophan

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Tryptophan is one of the 20 protein amino acids (Fig. 1). Its three-letter symbol is Trp and one-letter symbol is W. The molecular formula of tryptophan is $C_{11}H_{12}N_2O_2$ (molecular weight: 204.23). It is the largest among protein amino acids. Its isoelectric point (pI) is 5.89. It was first reported in 1901 in the hydrolysate of casein. Its side chain has an aromatic bicyclic group (indolyl group); it is grouped as an aromatic ► [amino acid](#)



Tryptophan, Fig. 1 Tryptophane

together with phenylalanine and tyrosine. It has poorer solubility in water and organic solvents than most of other amino acids. Since it is decomposed during acid hydrolysis of ► [proteins](#), alkali hydrolysis or enzymatic hydrolysis of samples is required to determine tryptophan. It has not been detected in extraterrestrial samples.

Cross-References

- [Amino Acid](#)
- [Protein](#)

TSI

- [Solar Constant](#)

TTG

- [Tonalite-Trondhjemite-Granodiorite](#)

Tumbiana Formation (Pilbara, Western Australia)

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

The Tumbiana Formation is a 2724 ± 5 Ma old, well-preserved series of calcareous and

micaceous sandstones interlayered with volcanogenic siltstone in the Fortescue Group of the ► [Pilbara craton](#) in Western Australia. These sediments were deposited in a shallow marine or lacustrine environment associated with the influx of riverine freshwater from the continent. The Tumbiana Formation has been the focus of many astrobiological studies due to its content of well-developed, genuine biogenic ► [stromatolites](#) and possible filamentous ► [microfossils](#). Carbon and sulfur isotopes show large variation range at a fine, centimeter to meter scale. Very depleted $\delta^{13}\text{C}$ values down to -60‰ suggest carbon cycling by various anaerobic or aerobic methane pathways, particularly aerobic or anaerobic methanotrophy.

Cross-References

- [Archaean Traces of Life](#)
- [Microfossils](#)
- [Pilbara Craton](#)
- [Stromatolites](#)

Turbidite

Nicholas Arndt
Maison des Géosciences, LGCA, Université
J. Fourier, St-Martin d'Hères, France

Definition

A turbidite is a sediment deposited from a turbidity current, which is a current of sediment-charged water that moves under the force of gravity; it is therefore the product of a mass flow type of sediment movement.

In turbidity currents, sediment grains are eroded and suspended (and thus transported) by turbulence, in contrast to debris flows or grain flows, the other common types of mass flow processes. Importantly, the sediment plays the

essential role in turbidity currents because they impose a density to the flow, which drives it downslope. The water only acts as dilutant, passive lubricant, and induces turbulence. During flow, the turbidity current “tunnels” through the bottom of a standing water column; it slows down (and thus gradually diminishes in turbulence and therefore drops sediment) when the gradient of the slope decreases. Because turbidity currents accelerate near the shelf margin, they can reach large dimensions, and flow steadily over inclined continental slopes, their runout distances can reach many hundreds of kilometers on the flat abyssal plains.

Turbidity currents are the principal transporting agents on continental margins. They remove sediments from the shelf in incised canyons and transport them downslope to the continental rise. There, turbidites accumulate and may form over time strata many km thick.

The sequence deposited from a single turbulent event is called a Bouma sequence and is anywhere from a few cm to several m thick. Provided that the generating turbidity current had a full range of clasts and grain sizes available, a Bouma sequence will be fining upward, often beginning with a granule or coarse-sand-grained layer at the base and pass through the sand to silt and shale at the top, each section also displaying characteristic sedimentary structures generated during a particular hydrodynamic flow phase.

Turbidites have been well documented in Archean supracrustal sequences, such as the Fig Tree Group of the ► [Barberton Greenstone Belt](#). The oldest turbidite has been identified in the 3.8-Ga-old ► [Isua Supracrustal Belt](#) of West Greenland, indicating that deep oceans were already present on the early Earth.

Cross-References

- [Earth, Formation, and Early Evolution](#)
- [Isua Supracrustal Belt](#)
- [Oceans, Origin of](#)
- [Sedimentary Rock](#)

Turbulence (Planetary Disks)

Avi M. Mandell

NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Keywords

Accretion · Migration · Planet formation

Definition

Turbulence is the state of hydrodynamic motion characterized by a chaotic and random direction of fluid flow on short timescales. Turbulence is thought to play a major role in the movement of material in gaseous ► [protoplanetary disks](#) in the radial direction by contributing to the fluid viscosity and leading to the accretion of gas onto the central star and in the vertical direction through stirring due to turbulent eddies. Understanding the effects of turbulence in disks is important in theories of planetary migration (as it can, e.g., lead to a random walk component in ► [planetary migration](#)), the efficacy of accretion from mm- to meter-sized bodies, and the global evolution of disks.

Overview

Turbulence occurs in fluids when the diffusion of momentum within a fluid is inefficient enough to cause the smooth flow of material (called a laminar flow) to become chaotic in direction and amplitude. This causes structures, such as eddies and vortices, to form in the fluid on both large and small spatial scales, leading to increased mixing within the fluid and an increase in energy and momentum convection (“fluid friction”). The efficiency with which the turbulent motions transfer momentum and energy between fluid particles can be summed up in a parameter called the “eddy viscosity.” The level of turbulence within a fluid can be estimated from the Reynolds number, a ratio of the inertial and viscous forces at work.

As material in a ► [protoplanetary disk](#) circles its central star, the gaseous component of the disk functions as a viscous fluid. The gas rotates in a laminar flow if the Reynolds number is low enough, but most likely, turbulence is present at some level. The turbulent motions in the disk may serve to stir up mm-sized bodies in the disk, enhancing collisions and leading to an increased particle accretion rate. However, turbulence may also cause accretion to stall if the stirring does not allow midplane densities sufficient for gravitational instabilities to form.

The mechanism for the growth of objects between 1 mm (where they are dominated by aerodynamic drag and fall rapidly into the Sun) and 1 m in size is one of the unsolved problems in planetary formation, and therefore the role of turbulence on accretion is of great interest. However, the source of turbulence in astrophysical accretion disks is still uncertain. The existence of accretion onto young stars demonstrates that turbulent viscosities cause material to spiral in, but pure molecular viscosity (caused by chaotic interactions between neutral molecules) is not sufficient. Most likely, a mechanism, such as the magneto-rotational instability (MRI), generates the needed turbulence, but this is an active area of research.

Cross-References

- [Accretion, Stellar](#)
- [Orbit](#)
- [Planetary Migration](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Protoplanetary Disk Midplane](#)
- [Viscosity](#)

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Turbulence, Interstellar

Steven B. Charnley

Solar System Exploration Division, Code
691, Astrochemistry Laboratory, NASA Goddard
Space Flight Center, Greenbelt, MD, USA

Keywords

Interstellar medium · Star formation

Definition

Interstellar turbulence describes the compressible and hydromagnetic bulk flow of interstellar gas on many physical scales.

Overview

Unlike the incompressible turbulent flows encountered in terrestrial physics, which are generally subsonic and hydrodynamic, turbulence in the interstellar medium is supersonic, highly compressible, and magnetic. The driving forces of interstellar turbulence are nonuniform and non-homogeneous, involving, for example, supernova blast waves and winds from young stars. Numerical simulations indicate that interstellar supersonic turbulence is dissipated in ► [shock waves](#) and forms gravitationally unstable density enhancements, which collapse to form stars. In dense ► [molecular clouds](#), observed scaling relations between density and ► [linewidth](#) and size (► “[Larson’s Law](#)”) are consistent with the presence of turbulent density and velocity fields.

Cross-References

- [Larson’s Law](#)
- [Linewidth](#)

- [Magnetohydrodynamics](#)
- [Molecular Cloud](#)
- [Shock, Interstellar](#)
- [Supernova](#)

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Two-Body Reaction

- [Bimolecular Reaction](#)

Tyrosine

Kensei Kobayashi

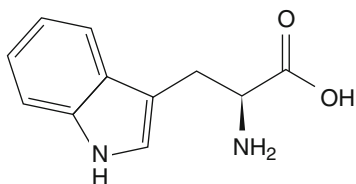
Yokohama National University, Yokohama, Japan

Synonyms

[4-hydroxyphenylalanine](#)

Definition

Tyrosine is one of the 20 ► [protein](#) amino acids (Fig. 1). Its chemical structure is $\text{NH}_2\text{CH}(\text{CH}_2\text{C}_6\text{H}_4\text{OH})\text{COOH}$. Its three-letter symbol is Tyr, and one-letter symbol is Y. Its molecular weight is 181.19, and its isoelectric point is 5.66. Tyrosine was found in cheese protein by von Liebig in 1846. Since its side chain has a phenol group ($-\text{C}_6\text{H}_4\text{OH}$), it is grouped as an aromatic ► [amino acid](#) together with phenylalanine and tryptophan. It has poorer solubility in water and



Cross-References

- [Amino Acid](#)
- [Protein](#)

Tyrosine, Fig. 1 Tyrosine

organic solvents than most of other amino acids. Tyrosine has recently been detected in the extracts from Antarctic carbonaceous chondrites.

U

UAE's Emirates Mars Mission

- [HOPE Mission](#)

UCAMMs

- [Ultra-carbonaceous Antarctic Micrometeorites](#)

UHPLC

- [HPLC](#)

UK Center for Astrobiology

Charles S. Cockell
UK Centre for Astrobiology,
Scottish Universities Physics Alliance (SUPA),
School of Physics and Astronomy,
The University of Edinburgh, Edinburgh, UK
Geomicrobiology Research Group, PSSRI,
Open University, Milton Keynes, UK

Keywords

Astrobiology · Science · Exploration ·
Education

Acronyms

UKCA

Definition

The UK Center for Astrobiology was set up in 2011 as a virtual center to contribute to astrobiology research, education, and outreach.

Its research has focused on studying life in extreme environments, the limits of life on Earth, and investigating the implications for habitability elsewhere. Work has involved a combination of laboratory-based and theoretical approaches. Examples of this research include efforts to understand how combinations of multiple extremes shape the “boundary space” for microbial cell division, studies on adaptations of life to low temperature, radiation, and saline environments. Work has been undertaken to investigate the molecular basis of microbial adaptations to extremes using –omics methods, for example the metagenomic and proteomic study of life in natural brine environments and in laboratory experiments.

Overview

The UK Center for Astrobiology is interested in using the study of life in extreme environments on Earth to understand the potential habitability of

extraterrestrial environments. In addition to laboratory and theoretical studies, the UKCA has been involved in using data from space missions, including ESA Mars missions and International Space Station experiments (e.g., BioRock), either in collaborative projects or in efforts led by the Center. Beyond our own Solar System, the Center's research on life in extreme environments can be used to inform predictions about the habitability of exoplanets.

International projects have included coordination of the European Union (EU) project, MASE (Mars Analogues for Space Exploration), aimed at examining anaerobic organisms in extraterrestrial analogue environments and leading the microbiology effort of the NASA-funded project BASALT (Biologic Analog Science Associated with Lava Terrains).

Among its research infrastructure projects, the Center has assembled the world's first permanent underground astrobiology laboratory, the Boulby Underground Laboratory. Boulby Mine is an active salt mine in the northeast of the UK that includes over 1000 km of roadways at a depth of ~1 km underground. The mine operates in vast evaporite deposits that are ~0.25 Ga old and were formed in the Zechstein Sea. To date, studies have included: genomic and metagenomic studies of organisms that inhabit brines of differing composition, investigations of the microbiome and biosignatures in Permian salts, analyses of gases associated with Permian salts, the study of life at below-background radiation.

Many of the challenges faced by planetary scientists (such as building small miniaturized instruments that are lightweight, require low energy, and operate in extremes) are also challenges faced by those in the deep subsurface mining sector who want instruments to detect and quantify ore quality, map and study subsurface tunnels and structures, and check underground environments for safety. A deep subsurface mine therefore provides an opportunity to carry out deep subsurface planetary science work in a real commercial setting where ideas can fluidly move from scientists and instrument developers to the mining environment. The Center established a

program called MINAR (Mine Analog Research) which uses the underground work to test instrumentation for planetary exploration and/or deep subsurface work. Since 2013, there have been six analogue campaigns that have involved testing a variety of instruments including those developed for Mars exploration, such as the ExoMars CLUPI (Close-Up Imager), Raman and PanCam emulator, and HABIT instrument. The MINAR program has also been used for basic astronaut training by ESA.

The Center has been involved in a diversity of educational activities. Its astrobiology academy, developed in 2013, has been used for the development of lesson plans and curriculum materials for primary and secondary schools. For example, the Center developed a complete astrobiology transition course for primary to secondary school transition in conjunction with the RAISE (Raising Aspirations in Science Education) in Scotland. The Center has overseen an initiative to take astrobiology into prisons. Life Beyond is a project that engages prison inmates in the design of stations for the surface of Mars and in the process develops their scientific and literary skills. The Center has been involved in university research teaching and has overseen the development of an undergraduate astrobiology course at the University of Edinburgh. The center has worked with the Kalam Center/Abdul Kalam University, India, to develop university astrobiology courses and primary and secondary school astrobiology materials. The Center developed the Mars Mission India program with the Kalam Center which involves Indian students in the development of technology for Mars exploration which they test in the underground astrobiology laboratory.

A full summary of the Center and its activities can be found in Cockell et al. (2018).

Cross-References

- [Earth](#)
- [Extreme Environment](#)
- [Habitability of the Solar System](#)
- [Space Biology](#)

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UK Space Agency

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[United Kingdom Space Agency](#)

Definition

The UK Space Agency, launched in March 2010 and replacing the previous partnership structure of the British National Space Centre, has responsibility for policy and key government budgets for civil space programs. It will contribute to the European Space Agency (ESA) (subscriptions previously funded by the Natural Environment Research Council), the Science and Technology Facilities Council (STFC), the Technology Strategy Board (TSB), and management of major EU space-based projects including GMES (Global Monitoring for Environment and Security). The UK Space Agency negotiates on the UK's behalf on international bodies such as the European Space Agency and is represented at all the key ESA bodies.

Involved in numerous space programs, the UK takes a major role in robotic exploration of the solar system. Currently it is the second largest contributor to the ESA ExoMars program. At the Council of Ministerial meeting at ESA in November 2008, an agreement was signed between the UK and ESA to establish a permanent ESA site at the Harwell Science and Innovation

Campus in Oxfordshire. This facility opened in July 2009.

In 2014, the UK Space Agency had around 50 employees.

Cross-References

► [BNSC](#)

Ultrabasic Rocks

► [Ultramafic Rocks](#)

Ultra-carbonaceous Antarctic Micrometeorites

Jean Duprat¹ and Cecile Engrand²

¹Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, CNRS-Muséum national d'histoire naturelle-Sorbonne Université, Paris Cedex 05, France

²IJCLab, CNRS/IN2P3, Université Paris-Saclay, Orsay Cedex, France

Keywords

Extraterrestrial matter · Meteorites · Comets · Interplanetary dust particles · Micrometeorites · Organic matter

Synonyms

[UCAMMs](#)

Definition

UltraCarbonaceous Antarctic Micrometeorites (UCAMMs) are submillimeter-sized extraterrestrial particles with high concentration in carbonaceous material. They most probably originate

from surface of icy parent bodies from beyond Neptune (i.e., comets).

Overview

By contrast with the many different existing types of ► [meteorites](#), the majority of micrometeorites collected at the Earth's surface show chemical and mineralogical similarities with a fairly rare class of meteorite – the ► [carbonaceous chondrites](#) – but do not strictly belong to a given class of carbonaceous chondrites. Among the rare types of particles departing from these “chondritic micrometeorites,” some exhibit extremely high bulk carbon content (>25 wt.%) that exceeds by far that observed in carbonaceous chondrites (typically <5 wt%). These rare micrometeorites are referred to as UltraCarbonaceous Antarctic Micrometeorites (UCAMMs).

So far, UCAMMs have been identified in snow and ice samples from Antarctica (Dome Fuji and Dome C) and might be present in the IDP collections from the stratosphere. The center of the Antarctic continent presents unique advantages to recover rare and unaltered interplanetary particles. It is well protected from terrestrial dust contamination (for particles with sizes greater than 10 μm) as the continent itself is surrounded by oceans and the dominant winds are blowing from the center of the continent to the coast, providing a natural shield against terrestrial particles. Dome C is located at 1100 km from the coasts of Adélie Land and Dome Fuji at about 1000 kms from the coasts of Queen Maud Land. Dome C is the location of the scientific station CONCORDIA (75°S, 123°E) operated by the french and italian polar instituts (IPEV and PNRA). The central Antarctic regions' temperatures stay far below 0 °C throughout the year. Trapped at low temperatures (about –50 °C) in layers of ultrapure snow, the micrometeorites are preserved from terrestrial weathering (mechanical constraints and aqueous alteration). Since the terrestrial component is minimal, it is possible to recover from central Antarctic snow rare and well-preserved micrometeorites.

The extraterrestrial origin of UCAMMs is attested by both their (minor) mineral components

that are similar to that of carbonaceous chondrites and by their isotopic compositions. The isotopic composition of UCAMMs from the Concordia Collection exhibits extreme enrichments in deuterium. The bulk D/H ratio of their organic matter exceeds that of terrestrial oceans by about a factor of 2, and more than a factor of 10 in specific extreme D-rich areas. Such high deuterium excesses trace gas-phase low temperature processes (about 30 K), compatible with the outer regions of the ► [protoplanetary disk](#). The mineral components of UCAMMs mostly consist in fine-grained silicates and Fe-Ni sulfides. The silicates appear as both amorphous and crystalline phases, with individual sizes down to ~50 nm. Among the amorphous phases, some are glassy aggregates containing metal and sulfides (► [GEMS-like](#)) that have been first identified in ► [interplanetary dust particles](#) (IDPs) collected by NASA in the stratosphere. Infrared and Raman analyses of UCAMMs indicate that the abundance of minerals embedded in the organic matter is highly variable, with atomic Si/C ratios of a few percent or lower. The UCAMMs contain both amorphous minerals that may be a direct heritage from the protosolar molecular cloud and crystalline phases that have been processed, in a later stage, within the protoplanetary disk itself. The association of extreme D-rich organic matter with high-temperature minerals confirms that material condensed or processed at close distances from the young Sun can be efficiently transported to several tens of astronomical units, in the outer regions of the protoplanetary disk.

The organic matter of UCAMMs has a polyaromatic structure, as deduced from transmission electron microscopy, IR and Raman spectroscopies. It has a relatively high-bulk nitrogen content compared to the insoluble organic matter (IOM) extracted from carbonaceous chondrites. The atomic N/C ratios of the UCAMM organic matter analyzed so far are ranging from 0.04 up to 0.2. Such values substantially exceed those currently reported in organic matter from primitive meteorites (► [carbonaceous chondrites](#)), chondritic micrometeorites, and most IDPs, which are in the range of 0.01–0.05. The bulk-atomic O/C ratio of organic matter in UCAMMs appears to be

low, a few percent at most. Scanning Transmission X-ray Microscopy coupled with X-ray Absorption Near-Edge Structure (STXM-XANES) showed that the organic matter of UCAMMs is composed of three different phases, two of them bearing resemblance with IOM from meteorites, the third being N-rich (with atomic N/C ratios up to 0.2).

UCAMMs do not have counterpart in meteorite collections. By contrast, UCAMMs bear similarities with a rare type of carbon-rich IDPs, the particles collected by NASA in the comet 26P/Grigg-Skjellerup dust stream, and with the CHON particles observed in comet 1P/Halley by the spatial missions VEGA and GIOTTO. Some rare IDPs exhibit N/C ratios similar to those of UCAMMs in specific sub-micrometer-sized areas, exceptionally as bulk values.

Altogether the chemical, mineralogical, and isotopic data of UCAMMs point toward a cometary origin. However, their extreme organic versus mineral ratio and the high N content of their organic matter require a specific parent body. Incorporating up to several tens of percent of N in the organic matter requires a carbonaceous precursor and energetic processes in an N-dominated environment. Such nitrogen-rich carbonaceous material can be formed by energetic irradiations of nitrogen-rich ices in low-temperature regions of the solar system. Such conditions are encountered at the surface of small objects beyond the trans-Neptunian region, that are submitted to Galactic cosmic ray irradiation.

The UCAMMs provide unique access to the intimate association of high- and low-temperature material from the surface of icy objects, in an unprecedented state of preservation. Therefore, UCAMMs may shed light on physicochemical processes that occurred beyond the nitrogen snow line, revealing organic material from the outer regions of the solar system that cannot be investigated by remote sensing methods.

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Ultracompact HII Regions

Stan Kurtz

Instituto de Radioastronomía y Astrofísica,
Universidad Nacional Autónoma de México,
Morelia, Michoacán, México

Keywords

Photoionization · Bremsstrahlung radiation · HII region · High-mass star · Pre-main-sequence star · Protostar · Protostellar envelope

Acronyms

UC HII region

Definition

It is the dense, ionized gas region surrounding a young, massive star. These regions are smaller and denser than classical HII regions, and they arise at an early stage in the life of a massive star or massive star cluster, after the onset of ultraviolet photon production by the star(s) which ionizes the circumstellar gas but before this over-pressured plasma is able to expand toward pressure equilibrium with the interstellar medium, thus forming a classical HII region.

History

Large-scale radio continuum surveys of the galactic plane, made in the 1960s, identified a number of very compact (unresolved) and bright centimeter-wave radio sources (e.g., Downes and Rinehart 1966). Further observations of these objects with radio interferometers in the 1970s resolved their internal structure, providing accurate measurements of the size and density of these plasma bubbles (e.g., Harris 1973). By the mid-1980s, a dozen or so of these compact HII regions had been identified, with the smallest and densest regions being known as ultracompact HII regions. The situation changed drastically in the late 1980s with the seminal works of Wood and Churchwell (1989a, b). Based on single-dish surveys of compact HII regions, they observed a sample of 80 objects with the Very Large Array and identified 75 ultracompact HII regions. Moreover, correlating their radio survey with the Infrared Astronomical Satellite Point Source Catalog (IRAS PSC), they estimated that as many as 1600 ultracompact HII regions might be present within the galaxy. Subsequent radio surveys have confirmed about half of these and prompted a substantial number of theoretical studies related to this early stage of massive stars.

Overview

Massive stars, i.e., those with a mass greater than about 8 solar masses, produce copious amounts of ultraviolet (UV) photons with energies greater than 13.6 eV, which are able to ionize hydrogen. These stars form within dense molecular cores with typical sizes of about 10^{17} cm and densities of order 10^7 hydrogen molecules per cubic centimeter. Hence, once UV photon emission by the star begins, the circumstellar molecular gas will be dissociated and ionized, forming a plasma bubble, with an initial electron density of order 10^7 cm⁻³ and a temperature of order 10^4 K. The ionized gas is about 100 times hotter than the molecular gas, with a concomitant increase in gas pressure. Hence, the plasma bubble will begin to expand, and the electron density will begin to fall. It is at this stage that the nebula is considered to be an ultracompact HII region, with a size of order 10^{17} – 10^{18} cm and density of order 10^4 cm⁻³.

The size of this photoionized region is determined by equating the rate of ionizing photon emission by the star to the rate of recombinations to excited states of the hydrogen atoms. This analysis was first carried out by B. Strömgren (1939), and the resulting plasma bubbles are known as Strömgren spheres. The hydrodynamic expansion of the Strömgren sphere is highly dependent on the interaction between the ionization front and the shock front, which has been studied quite extensively, both analytically and numerically.

Basic Methodology

Observations of UC HII regions are driven by three key considerations. First, their angular size is small, typically in the range of 0.5–5 arcseconds, and thus high angular resolution is required. Second, their spectral energy distribution peaks in the far infrared, as the stellar radiation is absorbed and reemitted by the dusty envelope of the protostar. Third, the ionized gas, emitting at radio wavelengths, is deeply embedded within dense and dusty molecular cloud cores that present hundreds of magnitudes of extinction

to visible light. This combination of attributes dictates that most observations are made with radio interferometers, operating in the centimeter and millimeter bands. Sub-millimeter and far-infrared observations often lack the angular resolution for studies of the internal structure of the UC HII regions; nevertheless, they can provide important information on the global energetics of the regions and are powerful probes of the molecular cores where the ionized gas is found. The current generation of infrared telescopes allows spectroscopy of less deeply embedded UC HII regions (e.g., Watson and Hanson 1997; Martín-Hernández et al. 2003; Beltrán et al. 2013). Access to this spectral window will be a powerful observational tool for future studies of UC HII regions.

Within the radio window, multifrequency continuum observations provide information on the morphology of the ionized gas and can be used to infer the electron density of the plasma and in turn the rate of ionizing photon emission by the exciting star(s). Radio recombination line observations of highly excited hydrogen atoms provide kinematic information which allow studies of the electron temperature and the internal dynamics of the plasma. Molecular masers, particularly of methanol, water, and hydroxyl, are commonly found in the vicinity of UC HII regions and afford an additional probe of local physical conditions and kinematics.

Theoretical studies of UC HII regions model the expansion process of the nebula and strive to explain the observed morphologies of the regions. Both semi-analytic (e.g., Roth et al. 2014) and numerical studies (e.g., Arthur and Hoare 2006) are common, with the latter using radiation hydrodynamic codes.

Applications

UC HII regions are fairly bright objects at radio wavelengths, and with modern radio telescopes they can be detected throughout the Milky Way, even in regions that are obscured to visible light by dust and interstellar gas. As a result – and in addition to their own intrinsic interest – they are a

useful probe of various galactic properties, including electron temperature, metallicity, and the spatial distribution of massive stars.

Key Research Findings

The most surprising result from Wood and Churchwell’s studies was the large number of UC HII regions. The classical expansion model of a Strömgren sphere, coupled with plausible massive star formation rates, suggests that at any given time we might expect to find at most a few hundred of these objects in the entire galaxy. The much larger number of regions inferred by Wood and Churchwell directly contradicts this expectation, and the discrepancy came to be known as the UC HII “lifetime problem.” Their work suggested that UC HII region lifetimes are several times 10^5 yr – roughly ten times longer than the $\sim 40,000$ yr required to expand beyond the ultracompact state if one assumes the classical expansion model (e.g., Dyson and Williams 1997).

An important consequence of the lifetime problem was the resulting theoretical effort to explain the longevity of these objects. Such efforts generally fall into one of two classes: confinement of the ionized gas by some additional pressure mechanism and replenishment of the (outwardly expanding) ionized gas by the ionization of new neutral material. Fundamental to both of these approaches is the acceptance that the interstellar medium is intrinsically heterogeneous and hence overly simple models (i.e., spherical expansion in a homogeneous isothermal environment) will necessarily miss important physical effects. In particular, the “clumpy” interstellar medium can slow the expansion of the ionized region, serve as a source of raw material to replenish the dense ionized gas, and define the shape (or morphology) of the UC HII region.

A key finding of the early UC HII region surveys was the existence of distinct morphological types. Wood and Churchwell (1989a) identified five morphologies: cometary, core-halo, shell, spherical, and multiply-peaked. A sixth, bipolar morphology has been described by De Pree et al. (2005) and Redman et al. (1998). The

morphology of any given region is determined by many factors, including the age of the region, the density distribution of the circumstellar gas, gas and radiation dynamics, motion of the star, and the presence and strength of a stellar wind, among others. Nevertheless, the fact that only six distinct morphologies have been observed suggests that there is a limited range of physical scenarios that gives rise to these same morphologies. Numerous physical models have been proposed (see review by Churchwell 2002), but observational tests of the models have often been ambiguous. Even so, these attempts to understand the morphologies have proven a rich source of insight into the details of the massive star formation process.

In general terms, the spectral energy distributions of UC HII regions are all the same: at the lowest radio frequencies (~ 1 GHz), the ionized gas is optically thick and presents a rising spectrum, which flattens above a (density-dependent) turnover frequency as the plasma becomes optically thin. Moving into the sub-mm regime, the spectrum rises by two or three orders of magnitude, peaking at wavelengths of a few hundred microns, with the emission arising from the warm dust cocoon surrounding the ionized gas which absorbs most of the stellar luminosity and re-emits it in the mid- and far-infrared. Details of the spectral energy distribution can provide important clues to the structure of the emitting regions. For example, an optically thick spectral index shallower than the nominal (homogeneous) value of +2 is an indication of density gradients within the HII region (Franco et al. 2000). Similarly, the shape of the sub-mm and infrared portions of the spectral energy distribution provides information on the size, location, and composition of the dust and can be used to infer mass accretion rates onto the star (e.g., Wolfire and Churchwell 1994; Osorio et al. 1999).

The electron density-size relation for UC HII regions has been studied by various authors (e.g., Garay and Lizano 1999; Kim and Koo 2001). If the UC HII regions evolve within a homogeneous medium, then one expects the electron density to be proportional to the diameter to the minus three-halves power. However, the exponent is found to be closer to -1 than to -1.5 . The reason(s) for the

shallower relation is not entirely clear. By now it is quite obvious that UC HII regions do *not* evolve in a homogeneous medium, but the smaller value of the exponent can be explained in various ways, both related to the density structure of molecular clouds and to the ionizing photon production of the exciting stars. A definitive understanding of this relation is yet to be established.

Future Directions

Although the lifetime problem is generally considered to be solved, and there is a fairly extensive understanding of the cometary morphology, there are still significant gaps in our knowledge of UC HII regions. The core-halo, multiply-peaked, and bipolar morphologies, in particular, have not been thoroughly investigated. In addition, several recent discoveries related to UC HII regions have yet to be fully explored. These include the presence of extended, lower-density ionized gas surrounding the ultracompact component (e.g., Kurtz et al. 1999; Kim and Koo 2001), the presence of compact radio sources within the ultracompact component (e.g., Rodríguez et al. 2014; Masqué et al. 2017), and the existence of an even smaller and denser class of hypercompact HII regions (e.g., Kurtz 2005; Cesaroni et al. 2019).

Cross-References

- [Bremsstrahlung Radiation](#)
- [High-Mass Star](#)
- [HII Region](#)
- [Photoionization](#)
- [Pre-Main-Sequence Star](#)
- [Protostars](#)
- [Protostellar Envelope](#)

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Ultramafic Rocks

Daniele L. Pinti

Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Ultrabasic rocks](#)

Definition

An ultramafic rock is an igneous rock made up to 90% of ferromagnesian silicate minerals (olivine and pyroxene). The Earth's mantle above 400 km depth has an ultramafic composition, comparable to that of a lherzolite, an ultramafic rock of the family of peridotites. The mantle of Mercury may also have a lherzolithic composition (Namur et al. [2016](#)), as that of Mars, though enriched in Na and K compared to the Earth (Kiefer et al. [2015](#)). Komatiite is an ultramafic effusive rock, essentially restricted to the Hadean and Archean age. Reaction of high-temperature hydrothermal fluids with ultramafic rocks at the base of the oceanic crust (Serpentinization) is a process that could have produced abiotically complex organics in the Hadean Earth.

Cross-References

- ▶ [Komatiite](#)
- ▶ [Peridotite](#)
- ▶ [Serpentine](#)
- ▶ [Serpentinization](#)

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Ultrasmall Bacteria, CPR, and Patescibacteria

Ricardo Amils

Departamento de Biología Molecular, Centro de Biología Molecular Severo Ochoa, Universidad Autónoma de Madrid, Madrid, Spain

Synonyms

[Candidate Phyla Radiation \(CPR\)](#)

Definition

Ultrasmall bacteria, also known as Candidate Phyla Radiation (CPR) and Patescibacteria, is a large group of bacteria which members are mostly uncultivated and only known from genomic reconstruction using metagenomics. A general characteristic of this not well-defined phylum is their small genomes and the lack of important biosynthetic pathways: complete TCA cycles, electron transport complexes, or ATP synthase, which has led to the idea that they are obligate symbionts dependent on fermentation for the generation of cellular energy. Due to their small size ($<0.1 \mu\text{m}^3$), they are not retained in $0.22 \mu\text{m}$ normally used in microbial ecology, so they have been missed until recently in most microbial diversity studies. Their rRNA genes have self-replicating introns and encode proteins, features not usually seen in bacteria. Many of these characteristics are common to the ultrasmall archaea known as DPANN. Their dependence on metabolic symbiotic relationships probably with other

members of the phylum offers an interesting symbiotic hypothesis for the evolution of life systems to a last common ancestor (LUCA).

Cross-References

- [ATP Synthase](#)
- [DPANN, Archaea](#)
- [Electron Transport](#)
- [Fermentation](#)
- [Genome](#)
- [Intron](#)
- [Last Common Ancestor](#)
- [Protein](#)

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Ultrastructure

Emmanuelle J. Javaux
Palaeobiogeology-Palaeobotany-
Palaeopalynology, Geology Department,
Université de Liège, Quartier Agora, Bâtiment
B18, Liège, Belgium

Definition

The ultrastructure of an object or ► [fossil](#) is its fine structure at the micrometer and nanometer scales.

The term ultrastructure is used to describe the fine structure of a ► [microfossil](#) cell wall, which can be composed of one or several organic layers of various textures and compositions. It is also used in biology of extant organisms to describe the various components of the cell interior, such as nucleus, organelles, internal membranes, and vesicles. The most common technique used to study ultrastructure is transmission electron microscopy.

Cross-References

- [Acritarch](#)
- [Biogenicity](#)
- [Biomarkers, Morphological](#)
- [Fossil](#)
- [Kerogen](#)
- [Microfossils](#)
- [Microfossils, Analytical Techniques](#)

Ultraviolet Radiation

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Ultraviolet light (UV) is an electromagnetic radiation with wavelengths between 10 and 400 nm in the domain between X-rays and optical visible light. The UV spectrum is subdivided in different energy domains, from near and medium UV (400–200 nm; 3.10–6.2 eV) to extreme UV, EUV (100–10 nm, 12.4–124 eV). ► [Vacuum ultraviolet](#) light, VUV, corresponds to light having a wavelength between 100 and 200 nm (or 6.2–12.4 eV).

Cross-References

- [Extreme Ultraviolet Light](#)
- [UV Radiation](#)
- [Vacuum Ultraviolet](#)

Ulysses Mission

Michel Viso
Innovaxiom, Paris, CX, France

Definition

The joint ESA/NASA Ulysses mission aimed to study the heliosphere as a function of the solar latitude. The spacecraft was launched from the US space shuttle on October 1990. The spin-stabilized spacecraft had a mass of approximately 370 kg at launch. It used the gravitational field of ► [Jupiter](#) (February 8, 1992) to swing out from the ► [ecliptic](#) plane and reach a solar polar orbit of inclination 80.2° at a distance varying from 1.34 to 5.4 AU that it covered in around 6.5 years. The power supply weakening and the ground station becoming unavailable, on June 30, 2009, the agencies stopped the mission after 18 years and 246 days of operations.

Umbriel

Therese Encrenaz
XLESIA, Observatoire de Paris – Section de
Meudon, Meudon, France

Definition

Umbriel is the third of the five big satellites of ► [Uranus](#), in terms of increasing distance to the planet. It orbits at 266,000 km (or ten planetary radii) from Uranus. Its diameter is 1170 km. Voyager 2 images revealed an old cratered surface, where the biggest impact crater, Wunda, is 160 km in diameter. Umbriel does not show any evidence for tectonic activity and appears to be a primitive, undifferentiated body that has remained largely inactive since its formation. Umbriel is the darkest satellite of Uranus, and it has been proposed that its surface could be

covered with a carbonaceous deposit comparable to the dark side of ► [Iapetus](#).

Cross-References

- [Giant Planets](#)
- [Iapetus](#)
- [Uranus](#)
- [Voyager, Spacecraft](#)

Uncertainty

- [Chance and Randomness](#)

Unicellular Organisms

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A unicellular organism is any life form that consists of just a single ► [cell](#). Most forms of life are unicellular. They can be found in the three domains of life, ► [Bacteria](#), ► [Archaea](#), and ► [Eukarya](#), although most ► [prokaryotes](#) are unicellular organisms. Unicellular organisms are ubiquitous; they can be found in many different types of environments. The oldest forms of life were unicellular. ► [Multicellular organisms](#) appeared later in the fossil record, and some authors correlate their appearance with an increase in oxygen, a by-product of ► [oxygenic photosynthesis](#), in the atmosphere.

Cross-References

- [Archaea](#)
- [Bacteria](#)
- [Cell](#)

- [Eukarya](#)
- [Multicellular Organisms](#)
- [Oxygenic Photosynthesis](#)
- [Prokaryote](#)

Unidentified Infrared Emission Bands

Sun Kwok
Faculty of Science, The University of Hong
Kong, Hong Kong, China

Definition

The term unidentified infrared emission (UIE) bands refers to a family of emission features observed in a variety of astronomical sources, including the aromatic features at 3.3, 6.2, 7.7, 8.6, and 11.3 μm ; aliphatic features at 3.4 and 6.9 μm ; and broad emission plateaus at 8, 12, and 17 μm , as well as a host of weaker features that are too broad to be atomic or molecular lines.

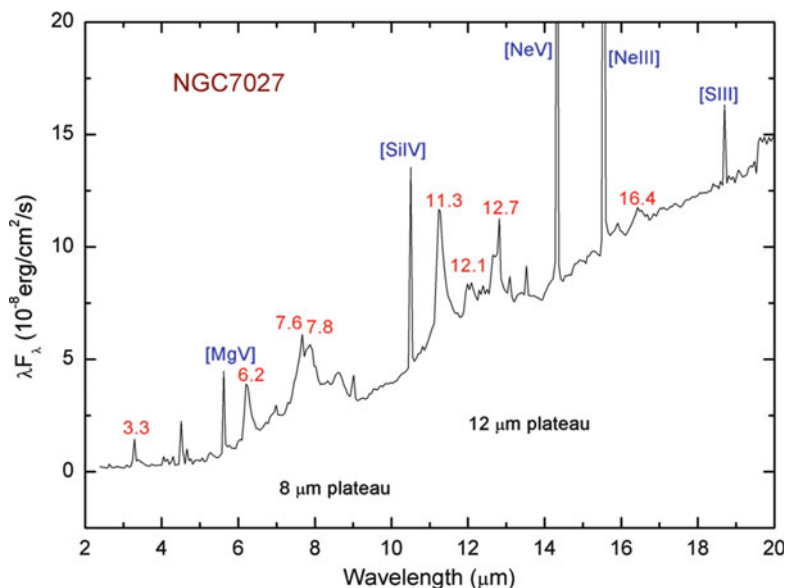
History

A family of strong infrared emission bands at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm were first detected in the young carbon-rich planetary nebula NGC 7027 (Gillett et al. 1973; Russell et al. 1977) (Fig. 1) and in the reflection nebula HD 44179 (Russell et al. 1978). Since the initial discovery, these features are now widely observed in ► [HII regions](#), reflection nebulae, planetary nebulae, ► [protoplanetary nebulae](#), and the diffuse ► [interstellar medium](#) of our own and other galaxies.

The UIE feature at 3.3 μm was first identified as the C–H stretching mode of aromatic compounds by Knacke (1977). The chemical origin of the UIE features was discussed by Duley and Williams (1981) who assigned the 3.3 and 11.3 μm features to graphitic (aromatic) materials. Subsequently, Léger and Puget (1984) identified the 6.2 μm feature as due to aromatic C–C stretch,

Unidentified Infrared Emission Bands,

Fig. 1 *Infrared Space Observatory (ISO)* spectrum of the planetary nebula NGC 7027 showing the UIE bands (labeled in red with the wavelength of peak emission in units of microns). Broad emission plateaus around 8 and 12 μm as well as a strong underlying continuum can be seen. The narrow lines (in blue) are atomic lines



the 8.6 μm feature as the C–H in-plane bend, and the 11.3, 12.4, and 13.3 μm features as due to solo, duo, and trio C–H out-of-plane bending modes. Since the UIE bands at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm almost certainly originate from aromatic materials, they are also sometimes referred to as aromatic infrared bands (AIBs).

Overview

The UIE phenomenon is more than a collection of emission features but is an integrated phenomenon of emission bands, underlying continua, and broad emission plateaus. Also present in astronomical spectra are emission features around 3.4 μm , which arise from symmetric and asymmetric C–H stretching modes of methyl and methylene groups (Puetter et al. 1979; Geballe et al. 1992). The bending modes of these groups also manifest themselves at 6.9 and 7.3 μm (Jourdain de Muizon et al. 1990; Chiar et al. 2000). In addition, there are unidentified emission features at 15.8, 16.4, 17.4, 17.8, and 18.9 μm , which have been observed in protoplanetary nebulae, reflection nebulae, and galaxies.

The emission bands themselves are often accompanied by strong, broad emission plateau

features at 6–9, 10–15, and 15–20 μm . The first two plateau features have been identified as superpositions of in-plane and out-of-plane bending modes emitted by a mixture of aliphatic side groups attached to aromatic rings (Kwok et al. 2001). The 15–20 μm plateau feature has been detected in young stellar objects, compact HII regions, and planetary nebulae, but is especially strong in some protoplanetary nebulae (Zhang et al. 2010). A possible origin of this broad feature arises from C–C–C in-plane and out-of-plane bending of aromatic rings (Van Kerckhoven et al. 2000).

The UIE features are always associated with a strong emission continuum which cannot be explained by free-free emission, reflected starlight, or thermal dust emission heated by stellar photons. For example, scattered starlight is expected to be strongly polarized, but the observed continuum emission is unpolarized. In the diffuse interstellar medium, the strength of the UIE features is strongly correlated with the dust continuum, suggesting that the emission bands are physically related to the continuum (Kahanpää et al. 2003) (Table 1).

The UIE features are seen in very different radiation environments, and their emission peak wavelengths and profiles also vary. The energy

sources responsible for the excitation of the features have temperatures ranging from tens of thousands of degrees in planetary nebulae

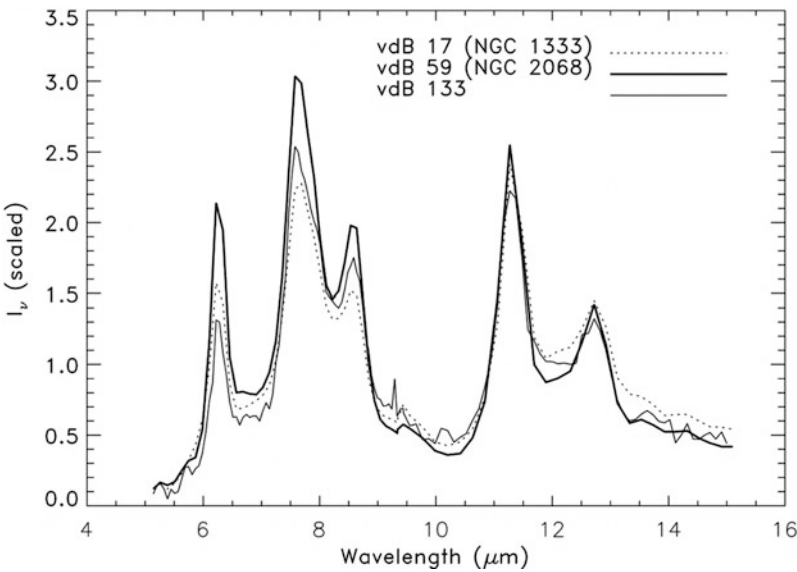
(the central star temperature of NGC 7027 is 200,000 K), to $\sim 30,000$ K in HII regions, and to only thousands of degrees in reflection nebulae and protoplanetary nebulae. The UIE features seen in the reflection nebula NGC 7023 are very similar to those seen in the planetary nebula NGC 7027 in spite of the very different intensities of UV background in the two nebulae. Figure 2 shows that the UIE features have very similar profiles, although the central stars of these reflection nebulae have very different temperatures, ranging from 6800 to 19,000 K.

A variety of chemical structures have been suggested as the carriers of the UIE bands. These include ► [polycyclic aromatic hydrocarbon](#) (PAH) molecules (Léger and Puget 1984), small carbonaceous molecules (Bernstein and Lynch 2009), hydrogenated amorphous carbon (HAC), soot and carbon nanoparticles (Hu and Duley 2008), quenched carbonaceous composite (QCC, Sakata et al. 1987) particles, kerogen and coal (Papoular et al. 1989), petroleum fractions (Cataldo et al. 2002), and mixed aromatic/aliphatic organic nanoparticles (MAON, Kwok and Zhang 2011). A complete explanation to the UIE phenomenon has to account for the peak wavelengths and profiles of the emission features, the broad emission plateaus, as well as the underlying continua.

Unidentified Infrared Emission Bands,
Table 1 Vibrational mode identification of some of the UIE bands

$\lambda(\mu\text{m})$	Mode
	Aromatic (sp^2)
3.29	=C-H stretch
6.2	C=C stretch
7.6–8.0	C-C stretch
8.6	=C-H in-plane bend
11.3, 12.7, 13.4	=C-H out-of-plane bend
	Aliphatic (sp^3)
3.38	Asymmetric CH_3 stretch
3.42	Asymmetric CH_2 stretch
3.49	Symmetric CH_3 stretch
3.51	Symmetric CH_2 stretch
3.46	-CH stretch
6.85	$\text{CH}_{(2,3)}$ asymmetric deformation
7.25	$\text{CH}_{(2,3)}$ symmetric deformation
	Plateau features
6–9	Superposition of aliphatic in-plane bending modes
10–15	Superposition of aliphatic out-of-plane bending modes
15–20	Superposition of C-C-C skeleton modes?

Unidentified Infrared Emission Bands,
Fig. 2 ► ISO spectra of the UIE features in three reflection nebulae from the van den Berg catalog, having very different central star temperatures. (Figure from Uchida et al. (2000))



Cross-References

- [Polycyclic Aromatic Hydrocarbon](#)
- [Pre-planetary Nebulae](#)

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Unimolecular Reaction

Steven B. Charnley

Solar System Exploration Division, Code 691, Astrochemistry Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Definition

A unimolecular reaction is a chemical process involving a single-step decomposition of a sole reactant into products or the isomerization of a molecule to form a lower-energy isomer.

Cross-References

- [Bimolecular Reaction](#)

United Kingdom Space Agency

- [UK Space Agency](#)

Universal Tree of Life

► [Phylogenetic Tree](#)

Upper Atmosphere Microbiology

► [Stratosphere Biology](#)

Uracil (Ura)

Shin Miyakawa
Kamagaya, Chiba, Japan

Definition

$C_4H_4N_2O_2$. M.W. 112.09. Uracil is one of the four nucleic acid bases found in ► [RNA](#). In double-stranded RNA, it pairs with ► [adenine](#), via two hydrogen bonds in Watson-Crick base pairing. Uracil can be formed by ► [deamination](#) of ► [cytosine](#). The half-life of uracil in water is 12 years at 100 °C and 3.8×10^8 years at 0 °C at pH 7. It has a UV absorption maximum at 260 nm in neutral solution. It has been found in the Murchison meteorite and has been synthesized in HCN polymerizations and Fischer-Tropsch-type reactions and by the action of electric discharges and irradiations of high-energy protons on simple gas mixtures such as $CO-N_2-H_2O$.

Cross-References

► [Adenine](#)
 ► [Cytosine](#)
 ► [Deamination](#)
 ► [Fischer-Tropsch-Type Reaction](#)
 ► [HCN Polymer](#)
 ► [Hydrogen Cyanide](#)
 ► [Murchison](#)
 ► [Nucleic Acid Base](#)
 ► [Proton Irradiation](#)
 ► [RNA](#)

Uraninite

Daniele L. Pinti
Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Uranium dioxide, pitchblende \(former name\)](#)

Chemical Formula (optional)

UO_2

Definition

Uraninite is economically the most important uranium-bearing mineral. The $U^{4+}O_2$ is the reduced form while the oxidized form is triuranium octoxide ($U_3^{4,6+}O_8$ or ideally $UO_2 \cdot 2UO_3$), which occurs in the pitchblende (a mixture of UO_2 and U_3O_8). Uraninite ore deposits are hosted in pegmatites and quartz veins, quartz-pebble conglomerates, and sandstones. Most uraninite-rich ores have ages older than 2.2 Ga. This is taken as evidence of the reduced state of the Archean atmosphere. Indeed, in an oxygenated environment, hexavalent uranium (U^{6+}) is transported in solution as soluble uranyl ($U^{6+}O_2$)²⁺, while in a reduced environment tetravalent uranium (U^{4+}) precipitate to form uraninite $U^{4+}O_2$.

Cross-References

► [Great Oxidation Event](#)
 ► [Oxygenation of the Earth's Atmosphere](#)

Uranium Dioxide, Pitchblende (former name)

► [Uraninite](#)

Uranus

Therese Encrenaz

XLESIA, Observatoire de Paris – Section de Meudon, Meudon, France

Keywords

Giant planets

Definition

Orbiting at 19.2 AU from the Sun, Uranus is, after Jupiter and Saturn, the third giant planet by order of size and heliocentric distance. However Uranus, with a mass of 14.5 terrestrial masses, is slightly less massive than the forth giant planet ► [Neptune](#). Uranus is 51,120 km in diameter with a density of 1.27 g/cm^3 . Both Uranus and Neptune consist mostly of an icy core which accounts for more than 50% of their mass, hence their name of “ice giants.” Like all ► [giant planets](#), Uranus has a ring system and several satellites (27 known in 2013). As seen from Earth, the diameter of Uranus is 3.5 arcsec.

Overview

History of Observations

Uranus is the first non-naked-eye planet to be discovered. After several observations by astronomers who mistook the object as a star, Uranus was identified by William Herschel in 1781 using a new-generation telescope. At first, Herschel could not decide whether the object was a comet or a planet; he definitely identified it as a planet in 1783. Still improving his instrument, Herschel detected in 1787 two of the five main Uranian satellites, ► [Titania](#) and ► [Oberon](#), and later the third, ► [Umbriel](#). The satellite ► [Ariel](#) was first detected by William Lassell in 1851 and ► [Miranda](#), the smallest one and closest to the planet, by Gerard Kuiper in 1948.

The orbits of the Uranian satellites gave evidence that the rotation axis of Uranus was tilted in an unusual way. Its angle relative to the north

ecliptic pole is 97.9° , so that the rotation axis of the planet is close to the ► [ecliptic](#) plane. There has been a long debate about the origin of this anomaly. The first possible explanation was that an early collision had tilted the planet, before the collapse of the surrounding gas and the formation of the equatorial disk and the accretion of satellites within this disk. However, recent dynamical calculations show that Uranus’ rotation axis might have been tilted during the planets’ migration, without the need of a major impact, provided that the planet had an additional satellite and a temporary large inclination.

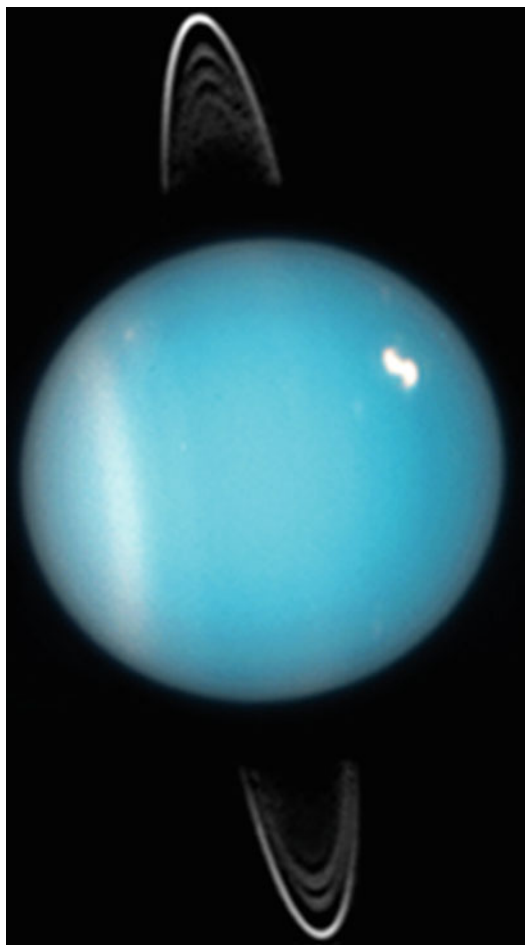
In 1932, R. Wildt discovered methane in the atmosphere of Uranus, as in the other giant planets. Due to its low density, hydrogen was suspected to be a major component of Uranus’ atmosphere, but it was not detected until the 1960s.

Uranus has been explored only by a single spacecraft, Voyager 2, which encountered the planet in 1986. The images returned by the Voyager camera were remarkably devoid of features. The main highlights of the Voyager 2 exploration of Uranus were the first observation of Uranus’ ► [magnetosphere](#), the direct imaging of its ring system, and the discovery of new satellites. Later, Uranus was imaged by the Hubble Space Telescope, which detected more dynamical activity (Fig. 1).

Composition and Structure

Like the other giant planets, the thermal structure of Uranus’ atmosphere is characterized by (1) a troposphere, where the temperature decreases with altitude, following an adiabatic gradient; (2) a tropopause, at a pressure level of about 100 mbar, where the temperature is minimum (about 50 K); and (3) a stratosphere where the temperature increases with the altitude. Due to the cold environment, the atmospheric species found in Uranus are hydrogen, helium, methane, and, in the stratosphere, hydrocarbons produced by the photodissociation of methane (C_2H_2 , C_2H_6). As in other giant planets, oxygen species (H_2O , CO , CO_2) have been found in the stratosphere of Uranus, although in less abundance.

Uranus shows very little atmospheric turbulence. In 1986, Voyager 2 images showed very



Uranus, Fig. 1 Uranus as observed by the Hubble Space Telescope in 2005. A bright cloud appears near the North Pole and a white collar is present in the Southern Hemisphere. (© NASA)

few contrasts. All atmospheric features were symmetric around the rotation axis; there was no evidence for isolated features. Ten years later, images taken with the Hubble Space Telescope (HST) showed a slight evidence of atmospheric activity, possibly correlated with the seasonal evolution. Indeed, cloud features were observed on the disk in 2004, as the planet was approaching ► [equinox](#).

Models of thermochemical equilibrium predict a CH_4 cloud at a level of about 1 bar ($T = 80$ K), an H_2S cloud at about 3 bars, and, at deeper levels of pressure (>20 bars), clouds of NH_4SH and H_2O . However, visible and infrared spectra seem to indicate that the atmosphere of Uranus is relatively cloud free down to a pressure of about

3 bars. Still, methane does condense in the upper troposphere as indicated by its stratospheric abundance, strongly reduced with respect to its tropospheric value.

As in the case of Neptune, the C/H ratio, as measured from the methane abundance below the condensation level of methane, is 20–30 times greater than the protosolar carbon/hydrogen value. This measurement is a strong argument in favor of the nucleation model of the giant planets, which states that their formation began with the accretion of an icy core of about 10–15 terrestrial masses. Another formation diagnostic is the deuterium/hydrogen ratio measured in HD, first detected by the ISO satellite and more recently by Herschel, which indicates, as for Neptune, an enhancement of D/H with respect to the protosolar value; this enhancement is a signature of the presence of a significant icy core. The helium abundance has been measured by Voyager with an uncertainty of about 20%. The inferred He/H ratio shows no difference with respect to its protosolar value (the helium mass fraction Y is 0.275).

Internal Structure

Unlike the other giant planets, Uranus does not exhibit any internal source of energy. The reason for this peculiarity is unknown, but it can probably account for the lack of dynamical activity on Uranus. Models of internal structure predict, at the center, a temperature of about 7000 K and a pressure of about 6 Mbar. As in the case of Neptune, the internal structure of Uranus would consist of a central core of metals and silicates, surrounded by a mixture of ices which would extend up to 0.8 of the planetary radius, covered by a layer of molecular hydrogen. According to this model, there is not supposed to be a layer of metallic hydrogen. As a consequence, in contrast with Jupiter's and Saturn's interiors, helium condensation is not expected to take place; thus, no helium depletion is predicted in the outer atmosphere, which is consistent with the measured helium abundance.

The Magnetosphere of Uranus

The ► [magnetosphere](#) of Uranus has been explored by Voyager 2. As for the other giant

planets, the magnetosphere is well represented by a dipole, but, surprisingly, the axis of the dipole is tilted by 58.6° with respect to the planet's rotation axis; in addition, the dipole shows an offset from the planet's center by a third of the radius. The origin of this anomaly is unknown.

Due to this peculiar geometrical configuration, the magnetosphere of Uranus is very complex. At the time of the Voyager 2 encounter, the rotation axis of Uranus was not far from the Sun-Uranus axis. The magnetosphere looked similar to a terrestrial magnetosphere, which would be in precession around the Sun-Planet axis with the rotation period of Uranus (17.2 h). Strong seasonal variations of the magnetosphere are expected as Uranus moves around its orbit. In 2007, as the planet passed ► [equinox](#), its rotation axis was perpendicular to the Sun-Planet axis and its magnetosphere was then more comparable to the terrestrial one.

Origin and Migration

As mentioned above, Uranus, like the other giant planets, is believed to have formed through the accretion of an icy core of about 10–15 terrestrial masses and the subsequent collapse of the surrounding nebula. According to this scenario, however, it is difficult to form such a massive core at heliocentric distances as high as 20 AU. According to a recent dynamical model developed at Nice Observatory, both Uranus and Neptune would have been formed closer to the Sun but migrated outward following the dissipation of the protoplanetary gaseous disk. This migration mechanism would explain, in particular, the structure of the Kuiper belt and the Late Heavy Bombardment.

Cross-References

- [Ariel Space Mission](#)
- [Giant Planets](#)
- [Late Heavy Bombardment](#)
- [Miranda](#)
- [Neptune](#)
- [Oberon](#)
- [Planet Formation](#)
- [Titania](#)
- [Umbriel](#)
- [Voyager, Spacecraft](#)

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Urea

Shin Miyakawa¹ and Didier Despois²

¹Department of Chemistry and Biotechnology, Faculty of Engineering, Yokohama National University, Chiba, Japan

²Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

Synonyms

[Carbamide](#); [Carbonyldiamide](#); NH_2CONH_2

Definition

Urea is an organic compound of molecular formula NH_2CONH_2 . It is an important metabolite (a product of metabolism) formed in the liver of animals through the degradation of three amino acids (arginine, citrulline, and ornithine). It is the main nitrogen-containing substance in the urine of mammals. Urea can be synthesized by spark discharge in simple gas mixtures such as CO , N_2 , and H_2O . Reactions involving urea have been proposed for the formation of the nucleic acid bases Uracil (Subbaraman et al. [1980](#)) and Cytosine (Shapiro [1999](#)). A tentative detection of urea in interstellar ices has been reported.

History

Friedrich Wöhler's synthesis of urea from an inorganic precursor in 1828 was the start of a

revolution in chemistry because it provided the first proof that an “organic” compound could be produced outside a living body. Raunier et al. (2004) proposed a tentative identification of urea in the infrared absorption spectrum of ice mantles of interstellar grains near the protostellar source NGC 7538 IRS9.

Cross-References

- [Formamide \(NH₂CHO\)](#)
- [Molecules in Space](#)

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Urey's Conception of Origins of Life

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

History

Harold Clayton Urey (1893–1981) was an American physical chemist who earned the Nobel Prize in Chemistry in 1934 for his work on the heavy isotope of hydrogen (deuterium). Urey isolated deuterium by repeatedly distilling a sample of liquid hydrogen and demonstrated the existence of heavy water (HDO). During WWII, Urey contributed to the

Manhattan Project by developing a gaseous diffusion method for separating ²³⁵U from ²³⁸U.

After the war, he moved to academic life where he dedicated to develop cosmochemistry and isotope geology. He firstly speculated that the early terrestrial atmosphere was composed of ammonia, methane, and hydrogen. In 1952, he suggested that experimentation on production of organic compounds from water and methane, in the presence of ultraviolet light or electric discharges, could be most profitable. He insisted on the fact that primitive atmosphere had to be reduced, and for this reason, he criticized Calvin's experiment on origins of life. In 1953, one of his students at the University of Chicago, Stanley Lloyd Miller (1930–2007), produced amino acids under this primitive Earth conditions. This experiment is often named Urey-Miller experiment.

Cross-References

- [Miller, Stanley](#)

Urotropine

- [Hexamethylenetetramine](#)

Utahite

- [Jarosite](#)

UV Absorption Bump

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Definition

The interstellar extinction curve as measured toward a particular star is normally plotted as

the relative extinction at a given wavelength λ , denoted $E(\lambda - V)/E(B - V)$ vs λ^{-1} , where the quantities E are defined in the entry ► [reddening, interstellar](#). This curve has a “bump” or local extinction maximum at a wavelength of 217.5 ± 1 nm in the ultraviolet, referred to as the UV absorption bump, which is almost invariably detected in the spectra of stars with appreciable reddening. An interesting observational characteristic of the “bump” is that variations in its width as observed along different lines of sight are not accompanied by variations in the wavelength of the maximum absorption. The carrier of this feature is thought to be very small interstellar dust grains, i.e., grains with dimensions ≤ 10 nm. Various carbon-containing substances have been proposed as the grain constituents, including ► [graphite](#), polycyclic aromatic hydrocarbons (PAHs), buckminsterfullerene (C_{60}), and Quenched Carbonaceous Composites (QCCs). This feature has been observed not only in the Milky Way, but also in external galaxies (e.g., Ma et al. [2018](#)).

Cross-References

- [Extinction, Interstellar or Atmospheric](#)
- [Fullerene](#)
- [Graphite](#)
- [Interstellar Dust](#)
- [Polycyclic Aromatic Hydrocarbon](#)
- [Quenched Carbonaceous Composite](#)
- [Reddening, Interstellar](#)

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UV Climate

Gerda Horneck

DLR German Aerospace Center, Institute of Aerospace Medicine, Radiation Biology, Köln, Germany

Keywords

Planetary UV radiation · Terrestrial UV radiation

Definition

The ultraviolet (UV) radiation climate describes the spectrum and intensity of solar UV radiation reaching the surface of a planet as part of the planet's overall climate that encompasses the interplay of various environmental atmospheric factors, such as temperature, radiation, humidity, atmospheric composition, and other elements in a given region over long periods of time.

Overview

The source of the terrestrial ultraviolet (UV) radiation climate is our Sun. At the distance of the Earth the intensity of solar radiation amounts to 1370 W/m^2 , which is called the ► [solar constant](#). This extraterrestrial solar UV spectrum spans over the whole UV range, from 400 nm to short wavelengths extending far into short wavelengths of UVC (100–280 nm) and VUV (100–200 nm) (Table 1).

Solar UV radiation undergoes absorption and scattering as it passes through the Earth's atmosphere. The absorption of solar UV radiation at wavelengths < 290 nm by stratospheric ► [ozone layer](#) is the most important process. As a consequence, the terrestrial UV radiation climate does not encompass energetic ranges at wavelengths < 290 nm (UNEP [1998, 2003](#)).

The ozone concentration in the stratosphere is measured in Dobson units (DU), which

UV Climate, Table 1 Spectral ranges of ultraviolet radiation, as described by the ISO standard (ISO-21348) “Process for determining solar irradiances compliance”

Name	Abbreviation	Wavelength range [nm]	Energy per photon [eV]
Ultraviolet A	UVA	400–315	3.10–3.94
Ultraviolet B	UVB	315–280	3.94–4.43
Ultraviolet C	UVC	280–100	4.43–12.4
Vacuum ultraviolet	VUV	200–100	6.20–12.4
Extreme ultraviolet	EUV	121–10	10.2–124

determines the total amount of ozone present in a vertical column of air above a certain location at the surface of the Earth. It gives the millimeter thickness of ozone at an atmospheric pressure of 1013 hPa and a temperature of 298 K: 1 mm of ozone is equivalent to 100 DU. Near the tropics values reach typically about 260 DU, though there are large seasonal fluctuations. Surface UV radiation levels are highly variable because of sun angle, cloud cover, and also because of local effects including pollutants and surface reflections. A decreasing stratospheric ozone concentration results in higher UV irradiances that may finally stretch into the UVB range of the spectrum. Ozone is photochemically produced from atmospheric oxygen. During the first two billion years of Earth’s history, before the increase of atmospheric oxygen by oxygenic [▶ photosynthesis](#), this effective UV screen by stratospheric ozone was lacking. As a result, the early terrestrial UV climate stretched to the energetic wavelength range up to 200 nm (Cockell and Horneck 2001).

The terrestrial UV radiation climate is beneficial as well as harmful to human health and terrestrial and aquatic ecosystems, depending on dose and wavelength range applied (Horneck 1995; Häder 1997). In biological systems, UV radiation causes temporary or permanent alterations that result from photochemical reactions of UV with different biological target molecules. Beneficial effects are vitamin D synthesis in the skin, harmful effects may lead to diseases of the skin, the eye, and the immune system. The most important UV target in biological systems is the genetic material, the DNA. UV lesions of the DNA may lead to [▶ mutations](#), cancer, and cell death (Hockberger 2002).

The terrestrial UV radiation plays an important role in evolutionary processes, for example, as energy source for chemical evolution on the early Earth and as driver of biological evolution through the generation of mutations. UV-induced mutations may lead to inactivation; however, they may also cause the appearance of new and better adapted attributes of life, such as the origin of efficient [▶ DNA repair mechanisms](#) or the development of sexual processes (Rothschild and Lister 2003).

Cross-References

- ▶ [Chemical Evolution](#)
- ▶ [DNA Damage](#)
- ▶ [DNA Repair](#)
- ▶ [Evolution, Biological](#)
- ▶ [Mutation](#)
- ▶ [Ozone Layer](#)
- ▶ [Photobiology](#)
- ▶ [Photosynthesis](#)
- ▶ [Solar Constant](#)
- ▶ [Solar UV Radiation, Biological Effects](#)
- ▶ [UV Radiation Dose](#)
- ▶ [UV Radiation, Biological Effects](#)

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UV Exposure

- [UV Radiation Dose](#)

UV Fluence

- [UV Radiation Dose](#)

UV Radiation

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Ultraviolet radiation](#)

Definition

UV radiation is an abbreviation for ultraviolet radiation and corresponds to the domain of ► [electromagnetic radiation](#) between X-rays and visible light, with wavelengths in the approximate

range 10–400 nm. Ultraviolet radiation has wavelengths that are too short to be seen by the human eye. All stars hotter than typically 3500 K (including the Sun) emit UV radiation, the hottest stars being very strong emitters.

Cross-References

- [Electromagnetic Radiation](#)
- [Electromagnetic Spectrum](#)
- [UV Radiation, Biological Effects](#)

UV Radiation Dose

Gerda Horneck
DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Synonyms

[UV exposure](#); [UV fluence](#)

Definition

Ultraviolet (UV) radiation is described using radiometric units. They describe the energy that is either emitted from a source or that arrives at a surface. The recommended radiometric SI (International System of Units, abbreviated “SI” from the French *Le Système International d’Unités* as the modern metric system of measurement) derived unit for the flux per unit-area incident on a small plane surface is called “UV irradiance.” It is given in watts/meter² (W/m²). The unit watt (W) is defined as a rate of energy of 1 Joule (J) per second. The UV ► [radiation dose](#), also called “UV exposure” is described in joule/meter² (J/m²), i.e., the energy per unit-area incident on one side of a small plane surface. $1 \text{ J/m}^2 = 1 \text{ W} \times \text{s/m}^2$.

Cross-References

- [Photobiology](#)
- [Photochemistry](#)
- [Photon](#)
- [Radiation Dose](#)
- [Solar UV Radiation, Biological Effects](#)
- [UV Radiation](#)
- [UV Radiation, Biological Effects](#)

UV Radiation, Biological Effects

Gerda Horneck

DLR German Aerospace Center, Institute of
Aerospace Medicine, Radiation Biology, Köln,
Germany

Keywords

DNA photoproduct · DNA repair ·
Inactivation · Mutation

Synonyms

[UV rays](#)

Definition

Ultraviolet (UV) radiation covers the part of the electromagnetic spectrum between the ionizing radiation region and the visible light. Based on the biological effects, it is subdivided into the following bands: UVC (100–280 nm), UVB (280–320 nm), and UVA (320–400 nm). The biological effects that result from UV irradiation are initiated by photochemical absorption by molecules of biological significance. The most important of these are the nucleic acids and to a much lesser extent the proteins and other molecules. If not repaired, the induced photochemical lesions may cause ► [mutations](#), cancer, and cell death.

History

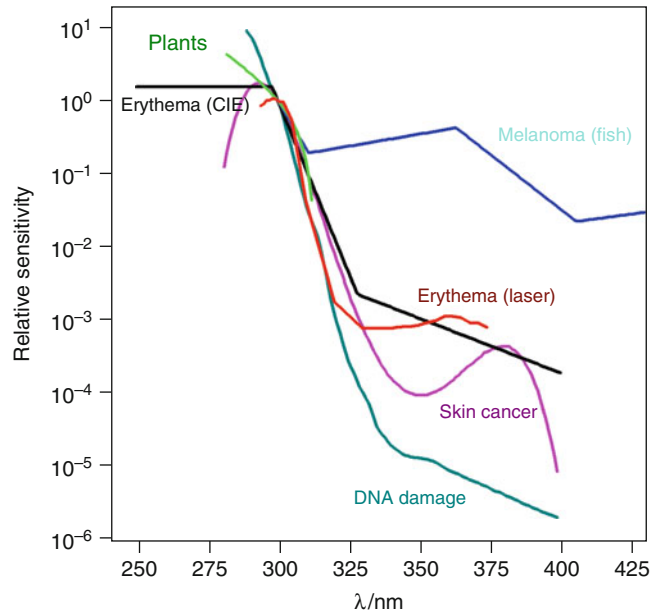
Ultraviolet radiation has been known as a ► [mutagen](#) and disinfectant for more than 100 years. UV from artificial sources, for example, germicidal irradiation, has been used in a variety of applications, such as food, air, and water purification and ► [sterilization](#). In 1903, Niels Finsen was awarded with the Nobel Prize for Medicine “in recognition of his contribution to the treatment of diseases, especially lupus vulgaris, with concentrated light radiation, whereby he has opened a new avenue for medical science.”

Overview

In biological systems, UV radiation causes temporary or permanent alterations that result from photochemical reactions of UV with different biological target molecules. The most important UV target in cells is the genetic material, the ► [DNA](#). The absorbing parts of DNA are the bases, the pyrimidine derivatives thymine and cytosine, and the purine derivatives adenine and guanine. Their absorption spectra dictate the biological sensitivity spectra, the so-called action spectra, which show a maximum in the 260 nm wavelength range (Fig. 1). Adjacent ► [pyrimidine bases](#) are the main DNA targets of direct effects of UVC and UVB radiation. Their excitation leads to the formation of cyclobutane pyrimidine dimers and pyrimidine (6-4) pyrimidone photoproducts (Cadet et al. 2005). In bacterial endospores, due to the structural characteristics of their DNA, UVC induces predominantly 5,6-dihydro-5(α -thyminyl) thymine, the so-called spore photoproduct (Douki et al. 2005). UVA radiation affects the DNA mainly indirectly, mediated by endogenous photosensitizers (Cadet et al. 2009).

During its evolution, life has invented a variety of mechanisms to repair the damage that is induced in its DNA, for example, by UV radiation or other agents. It should be noted that errors occur very often in the DNA during its replication. Therefore, there exists a whole set of mechanisms

UV Radiation, Biological Effects, Fig. 1 Action spectra for different biological effects of UV radiation



to control the integrity of the DNA and to initiate its repair if necessary. Each of these repair mechanisms is catalyzed by a different set of enzymes.

The main ► **DNA repair** processes can be divided in:

- Direct repair pathways, where the abnormality in the DNA is reversed in situ; an example is the photoreactivation of UV radiation damage, where the photoproduct, the cyclobutane thymine dimer, is enzymatically split under the activation of visible light.
- Excision repair pathways, where the section of the DNA containing the abnormality is excised from the strand and repair patch is synthesized using the intact sister strand as template.
- Recombination repair, where the abnormality is repaired by homologous recombination with a second DNA strand.
- SOS repair, which is an inducible repair process that is initiated after the DNA has been severely damaged; this is a highly error-prone repair leading to a high frequency of mutations.

Some of these repair pathways are very old and have been preserved in the different domains of

life. Photoreactivation is a very universal process, which is found in representatives of all three domains of life, in Bacteria, Archaea, and Eukarya. Other repair pathways, for example, the nucleotide excision repair, have a separate origin in prokaryotes and eukaryotes (Friedberg 1995, 2008). If not or inaccurately repaired, the UV-induced DNA photoproducts may lead to mutations and finally to cell death.

Solar UV radiation was an important energy source for chemical evolution on the early Earth, long before life arose. Since the appearance of life on Earth, solar UV radiation has provided an evolutionary challenge. On the one hand, because of its damaging nature to the genome, UV radiation has acted as a selective agent. On the other hand, UV-induced mutations may have had all sorts of evolutionary consequences, ranging from the development of efficient DNA repair pathways to sexual processes (Rothschild and Lister 2003).

Cross-References

- **DNA**
- **DNA Damage**

- [DNA Repair](#)
- [Electromagnetic Spectrum](#)
- [Endospore](#)
- [Mutagen](#)
- [Mutagenesis](#)
- [Mutation](#)
- [Photobiology](#)
- [Purine Bases](#)
- [Pyrimidine Base](#)
- [Sterilization](#)
- [UV Radiation Dose](#)

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UV Rays

- [UV Radiation, Biological Effects](#)

V

Vacuum Ultraviolet

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Definition

Vacuum ultraviolet, VUV, light corresponds to light having a wavelength between 100 and 200 nm (or 6.2–12.4 eV).

Cross-References

- ▶ [Extreme Ultraviolet Light](#)
- ▶ [Ultraviolet Radiation](#)
- ▶ [Vacuum Ultraviolet Light](#)

Definition

Ultraviolet light (UV) is electromagnetic radiation with wavelengths between 10 and 400 nm in the domain between X-rays and optical visible light. The UV spectrum is subdivided in different energy domains, from near UV (400–300 nm; 3.10–4.13 eV) to Extreme UV (121–10 nm; 10.2–124 eV). Vacuum ultraviolet light, VUV, corresponds to light having a wavelength between 100 and 200 nm (or 6.2–12.4 eV).

Cross-References

- ▶ [Extreme Ultraviolet Light](#)
- ▶ [UV Radiation](#)
- ▶ [Wavelength](#)

Vacuum Ultraviolet Light

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Synonyms

[Vacuum ultraviolet](#)

Valine

Kensei Kobayashi
Yokohama National University, Yokohama, Japan

Definition

Valine is one of the 20 ▶ [protein](#) amino acids. Its chemical structure is $(\text{CH}_3)_2\text{CHCH}(\text{NH}_2)\text{COOH}$. Its three-letter symbol is Val, and its one-letter

symbol is V. Its molecular formula is $C_5H_{11}NO_2$ which translates into a molecular weight of 117.15. Its isoelectric point is 5.96. Valine's side chain is a simple hydrocarbon and is thus considered to be an apolar amino acid. Among the protein amino acids, alanine ($C_3H_7NO_2$), leucine, and isoleucine (both $C_6H_{13}NO_2$) are in the same group, but strangely, none of the isomers with four carbons ($C_4H_9NO_2$) are protein amino acids. Valine has 11 nonprotein ► [amino acid](#) isomers, including norvaline and ► [isovaline](#). All of them have been identified in the extract from ► [Murchison meteorite](#). Valine is a hydrophobic amino acid and has often been used to make thermal microspheres from amino acids.

Cross-References

- [Amino Acid](#)
- [Isovaline](#)
- [Murchison](#)
- [Protein](#)
- [Proteinoid Microsphere](#)

Valles Marineris

Ernst Hauber
Deutsches Zentrum für Luft- und Raumfahrt
(DLR) e.V., Institut für Planetenforschung,
Berlin, Germany

Definition

The Valles Marineris is a system of rectilinear, parallel troughs that extend near and parallel to the equator in the western hemisphere of ► [Mars](#). The total length is about 4000 km, the maximum width is ~600 km, and the greatest depth is ~10 km. The exact mechanism by which the troughs formed is unknown, but it was likely a multistage process, involving tectonism and collapse. The trough walls consist of thick, layered

► [rock](#) sequences, probably lava flows intermingled with mechanically weaker layers like ash. Layered sedimentary deposits of different morphologies and compositions exist within the troughs and on top of the surrounding plateaus. Some of these layers show the spectral characteristics of aqueous alteration products, such as ► [phyllosilicates](#), sulfates, and perhaps ► [opaline silica](#).

Cross-References

- [Mars](#)
- [Opaline Silica on Mars](#)
- [Phyllosilicates, Extraterrestrial](#)
- [Rock](#)
- [Sedimentary Rock](#)
- [Sulfates, Extraterrestrial](#)

Valley

- [Vallis, Valles](#)

Valley Networks

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Channels](#); [Riverbeds](#)

Definition

Assemblage of small- to medium-scale channels, usually acting as pathways for rivers on planetary bodies. In addition to ► [Earth](#), valley networks have been identified on ► [Mars](#) and ► [Titan](#).

Depending on the liquid-release mechanism, these networks can have a dendritic or longitudinal pattern corresponding to surface runoff or groundwater release, respectively. Whereas terrestrial and Martian valley networks are known to be fed by ► [water](#), Titan's networks are supposed to be fed by liquid ► [methane](#). Martian valley networks are not filled with water today and thus represent paleo-riverbeds resembling terrestrial wadis.

Cross-References

- [Earth](#)
- [Mars](#)
- [Methane](#)
- [Outflow Channels](#)
- [Titan](#)
- [Water](#)

Vallis, Valles

Daniela Tirsch
German Aerospace Center DLR, Institute of Planetary Research, Berlin, Germany

Synonyms

[Graben](#); [Valley](#)

Definition

Term used for valleys or valley systems. These longitudinal channels are commonly carved by liquids (e.g., ► [water](#), lava) but can also develop as a result of tectonic activity (i.e., rifts) and collapse. The geomorphologic shape of a vallis is controlled by ► [rock](#) type, liquid release mechanism, and climate. Extraterrestrial valleys named valles or vallis can be found on ► [Mars](#), ► [Venus](#), ► [Mercury](#), ► [Io](#), ► [Ariel](#), and the Moon.

Cross-References

- [Ariel Space Mission](#)
- [Io](#)
- [Mars](#)
- [Mercury](#)
- [Moon, The](#)
- [Rock](#)
- [Valles Marineris](#)
- [Valley Networks](#)
- [Venus](#)
- [Water](#)

Value

- [Socioeconomic Benefits of Space](#)

Van der Waals Forces

Gilles Bruylants
Engineering of Molecular NanoSystems,
Université Libre de Bruxelles, Brussels, Belgium

Keywords

Debye induction force · Keesom orientation force · Lennard-Jones potential · London dispersion force · Molecular interactions · Pauli repulsive force

Synonyms

[Molecular interactions](#)

Overview

The interactions between electrons and nuclei, whether they are or not part of the same molecule, are electromagnetic. This means that, at least in principle, the same theoretical tool, quantum

mechanics, can be used to calculate the interaction energies between bonded atoms or nonbonded atoms. At the intramolecular level, various methods can be used to calculate these energies, from truly theoretical *ab initio* methods to semiempirical methods like the “old” Hückel method or the “modern” Density Functional Theory (DFT) method. As soon as the number of nuclei and electrons increases, *ab initio* calculations become too time-consuming and semiempirical methods are preferred. In the case of intermolecular interactions, except in the case of pair interactions between small molecules like water or methane, the interaction energies are furthermore generally calculated using classical methods, and the van der Waals approach, named after the Dutch scientist Johannes Diderik van der Waals (1837–1923), is frequently used. The basis of this approach is very simple: the interacting molecules are described as ensembles of electric charges (positive for the nuclei, negative for the electrons). The ensemble of charges is neutral except if the molecules are charged (ions). As soon as the distance between the charges inside each molecule is much smaller than the distances between the molecules, it is possible to approximate the charge distribution of each molecule by a series of electric multipolar moments (multipolar expansion). The condition concerning the distances between the electric charges is of course better fulfilled in the gas phase than in the liquid phase, and this explains why the use of the multipolar expansion gives, at best, only a rough estimation of the intermolecular interaction energies in the liquid phase.

The first nonzero multipolar moment of a molecule is the monopole in the case of ions. In the case of neutral molecules, it can be the dipole moment, as in the case of water or HCl molecules. It is the quadrupolar moment in the case of methane or benzene, and for highly symmetrical (octahedral) molecules, like SF₆, the first nonzero moment is the octupolar moment. The only molecules, which are truly apolar, are the monoatomic rare gases. Frequently, the multipolar expansion is truncated to the dipole term, which means that the electrostatic interaction energies between neutral molecules are often described as dipole-dipole

interactions, called Keesom interaction energies. For molecules able to reorient themselves, the Keesom term is always negative and is a function of r^{-6} , where r is the average intermolecular distance, i.e., the distance between the centers of mass of the interacting molecules. The truncation of the multipolar expansion to the dipolar term can be misleading in the case of molecules, which do not possess a dipole moment and which are consequently considered “apolar.” For example, the “T-shape” geometry of the benzene dimer observed in the gas phase is easily explained by taking the (quadru)polarity of benzene into account.

Any molecular charge distribution immersed in an electric field is polarized as the distribution is slightly modified by the electric field. Consequently, a molecule immersed in the electric field created by another polar molecule acquires induced moments. For example, an apolar xenon atom acquires a small dipole moment in the vicinity of a dipolar molecule. A multipole-induced multipole interaction energy must therefore be taken into account in the estimation of intermolecular interaction energies. This contribution to the intermolecular interaction is called, in the case of a dipole-induced dipole interaction, the Debye term. It is always negative and is also a function of r^{-6} . It is smaller in absolute value than the Keesom term.

The Keesom and Debye terms can however not explain why, for example, monoatomic rare gases can be liquefied or why the transition from the liquid to the gas phase requires energy (heat of vaporization). The favorable (negative) interaction energy at the origin of these phenomena is ubiquitous: it exists between xenon atoms but also between water molecules. Furthermore, except in the case of molecules with a large dipole moment (like water molecules), this interaction energy term, which is named the London term, is always larger in absolute value than the Keesom term. It is not possible to give an explanation of the origin of the London interaction energies using classical physics; quantum physics is required. At best, it is possible to give a crude model by saying that a charge distribution is always fluctuating. In the case of a monoatomic species, which can be

described as a spherical distribution of electrons around a positive nucleus, a fluctuating distribution means that the instantaneous electronic distribution can be nonspherical leading to the formation of an instantaneous dipole. Any instantaneous dipole is itself able to induce an instantaneous induced dipole in a charge distribution in its vicinity. These instantaneous dipoles can be very large, and this is the reason why the London contributions to the intermolecular interaction energies are generally the largest of all the energies responsible for the cohesion of liquids and solids. As in the case of the Keesom and Debye terms, the distance dependence is a r^{-6} law.

The three abovementioned terms are negative and cannot explain why matter is not infinitely compressible. A repulsive force, a positive energy contribution, must necessarily also be present. The origin of this contribution cannot be explained on the basis of classical physics; it is related to the Pauli principle, which implies that it is impossible to place more than two electrons in the same orbital. The distance dependence of the Pauli positive interaction energy is frequently given by a r^{-12} law; however, other laws are also used.

What is often called the van der Waals interaction includes the Keesom, Debye, London, and Pauli contributions and represents the electrostatic interaction between nonbonded atoms other than the ionic interaction. Some authors, however, only use the term for the attractive contributions, and some even use it solely as a synonym for the London dispersion forces.

The intermolecular potential between monoatomic species, which can interact only through the attractive London force and repulsive Pauli force (the isotropic terms), is frequently approximated by an empirical law of the type

$$E = -A/r^6 + B/r^{12}$$

where A and B are constants depending on the nature of the interacting atoms. The potential with this type of analytical form is called a Lennard-Jones potential. A law of this kind is characterized by a minimum, and the r value of this minimum corresponds to the sum of the van

der Waals radii of the two interacting species. It can be used to describe interactions between nonbonded atoms, these atoms being in the same molecule (intramolecular interactions) or in different molecules (intermolecular interactions), and tables give the so-called van der Waals radii of all atoms. In molecular models, when atoms are represented by spheres of various sizes (and colors), the radii of these spheres are generally (but not always) proportional to the van de Waals radii of the corresponding atoms.

Cross-References

- [Molecular Recognition](#)
- [Noble Gases](#)

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Variability, Stellar

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Variability characterizes the changes over time of the apparent brightness of a star. Stars may exhibit long-term variations of their intrinsic luminosity, as the Sun, for instance, whose luminosity changes by about 0.1% over an 11-year solar cycle. Active stars with numerous spots present a large variability. Stars can also show a periodic variation on a shorter time scale of minutes (oscillations) to years (pulsations). The change can be dramatic as in cataclysmic variables or

extremely subtle when it's a mere oscillation. Finally, stars may also suffer partial eclipses from an orbiting companion (another star or planet). Variability is typically measured in mmag (milli-► [magnitudes](#)).

Cross-References

- [Activity](#)
- [Transit](#)

Vastitas, Vastitates

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Extensive plain](#)

Definition

Descriptor term for an extensive plain as defined in the planetary nomenclature by the International Astronomical Union (<http://planetarynames.wr.usgs.gov/DescriptorTerms>) for the Vastitas Borealis region on ► [Mars](#). This lowland region spans the northern hemisphere north of 55 °N up to 80 °N. It is characterized by a flat surface and a low impact crater record, which indicates a relative young age or extensive resurfacing processes in upper ► [Hesperian](#) times. It is still debated whether this region has formerly been the floor of an extensive ocean, the Oceanus Borealis. Indications for this theory came from the so-called Vastitas Borealis Formation (VBF), a knobby-textured surface that is interpreted to be the sublimation residue from ponded flood runoff. This area is bordered by continuous contacts, interpreted as shorelines by some authors.

Cross-References

- [Crater, Impact](#)
- [Hesperian](#)
- [Mars](#)

VeGa

- [Venus Express](#)

Vega 1 and 2 Spacecraft

Anny-Chantal Levasseur-Regourd
Sorbonne Univ., Campus P. & M. Curie /
LATMOS, Paris, France

Keywords

Comets · Nucleus · Coma · Organics · CHON
· Halley · Vega · Giotto

Definition

Vega 1 and Vega 2 (contraction of Venus and Halley in Russian) were two identical spacecraft designed by the USSR in cooperation with European countries to investigate ► [Venus](#) and ► [Comet Halley](#). Launched from Baikonur by Proton rockets, respectively, on 15 and 21 December 1984, they released modules into Venus's atmosphere and then flew through Halley's coma on 6 and 9 March 1986, at 8900 and 8000 km nucleocentric distance. The television system (TVS) provided, after noise cleaning, the first evidence for the existence of a cometary nucleus. The dust mass spectrometers (PUMA) allowed a major discovery to be made. It indeed detected the presence of a large amount of organic molecules within cometary dust particles, so-called CHON, where this acronym stands for the most abundant elements: carbon, hydrogen, oxygen, and nitrogen.

The close flyby of the nucleus of comet Halley on 13 March 1986 by the ESA (European Space Agency) Giotto mission was made possible by the navigation data of the two Vega spacecraft. They were indeed playing the role of pathfinders for Giotto, which could flyby Halley nucleus at a distance of only 600 km.

Cross-References

- [Comet Halley](#)
- [Giotto Spacecraft](#)

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Venus

François Forget¹ and Jörn Helbert²

¹Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique, UMR 8539, Université Paris 6, Paris, France

²DLR, Institut für Planetenforschung, Berlin, Germany

Keywords

Atmosphere · Climate · Clouds · Habitability · Interior · Photochemistry · Surface · Tectonics · Volcanism · Water

Definition

Venus is the second ► [terrestrial planet](#) from the Sun. It is in many of its key parameters very similar to ► [Earth](#). The planet, however, has a thick CO₂ atmosphere with a ground pressure of 95 bar (compared to 1 bar for the Earth) and sulfuric acid clouds that permanently shroud the planetary surface. The atmosphere induces a strong ► [greenhouse effect](#) with surface temperature of more than 500 °C. Surface landforms are dominated by volcanic and tectonic activities. Based on the random distribution of craters, the global surface seems to be young, with an average age of 500 million to 1 billion years.

History

Galileo's observations of the phases of Venus provided crucial evidence for Copernicus' heliocentric theory of the solar system. Mikhail Lomonosov discovered the atmosphere of Venus during its 1761 transit of the Sun (cf. M. Marov, *Transits of Venus: New Views of the Solar System and Galaxy*, Proceedings of IAU Colloquium #196). The high surface temperature was first measured by radio astronomers in the 1950s, while the rotation period and obliquity were determined by ground-based radar in the 1960s. The nature of the clouds as sulfuric acid droplets was deduced from observations of the polarization of reflected sunlight as a function of wavelength and phase angle (the angle Sun-planet-Earth) by Hansen and Hovenier (1974).

Basic Methodology

Most of what we know about Venus is based on spacecraft exploration:

- First flyby by NASA spacecraft: Mariner 2 (1962) and Mariner 5 (1967).
- After several attempts, several Soviet probes were able to descend through the atmosphere (Venera 4, 1967; Venera 5 and 6 in 1969) and

land successfully, starting with Venera 7 (1970) and Venera 8 (1972). The increasingly sophisticated landers Venera 9–14 (1975–1981) and Vega 2 (1986) were able to transmit images and analyses from the surface.

- NASA sent a major exploration mission, “Pioneer Venus,” composed of one orbiter and four atmospheric probes in 1978.
- The detailed surface, previously hidden by the clouds, was revealed by the Soviet missions, Venera 15 and 16 (1983), and especially by the NASA orbiter Magellan (1989) which mapped the planet with a 100–200-m resolution.
- The Vega 1 and 2 missions put two balloons in the atmosphere in 1986. They flew for 2 Earth days, covering almost 12,000 km around the planet.
- Since April 2006, the European Space Agency orbiter Venus Express has resumed the monitoring of Venus, focusing on the atmosphere and the climate of Venus and mapping the surface for the first time in the near-infrared spectral range.
- The Japanese space agency JAXA launched the Venus Climate Orbiter (“Akatsuki”) in May 2010. Unfortunately, the probe failed its insertion into Venus orbit on December 7, 2010.

Key Research Findings

Key Characteristics

Venus is the nearest planet to the Earth, both in terms of distance and in overall size and mass (Table 1).

The rotational axis of Venus is nearly perpendicular to the ecliptic, and the orbit is nearly circular, so seasonal changes in the climate are probably very small. The Venusian year is 224.7 Earth days, longer than the time for Venus to rotate on its axis, which is 243 Earth days. The solar day, defined as the time for the Sun to go from noon to noon as seen from the surface of Venus, is about 117 Earth days. This very slow rotation of the solid body of Venus is retrograde, that is, backward, compared to the other planets.

Venus, Table 1 Basic data for Venus and the ratio to the value of the same parameter for the Earth

	Venus	Venus/ Earth
Mass	4.87×10^{24} kg	0.815
Radius	6051 km	0.95
Density	5.2 kg/m^3	0.943
Equatorial gravity	8.87 m s^{-2}	0.907
Rotation period	243 Earth days (retrograde)	243
Orbital period	224.7 Earth days	0.615
Obliquity	2.7°	0.115
Orbital eccentricity	0.007	0.407
Mean distance from the Sun	108.2×10^6 km	0.723

Surface Geology

The surface of Venus is dominated by tectonic and volcanic landforms. Radar images and altimetry data show that a mosaic of volcanic plains covers about 80% of the surface. Among the plains stand several continent-sized upland plateaus made of intensely deformed “tessera” terrain and broad topographic rises with associated volcanoes and converging rifts (Basilevsky and Head 2002).

Plains

The most abundant unit among the plains is the so-called regional plains, which occupy 65–70% of the surface and are represented by two major varieties:

- The *wrinkle ridge plains* have a rather smooth surface, often with flow-like features most likely made of solidified lava flows. These plains are deformed with a network of relatively narrow wrinkle ridges, which are the result of moderate horizontal compression. Large areas occupied by the flow-like features and very gentle slopes, along which the material flowed, indicate high-yield eruptions of liquid, nonviscous, probably basaltic lava which formed plains, subsequently deformed by wrinkle ridges. The suggestion of basaltic composition of the lava is supported by the analysis of the Magellan images for the location of the Venera/Vega landers.

- The *shield plains* are less abundant and usually form fields of a few hundred kilometers across. Their surface is peppered with gentle-sloping volcanic shields 5–15 km in diameter. Coalescing flanks of the shields form most of the plains' surface. The gentle slopes of the shields imply that they are made of nonviscous, probably basaltic lava. However, the differences in morphologies of the shield plains and plains with wrinkle ridges could be due to compositional differences of the composing lavas.

About 10–15% of Venus' surface is occupied by younger volcanic units, which are obviously superposed on regional plains and are not deformed by wrinkle ridges. Many of them consist of numerous volcanic flows with lobate morphology. The large length of the flows on gentle to almost horizontal surfaces implies low viscosity of the lava. This, in turn, is usually considered as evidence of basaltic composition (Basilevsky and Head 2002).

Among the regional plains, more often in association with the shield plains, are observed steep-sloped volcanic domes of a few to several tens of kilometers in diameter. The high steepness of their slopes is believed to be due to high viscosity of the composing lavas. One of the possible explanations of this high viscosity is that the lava is geochemically evolved, with a rather siliceous composition. However, the high viscosity of the dome-forming materials could also be the result of the presence of gas. The high atmospheric pressure on Venus' surface is not favorable for the near-surface degassing of ► [magma](#), so lavas on the surface may be saturated with gas bubbles and thus be viscous, even if their chemistry is rather usual (Head et al. 1992).

About 20% of the surface of Venus is occupied by terrains that are topographically rough due to tectonic deformation. These are the so-called ridge belts, densely fractured plains, tesserae, and the mountain belts surrounding plateau Lakshmi, as well as rift zones. The regional plains embay and partly bury almost all of them except the majority of rifts.

Ridge belts form a global-wide system, which is now seen only in fragments standing high

enough not to be flooded by lava from the surrounding regional plains, which in most observed cases embay the belts. The ridge belts are composed of plains-forming material looking very similar to that of the plains with wrinkle ridges. It is probably also a solidified basaltic lava folded into relatively broad ridges arranged into parallel bands.

Plateau, "Tesserae," and Mountains

Tesserae form "islands" and "continents" standing above the surrounding regional plains, which obviously embay the tessera (Fig. 2). When tesserae are in contact with ridge belts and densely fractured plains, it is seen that materials composing these two units embay tessera terrain. The surfaces of tesserae are very rough, being dissected by numerous crisscrossing ridges and grooves a few kilometers wide and tens of kilometers long. The ridges are evidently formed by compressional tectonic deformation, while many grooves are extensional structures. The surface of tessera terrain looks bright on the Magellan images. This is due to high roughness on meter to decameter scales, also resulting from the tectonic deformation. The compositional nature of tessera terrain material is unknown. Some researchers suggest that it has a basaltic composition. Others believe that tessera may be made of more feldspathic material resembling to some degree the anorthosites of the Moon or granites of the Earth. A recent analysis of data from the VIRTIS instrument on the ESA mission Venus Express, providing images at the wavelength of the atmospheric window at 1.02 μm , shows evidence for variation of surface emissivity on the Southern Hemisphere (Mueller et al. 2008). The inferred surface emissivity is correlated to some extent with morphological units identified from radar images of the NASA/JPL Magellan mission. Alpha and Phoebe Regios are highlands mostly composed of tessera terrain. In comparison to lowland plains and other less-tectonized highlands, these regions generally emit less thermal radiation, which implies lower emissivity. An analysis of near-infrared wavelength data from the Galileo flyby in 1990 also finds that highland regions on Venus on average have a lower

emissivity than lowlands (Hashimoto and Sugita 2003). As a significant part of the Venus highlands in the area observed by Galileo is composed of tessera, this observation is consistent with the more global observation of VIRTIS on Venus Express (Mueller et al. 2008).

Mountain ranges surrounding the volcanic plateau Lakshmi form a specific terrain type. They consist of clusters of parallel (within the given range) ridges resembling the ridge belts described above on plains. But mountain ranges differ from the ridge belts in that their heights are very large. The summit of the highest of them, Maxwell Montes, stands more than 11 km above the mean planetary radius. Parallel ridging and high altitudes of the mountain ranges imply that they formed due to intense horizontal compression. As in the case of tessera terrain, the composition of the mountain range material is unknown.

The top parts of the mountain ranges (and of some other highlands of Venus as well) have extremely high radar reflectivity and look very bright on the Magellan radar images. This brightening appears above some critical altitude (somewhat changing from place to place), which is often referred to as the “snow line.” The chemical composition of the lower atmosphere (in particular the CO/CO₂ and COS mixing ratios) is crucial to understanding the effects of chemical weathering on the surface of Venus. In this process, the iron in silicates, such as pyroxenes and olivines, was believed to segregate into minerals having a high electric conductivity (iron oxides or sulfides). These minerals very efficiently reflect the radio waves, making the surface very radar bright. The mineral responsible for the radar anomalies on mountain tops and volcano edifices appears to be the electrical semiconductor pyrite, whereas ► [magnetite](#) is thought to characterize the regions of lower altitude. Other researchers suggested that the high reflectivity is due to surface films of some metals vaporized from the rocks at the lower hotter places and deposited on the cooler mountain tops. Interestingly, Maat Mons volcano, which reaches ~6000 m of height, does not show this low emissivity at the summit. This has been interpreted as possible evidence for

recent volcanic activity, which prevented the weathering effect at high altitude.

Rifts

Venusian rifts are rather similar to continental rifts on Earth and form a global system up to 40,000-km long. They are typically troughs, whose floor may be several kilometers below the neighboring non-rifted terrain, while the rims of the troughs are often uplifted above the neighboring terrain. The walls and floors of the troughs are fractured, often very heavily. Young post-regional-plains lava fields and volcanic constructs are frequently associated with rifts. The general consensus is that rifts formed in the environment of tectonic extension. Rifts of Venus cut not only post-regional-plains units but all other geologic units of this planet as well. Most of the observed rifts are younger than the regional plains, but some are older (designated by some researchers as fracture belts) and seen as fragments partly flooded by the lavas of regional plains.

Coronae

Several hundred specific volcanic-tectonic structures called “coronae” (“corona” singular) are observed on the surface of Venus. Coronae are oval to circular features typically of 100–300 km in diameter. A few of the coronae are even larger. They have a circular or nearly circular, tectonically deformed annulus, which usually stands a few hundred meters above the surrounding plains. The area inside the annulus is typically lower than the surrounding plains and flooded with plains-forming volcanics. Aprons of young lobate volcanic flows are seen radiating from many coronae. At the center of some coronae, an elevated and tectonically deformed area, the corona core, is seen. Coronae are considered to form as a result of the rising of hot material in the ► [mantle](#). The potential compositional similarity or difference of coronae with other landforms and terrains makes the largest of them a target for study with the Venus Express instruments (Helbert et al. 2008).

Impact Craters and Surface Age

The thick atmosphere of Venus effectively screens the surface from impacts of smaller bodies. Typically, objects with a diameter smaller than 30 m

should not make it to the surface with enough of their initial velocity to produce a crater. Radar imaging of the surface shows more than 960 impact craters from 1.5 to 270 km in diameter. Of this, only a very small percentage of impact craters are smaller than 30 km, confirming the atmospheric screening effect. Surprisingly, the distribution of these approximately 1000 craters on Venus seems undistinguishable from (or very close to) a random scattering. Unlike on ► [Mars](#) or ► [Mercury](#), no heavily cratered older terrains are found on Venus. All craters on Venus appear to be very pristine, indicating that erosion plays no important role on Venus, in contrast to Earth where craters are effectively removed by erosion and resurfacing. Exogenic resurfacing on Venus is essentially dominated by eolian processes. The observed eolian features are represented by radar-dark mantles, wind streaks, yardangs, and dunes.

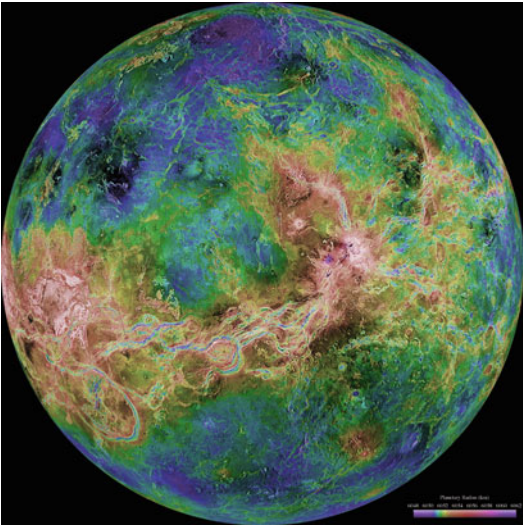
The crater size and density distribution as a proxy for the surface age (see chronology) indicates that the surface was globally formed between 500 million and 1 billion years ago. There are two competing theories to explain this apparently young surface age. The so-called equilibrium theory assumes volcanic activity destroys craters at approximately the same rate as new craters are formed. Therefore, always the same number of craters is observed on the surface of Venus. This would imply a constant volcanic activity over large parts or even the whole geological history of Venus. The competing so-called catastrophic theory assumes that a catastrophic resurfacing event approximately 500 million years ago reformed the whole surface of the ► [planet](#) in a very short time period. All craters and the entire earlier geological record were erased in this resurfacing event. After this event, only faulting and localized volcanic activity has further altered the surface. Between these two end-member theories, any combination of these two is possible. Without actual dating of surface samples at various locations, it seems impossible to obtain a final answer. Recent results from Venus Express indicate that hot spot volcanism in localized areas has been ongoing on Venus in the very recent geological history (Smrekar et al. [2010](#)).

Venus Crust and Mantle Dynamics

Venus and Earth lose heat in very different ways (compare heat transfer). ► [Plate tectonics](#) on Earth leads to a recycling of the ► [crust](#) through plate growth, motion, and subduction. For Venus, there is no indication for plate tectonics on a global scale at all. At the same time, widespread volcanism and tectonic deformation are observed. This might indicate that Venus volcanism triggered by mantle upwellings may contribute to the heat loss from the interior while the tectonic deformation may be indicative of and caused by mantle downwelling.

In situ measurements by the Venera and Vega landers are at most places consistent with a basaltic surface composition. The hypsometric curve of Venus is unimodal. As discussed above, the inferred lava viscosity of most volcanic features is low, consistent with basaltic composition. All these observations point toward a crust mostly composed of ► [basalt](#). However, no landing site was on tessera terrain, tesserae are elevated, and the morphology is dominated by tectonic deformation. As stated before, these considerations lead to the hypothesis that tessera highland crust is more abundant in feldspar and silica, relative to lunar highlands or continents on Earth. Recent near-infrared mapping supports this hypothesis, although other interpretations of the near-infrared data cannot be ruled out.

Generation of felsic crust is unlikely under the current climatic and tectonic regime on Venus. The lunar highland crust is believed to be a remnant of a magma ocean. Enrichment in silica as in the ► [continental crust](#) of Earth requires recycling of water into the mantle. The surface of Venus is extremely dry and crustal recycling by plate tectonics does not operate at present. Any crust with felsic bulk composition would have had to be created during the early history of the planet. From a stratigraphic analysis, tessera terrain predates all units it is in contact with (Ivanov and Head [1996](#)). Tessera terrain is characterized defined by an extensive history of tectonic deformation. Assuming that tessera highlands indeed represent less-dense crustal blocks created early in the history of Venus, implications arise from their persistence on the surface of Venus regarding



Venus, Fig. 1 A hemispheric view of Venus centered at 180° east longitude. The 3-km surface roughness is shaded (with illumination from the west) and is color-coded to represent elevation. The image is mostly based on Magellan images, complemented by Earth-based radar data as well as Venera and Pioneer Venus altimetry

resurfacing mechanism, crustal recycling, and thermal evolution. If tessera highlands are enriched in silica relative to basalt, this implies existence of a primordial ocean on Venus. In either case, Venus would even more closely resemble the Earth than previously assumed, making Venus an excellent subject for general studies of earthlike planets (Figs. 1 and 2).

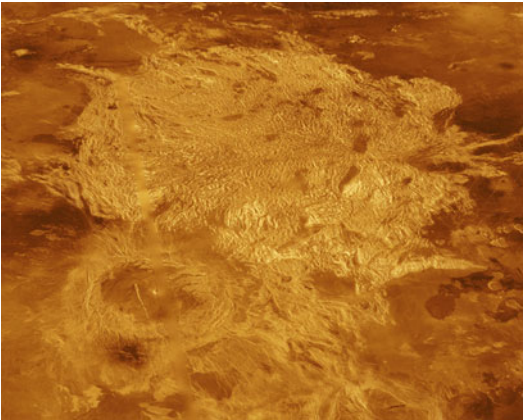
Venus Atmosphere and Climate

Present Atmospheric Composition

The massive Venus atmosphere (about 90 bar) is primarily composed of ► carbon dioxide (96%) and a few percent of inert gases (nitrogen, argon). The relatively high abundance of sulfur dioxide in Venus’ clouds is suggestive of extensive volcanic activity. This sulfur dioxide combines with liquid water to make thick H₂SO₄-H₂O ► clouds (Table 2).

Thermal Structure and Greenhouse Effect

Venus is closer to the Sun than the Earth and receives about twice the incidence of solar energy. However, the highly reflective cloud cover on



Venus, Fig. 2 A radar image of a Venus “tessera”: Alpha Regio is a roughly square region of tessera about 1500 km across and centered at 22°S, 5°E. The surrounding volcanic plains appear to have flowed around Alpha’s margins and thus are younger than Alpha

Venus, Table 2 Composition of the Venus and Earth atmospheres as fractional abundances (volume mixing ratio) except where ppm (parts per million) is stated

	Venus	Earth
Carbon dioxide	0.96	0.0003
Nitrogen	0.035	0.770
Argon	0.00007	0.0093
Water vapor	~0.0001(?)	~0.01
Oxygen	0.0013	0.21
Sulfur dioxide	0.00015	0.2 ppb
Carbon monoxide	0.00004	0.12 ppm
Neon	5 ppm	18 ppm

Venus reflects 76% of the incoming solar flux and which results in a *smaller* net ► solar constant for Venus than for Earth. An airless body with the same ► albedo and at the same distance from the Sun as Venus would reach equilibrium at a temperature below –40 K.

Therefore, the high surface temperature primarily results from a 500 °C greenhouse warming produced by the thick, cloudy atmosphere. The details of Venus greenhouse effect are not easy to quantify, however. The massive amounts of carbon dioxide are very effective at blocking the emission of thermal infrared radiation, but only at those wavelengths where the gas has absorption bands, which are far from covering the entire

spectrum. Moderate amounts of water vapor are also required, and even then considerable spectral gaps or “windows” remain. These are thought to be blocked by the clouds made of sulfuric acid droplets. These have the property of being highly absorbing at thermal infrared wavelengths, while being nearly conservative (non-absorbing) scatterers in the visible and near infrared. Thus, the clouds tend to diffuse downward those of the incoming solar photons that they do not reflect to space, while blocking thermal emission from the lower atmosphere and surface. Overall, radiative transfer models, involving weak as well as strong bands of CO₂ and H₂O, plus those of the minor constituents CO, HCl, and SO₂, can account for the high surface temperatures by careful incorporation of the scattering and absorbing properties of the clouds.

Figure 3 shows the mean Venus temperature profile. The solar radiation that penetrates the clouds warms the lower atmosphere, which is prevented by the ► [opacity](#) of the overlying layers from cooling by radiation (see heat transfer) to space. It therefore forms a deep convective region, the troposphere. This links the high surface temperature of around 730 K with the level at which the temperature is close to the effective bolometric temperature of Venus (about 230 K), where strong radiative cooling to space can occur.

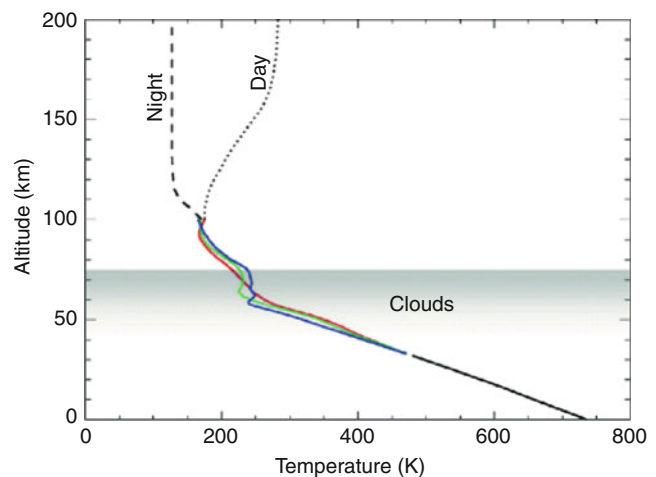
Above the troposphere and the clouds’ top, between 60 to about 100 km, the temperature can remain close to the adiabatic lapse rate, that

is, it is largely convectively driven. However, in the upper part of this lower mesosphere region, the temperature tends to become constant with height as the atmosphere becomes optically thinner, and, to a first approximation, each layer tends to find a radiative equilibrium temperature. On the Earth, this situation is altered by the ► [ozone layer](#), which is responsible for substantial heating in the stratosphere and the mesosphere. There is no corresponding effect on Venus, except for small amounts of absorption of solar and thermal energy in the near-infrared bands of water vapor and carbon dioxide. This absorption produces a mesopeak (or local temperature maximum) in global radiative equilibrium models around 110 km. The thermosphere is reached at heights of more than 120 km above the surface. Here, the atmosphere is very rarified, and short-wavelength solar radiation and energetic particles drive rapid photochemical reactions and produce high temperatures by day. At night, when the heating is absent, efficient radiative cooling by CO₂ results in a rapid decline of temperature, so there is a sharp gradient across the terminator, from over 300 K on the illuminated hemisphere down to 100 K or less on the nightside.

Atmospheric Circulation

The atmospheric circulation is characterized by a super-rotation of the atmosphere; that is, at almost all latitudes, near the cloud top, the wind is prograde and the wind speed larger than 100 m/s. The

Venus, Fig. 3 Vertical structure of the Venus atmosphere based on the Venus International Reference Atmosphere (VIRA)



clouds thus seem to rotate in about 4–5 Earth days, much faster than the surface. Below the clouds (about 60 km), the four Pioneer Venus and many Venera entry probes have shown that the winds fall gradually in velocity as the atmosphere becomes denser. The super-rotation of the Venus atmosphere remains a scientific puzzle. The mechanism that maintains this super-rotation should involve transport of angular momentum by the Hadley circulation and by planetary atmospheric waves. However, key aspects of the three-dimensional structure of the global circulation on Venus have not yet been measured. A key question is the role of the waves induced by the diurnal cycle (thermal tides).

Above the cloud tops (80–140 km), the Venus atmosphere shows two flow regimes – (1) a stable subsolar to antisolar point circulation driven by solar near infrared and extreme ultraviolet heating and (2) a super-rotating zonal flow that varies greatly over time. Breaking gravity waves

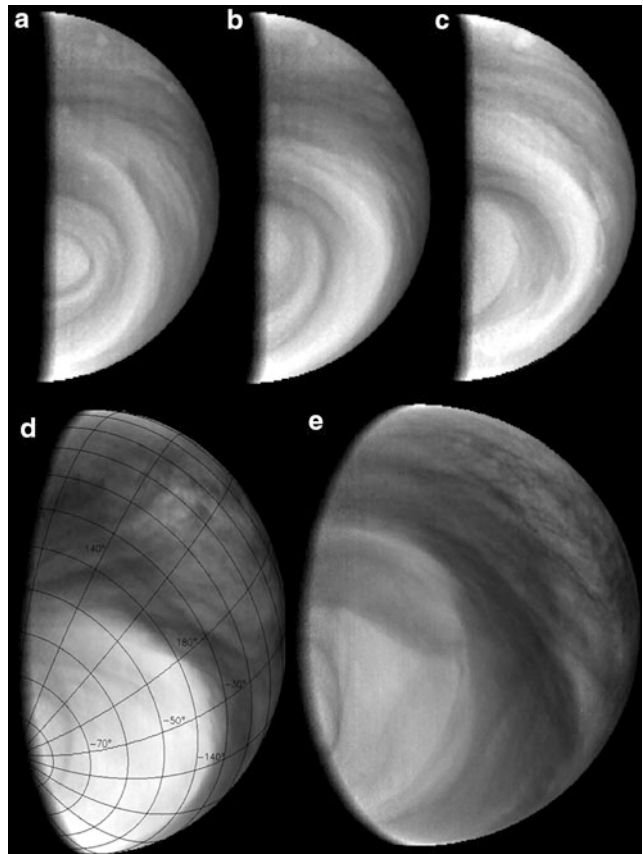
propagating from below have been observed and appear to dissipate in the 140–150-km region.

Near the poles on Venus, a complex, a polar collar takes the form of a ribbon of very cold air, some 10-km deep and a thousand kilometer in radius, centered on the pole. Inside the collar, temperatures are some 40 K cooler than outside the feature. Poleward of the inner edge of the collar lies a polar “dipole” consisting of a pair of wide coupled vortices circulating around the pole. The dynamics of this structure is active and complex. It can even sometime become a tripole (Fig. 4).

Clouds and Photochemistry

Venus is completely enshrouded by clouds in a complex layered structure over 30-km deep, between altitudes of 45 km and about 75 km (in some locations, a thin haze may extend down to 30 km). Sulfuric acid particles with radii around 1–10 μm are thought to dominate the composition

Venus, Fig. 4 Venus observed by Venus Express (VMC camera). These images obtained in the ultraviolet (UV) illustrate the complex atmospheric dynamics and the cloud variability near the pole. Images (a–c) are separated by less than 24 h in June 2006. Figure (d) was obtained on January 13, 2007. (Credits: ESA)



of the clouds of Venus. They are generated photochemically from SO_2 and OCS in the upper Venus atmosphere. However, the photochemical processes likely also involve chlorine, which has long been detected in the Venus atmosphere. Active photochemical processes not unlike those observed in the Earth's stratosphere have been postulated to occur on Venus (DeMore and Yung 1982). They must also stabilize Venus' atmosphere, where various catalytic cycles or heterogeneous processes convert the photodissociated products of CO_2 , CO , and O_2 , back to CO_2 .

Structure can be seen in the clouds if they are observed in reflected sunlight through an ultraviolet filter, due to the presence of an absorber mixed with the sulfuric acid droplet. The nature of the UV absorber is still unclear. Monitoring of the UV contrasts through imaging from Venus Express has shown a dynamic behavior that has been suggestive of convective connections in equatorial latitudes (Titov et al. 2008).

The lower cloud region is less well known. It is also likely to be composed primarily of sulfuric acid droplets. X-ray fluorescence data from the Soviet Vega descent probes also found significant and spatially variable quantities of Cl, P, and Fe in the lower cloud particles, although it is not clear in what chemical form.

Water, Climate Evolution, and Habitability

Observational Clues

The amount of water present as gas and bound up with sulfuric acid and other compounds in the clouds is between 10 and 100,000 times less than exists in the oceans and atmosphere of the Earth. Thus, Venus is overall very dry compared to the Earth.

At the same time, ► [deuterium](#) (D) is about 100 times more abundant (relative to H) in the atmosphere of Venus than in that of the Earth. The discovery of this 150-fold enrichment in deuterium in the Venus atmosphere has traditionally been considered as evidence for the presence of significant amounts of water on early Venus, which would have been lost in the past (Donahue et al. 1982). Indeed, loss of water takes place by dissociation of the water in the

upper atmosphere by solar ultraviolet radiation and the subsequent escape of the ► [hydrogen](#). Both deuterium and normal hydrogen escape from the atmosphere, but the heavier isotope escapes less efficiently, leading to the observed isotopic fractionation.

Note, however, some authors have suggested that this enrichment could be explained by other mechanisms not requiring a planet very different than today (if one assumes that Venus started dry, the balance between cometary input and escape could create such an enrichment, Grinspoon 1987). New remote sensing measurements of the D/H ratio in the upper atmosphere above the clouds have revealed even higher D/H ratio (~ 240 times the terrestrial value). This may indicate shorter timescales for the loss of water from the top of the atmosphere than previously thought.

The Classical Scenario of Venus Evolution

Why is Venus so different from the Earth? Both planets formed at about the same time within the inner solar system, from similar chemical and isotopic reservoirs. Yet they have followed very different evolutionary paths. Unfortunately, as mentioned above, there are no direct geological records about Venus environment early in its history. The surface has been completely resurfaced a few hundreds of million years ago. Nevertheless, the presence of large amounts of water billions of years ago is expected by most planet formation models. Early conditions may have been more clement than today's extreme, in particular if the early Sun was as faint as expected by the standard Sun evolution models. Early Venus could have thus been covered by oceans of liquid water. As the Sun's luminosity slowly increased, these oceans warmed, more water evaporated to become part of the atmosphere, the greenhouse effect increased, enhancing water evaporation (positive feedback). Ultimately the entire oceans could have boiled. This process is termed the "runaway greenhouse effect." In reality, a full runaway greenhouse process may not have been possible because of moist convection and the high albedo produced by water cloud formation. However, it is likely that the ocean temperature was high enough to generate a relatively wet upper atmosphere ("moist greenhouse

effect”), so that water would have been rapidly lost by photodissociation followed by hydrogen escape (Kasting 1988). From then on, any carbon dioxide exhaled by volcanoes or delivered by impacts on Venus could no longer be removed from the atmosphere by chemical weathering (as on Earth) because of the lack of liquid water. As carbon dioxide accumulated in the atmosphere, the greenhouse effect grew ever more intense, leading to the planet that we know today. In particular, the lack of an ocean on Venus has at least three consequences for the atmosphere. First, most of the planet’s CO₂ remains in the atmosphere, in contrast to Earth, where most of the 50 bar of CO₂ are sequestered as carbonate rock in the sediments. Second, the atmosphere of Venus contains large quantities of SO₂. On Earth, most of the volatile sulfur resides in the ocean as sulfate ions. The presence of this large amount of SO₂ in the atmosphere is responsible for the production of a dense H₂SO₄ cloud on Venus. Third, the atmosphere of Venus contains large amounts of HCl. On Earth, the bulk of chlorine is in the form of salt (NaCl) in the oceans. The photochemistry of the atmosphere of Venus is driven by the catalytic chemistry of chlorine in the atmosphere.

Nowadays, Venus’ climate may also experience some variations, not because of changes in orbital parameters or obliquity (see ► [Mars](#)) but due to volcanic events that may have resulted in the release of atmospheric water and sulfur dioxide which was able to affect the atmospheric greenhouse effect and the cloud properties (Bullock and Grinspoon 2001).

Astrobiology of Venus

Present-day Venus’ surface is clearly hostile to carbon-water-based organisms. Nevertheless, it can be noted that the cloud layer between 50 and 60 km presents temperatures and pressures similar to Earth conditions (temperature ranging between –20 °C and +40 °C, pressure between 200 and 1000 mbar). Some have speculated that some microbial life could thrive in this aqueous, energy-rich environment with abundant nutrient and radiative energy. Some extremophile ► [archaea](#) observed on Earth could cope with the extreme acidity. However, a major issue lies in the

fact that the residence time of cloud droplets is limited. Because of that, for instance, there is no obvious bioactivity in terrestrial clouds (some bacterial growth has been reported, though). From that point of view, the residence time of Venus cloud particles is significantly longer than on Earth (months vs. days). Therefore, although the suggestion of life forms in Venus clouds remains a wild speculation which is not widely accepted, it remains difficult to prove it wrong at this time.

Venus’ interest for astrobiology goes beyond such speculations. For instance, the CO₂ dominated atmosphere of Venus may be an analog to the conditions of Earth’s earliest atmosphere, when the origin of life is believed to have taken place. It may also resemble the atmospheres of many extrasolar terrestrial planets. In the past, Venus may once have had warm, habitable oceans. The duration of this phase is poorly understood, but during this time, the terrestrial planets were not isolated. Rather, due to frequent impact transport, they represented a continuous environment for early microbial life. Venus may even have been a special place in the past, because the evaporation of these oceans, and subsequent escape of hydrogen, might have resulted, at least temporarily, in an oxygenated atmosphere.

More generally, Venus as we know it is the product of the evolution of an earthlike planet that formed at nearly the same distance from the Sun and is of similar age, size, and composition as the Earth. Therefore, the physics governing the state and recent evolution of its atmosphere are of high interest in understanding how the atmospheres of potentially habitable, earthlike planets evolve to different states. Venus presents us with a unique opportunity for putting the bulk properties, evolution, and ongoing geochemical processes of Earth into a wider context.

Cross-References

- [Albedo](#)
- [Anorthosite](#)
- [Basalt](#)
- [Carbon Dioxide](#)
- [Continental Crust](#)

- ▶ Corona, Coronae
- ▶ Crater, Impact
- ▶ Cratering Chronology
- ▶ Crust
- ▶ Deuterium
- ▶ Galileo Galilei
- ▶ Granite
- ▶ Greenhouse Effect
- ▶ Heat Transfer, Planetary
- ▶ Hydrogen
- ▶ Isotopic Fractionation (Planetary Process)
- ▶ Magma
- ▶ Magnetite
- ▶ Mantle
- ▶ Mars
- ▶ Mercury
- ▶ Moon, The
- ▶ Obliquity and Obliquity Variations
- ▶ Opacity
- ▶ Ozone Layer
- ▶ Photochemistry
- ▶ Pioneer Spacecraft
- ▶ Planet
- ▶ Plate Tectonics
- ▶ Rock
- ▶ Rotation Planet
- ▶ Silicate
- ▶ Solar Constant
- ▶ Solar System, Inner
- ▶ Sun (and Young Sun)
- ▶ Terrestrial Planet
- ▶ Tessera, Tesserae
- ▶ Vega 1 and 2 Spacecraft
- ▶ Venus Clouds

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Venus Clouds

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, Université Paris 6,
Paris, France

Definition

The clouds of ▶ **Venus** completely enshroud the planet in a complex-layered structure lying

between 45 and 75 km above the surface of the earth. The cloud droplets are formed of sulfuric acid (H_2SO_4) mixed with typically 25% water, with droplet diameters ranging from less than 1 to over 30 μm . Depending on the altitude, their temperature ranges between $-50\text{ }^\circ\text{C}$ and $+80\text{ }^\circ\text{C}$. In theory, they could provide a ► [habitat](#) to adapted life-forms, but this remains an unlikely speculation.

Cross-References

- [Climates, Diversity in the Solar System](#)
- [Climates, Terrestrial Planets](#)
- [Habitat](#)
- [Venus](#)
- [Venus Clouds, Potential for Life](#)

Venus Clouds, Potential for Life

Sabrina Guilbon
LATMOS, IPSL, Paris, France

Keywords

Clouds · Venus · Life · Extremophile · Exobiology

Definition

From hypotheses describing habitability of the primitive Venus to observed current conditions in the Venusian cloud layers, the question of the potential presence of life in these clouds can be studied. Indeed, some analogies may be drawn to Earth life forms that live in extreme conditions.

Overview

Venus is located outside the habitable zone defined by Hart in [1979](#) and in which water is present in liquid form. Barnes et al. ([2016](#))

proposes to define a transition region in which the possible habitability gradually decreases rather than defining a strict border separating two completely different areas.

Despite the extreme unfavorable current conditions for the life development, the primitive Venus seems to present better conditions for the emergence of life.

Primitive Venus or Paleo-Venus

During its formation, Venus received the same inventory of volatile species as Earth, including water. The Deuterium/Hydrogen ratio (or D/H) allows to assert that Venus has lost an important quantity of water in its history. However, it is still difficult to determine when and what part of this loss occurred (Donahue [1999](#)). Some scenarios advocate an escape of water from the Venus' atmosphere during its formation following an early greenhouse effect (Luger and Barnes [2015](#)), while others propose the formation of an ocean that has entirely evaporated (Way et al. [2016](#)).

A three-dimensional model taking into account the relief of the planet allows the study of an ancient Venus. This model reveals that a moderate temperature is possible on the surface if Venus has a slower rotation period than 16 Earth days despite a solar flux 46–70% higher than what receives modern Earth (Way et al. [2016](#)). Thus the ancient Venus could have remained habitable 700 million years ago if there was a primitive shallow ocean.

Donahue and Russell ([1997](#)) estimates that the liquid water uniformly distributed on the early planet would have reached a height from 4 to 525 m.

Then, Venus experienced in its history a runaway of the greenhouse effect causing the vaporization of its primitive oceans (Hashimoto et al. [2008](#)). Despite their total evaporation, the oceans may have persisted for several billion years (Grinspoon and Bullock [2003](#)), leaving the possibility of an environment that is sufficiently merciful long enough for the development of life.

Habitable Area in the Clouds

The atmospheric conditions have sterilized Venus' surface. Any biosphere that may have

developed in the early history of the planet has therefore been destroyed. However, the idea of migrating microorganisms to a more habitable area could be possible. Life on Venus may continue today in the upper atmosphere where the temperature and pH are tolerable for known terrestrial extremophilic organisms. It is therefore an aerial habitable zone. The high atmosphere combined with the high acidity allowed to define a cloud habitability zone located between an altitude of 51 km (65 °C) and 62 km (−20 °C) altitude. On the other hand, if this narrow field is sterilized, there is no life reservoir at the surface to recolonize this habitable aerial area.

Using samples taken at 3106 m of altitude, Sattler et al. (2001) show that bacteria on Earth grow, reproduce and produce proteins at high altitudes in the atmosphere. According to the authors, the only limiting factor of life in the terrestrial clouds is the residence time. Unlike terrestrial clouds, Venusian clouds are stable and represent a global and continuous environment where aerosols are in suspension for several months instead of a few days compared to Earth. This stability allows a residence time of microbes much longer than on our planet which is ideal for microorganisms (Schulze-Makuch et al. 2013). As Schulze-Makuch points out in his article of 2004, the conditions are therefore more favorable to life in the clouds of Venus than in terrestrial ones.

In addition, super-rotation of clouds improves the potential of photosynthetic reactions by reducing the time of darkness. Moreover, even if the habitable zone is in the clouds, the solar flux does not seem to constitute an obstacle to life.

Solar Flux and Cosmic Flux

Ultraviolet rays are harmful to biological macromolecules. The maximum absorption in clouds is at 285 nm (near UV) which damages microorganisms but does not constitute an insurmountable obstacle to life as shown in the work of Dartnell et al. (2015). Some microbes such as cyanobacteria and *Deinococcus radiodurans* use mechanisms to repair their DNA and UV-sensitive proteins (Ehling-Schulz and Scherer 1999). Another example of adaptation to large UV rays

known on Earth is the *Fusarium alkanophylum* fungus.

Schulze-Makuch's et al. (2004) hypothesis is that a layer of liquid sulfuric acid which engulfs a nucleus of S₈ absorbs a significant portion of UV radiation encountered by microorganisms thus allowing it to survive. The use of S₈ against UV radiation as a protective layer by microorganisms would explain why absorption by hydrocarbons is not observed (Plummer 1969).

The cosmic radiations create a field of ionic radiation which is harmful for organic molecules. At 62 km of altitude, Venus receives 0.200 kg/cm² which is far less than what the Earth receives on its surface (1.033 kg/cm²; Schulze-Makuch et al. 2004). However, the Venusian biosphere could be exposed to more ionized cosmic radiation because this planet has no magnetic field and its orbit is closer to the Sun. In addition, the consequences of ion flux in clouds are still under study (Dartnell et al. 2015).

Terrestrial Extremophiles

Clouds are a real niche for microorganisms and not a simple way of transport between surfaces (Womack et al. 2010). In the terrestrial stratosphere, samples taken by space balloons have shown the presence of bacteria at these altitudes (Wainwright et al. 2003). The discovery of this biosphere has been confirmed by high-altitude aircraft flights (Smith et al. 2010).

In order for microorganisms to live, it is necessary to have available energy sources. Dartnell et al. (2015) lists the following ones: photosynthesis, possible absorption in the UV using the oxidation of hydrogen sulfide or the chemotrophic reduction of sulfate. Indeed, Schulze-Makuch et al. (2013) define a Venusian ecosystem that conjugates sulfur-oxidizing photoautotrophic organisms and sulfur-reducing chemotrophs.

In general, terrestrial extremophilic microorganisms live between 120 °C and −20 °C (Cavicchioli 2002). Acidophilic hyperthermophilic organisms have been found in warm acidic waters, such as *Acidianus infernus* (Segerer et al. 1986). These microorganisms have an optimal growth temperature of 88 °C and can live in an environment where pH is close to 0.5.

Although terrestrial analog sites do not offer a temperature and acidity comparable to that of Venus, there are terrestrial thermoacidophilic extremophiles known to tolerate both high temperatures and low pH named *archaea*. In this family of microorganisms, the most extreme organisms known to date are *Picrophilus* genus. These archaea grow at pH null or below zero for temperatures not exceeding 65 °C (Thürmer et al. 2011).

Despite all these terrestrial analogies, there is still no evidence to this day of extremophile terrestrial life for a pH~2 around 45 °C.

Earth-Like Life or New Life Forms Specific to Venus?

Based on the current understanding of Earth life and Venus environmental conditions, a life cycle of the Venusian aerial biosphere inside cloud droplets is proposed by Seager et al. (2020).

The acidity of the Venusian atmosphere increased during the first 600 million years after the formation of Venus (Kumar et al. 1983). Life forms may very well have evolved differently to gradually adapt to the acidic conditions of this planet.

To clarify the potential life existence in a rocky planet's atmosphere, the detection of phosphine (PH₃) was defined as a biosignature in exoplanet atmospheres (Sousa-Silva et al. 2020) as it can be produced on Earth by anthropogenic activity or microbial presence. The presence of this gas on Venus was reported by Greaves et al. (2021) and then some inconsistencies were raised by the study of Lincowski et al. (2021) that conclude that SO₂ is a more plausible explanation of the detected gas.

The unambiguous proof of the existence of life on Venus can only be established by a mission with return of samples taken from the cloud layer of Venus (Schulze-Makuch and Irwin 2002).

Cross-References

- ▶ [Biomarkers Atmospheric, Evolution over Geological Time](#)
- ▶ [Climates, Terrestrial Planets](#)
- ▶ [Habitability of the Solar System](#)

- ▶ [Habitability, Role of the Atmosphere](#)
- ▶ [Habitable Zone](#)
- ▶ [Venus](#)
- ▶ [Venus Clouds](#)

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Venus Express

Dmitrij Titov, Håkan Svedhem and Colin Wilson
European Space Agency (ESA), European Space
Research and Technology Centre (ESTEC),
Noordwijk, The Netherlands

Keywords

Venus · Orbiter · Atmosphere · Plasma
environment

Synonyms

ASPERA-4; EADS; ESA; MAG; PFS; SPICAV;
VeGa; VeRa; VEX; VIRTIS; VMC

Definition

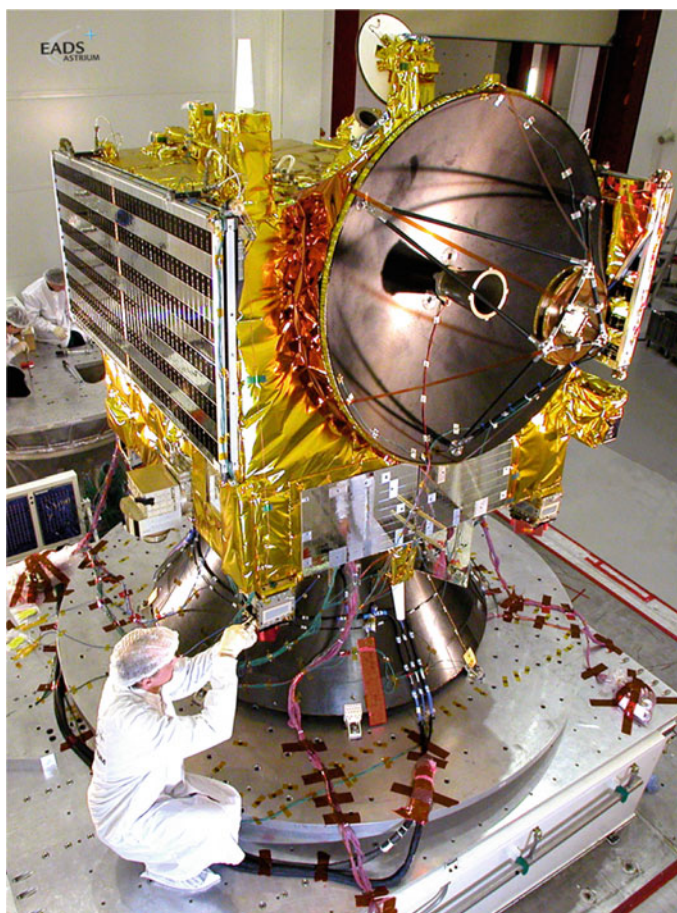
Venus Express was the first ESA mission to Venus, operational from 2005 to 2014. It performed a global investigation of the atmosphere and the plasma environment of the planet, and addressed several important aspects of geology and surface physics.

History

The first phase of Venus spacecraft exploration (1962–1985) by the Soviet Venera and Venera-Halley (VeGa) and American Pioneer Venus missions established a basic description of the physical and chemical conditions prevailing in the atmosphere and at the surface of the planet. At the same time, they raised many questions on the physical processes sustaining these conditions. Extensive radar mapping by the Pioneer Venus Venera-15, -16 and Magellan orbiters, combined with earlier glimpses from landers, have expanded considerably our knowledge of Venus' geology and geophysics. By the end of 1990s a similar systematic survey of the atmosphere with particular emphasis on its lower part below the clouds was due. In March 2001 ESA issued a *Call for ideas* from the scientific community on a reuse of the spacecraft platform developed for the Mars Express mission, equipped by “off-the-shelf” instruments. In 2002 Venus Express was selected as the winning proposal. The MEX spacecraft design was adapted to the Venus environment and then built by the industrial team led by EADS Astrium, now Airbus Defence and Space. The science payload was mainly inherited from Mars Express and Rosetta missions complemented by instruments specifically designed and built for Venus Express. Due to reuse of the platform elements and payload the

Venus Express,

Fig. 1 Preparation of the Venus Express spacecraft for vibration tests in summer 2005 at Intespace facilities in Toulouse, France. (Credit: EADS Astrium)



spacecraft was built in only 33 months – a remarkably short period of time for such a complex mission (Fig. 1).

Basic Methodology

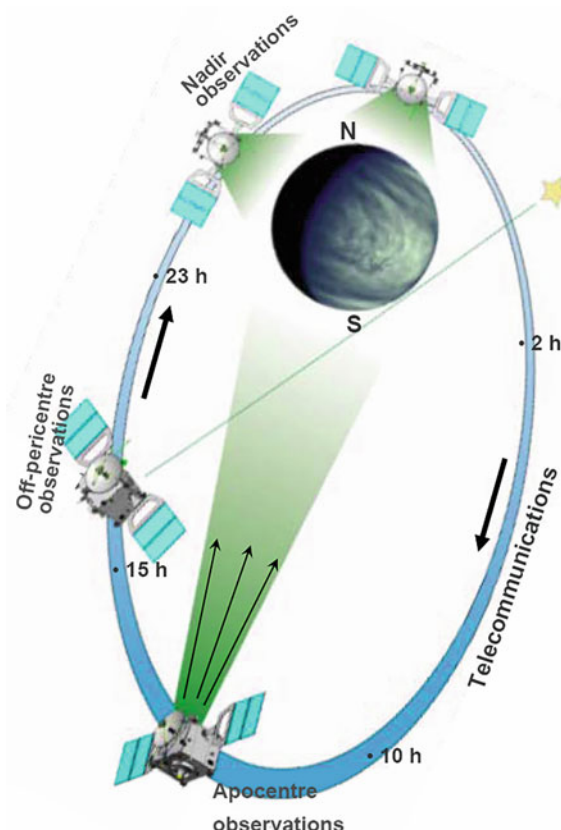
Science objectives. The mission overarching theme was to perform a global investigation of the atmosphere and plasma environment of the planet and to address several important aspects of the geology and surface physics. It was broken down into several top-level science objectives: (1) vertical structure of the mesosphere and upper troposphere; (2) general circulation and dynamics; (3) morphology and structure of the clouds and hazes; (4) composition and chemistry of the mesosphere and upper troposphere; (5) radiative energy balance; (6) aeronomy, plasma

environment, and escape processes; and (7) limited studies of geology and surface properties.

Orbit and scenario. Venus Express was launched on 9 November 2005 by a Russian Soyuz-Fregat launcher from the Baikonur cosmodrome in Kazakhstan. After the orbit insertion on 11 April 2006 the spacecraft successfully operated until 17 December 2014 making it the longest duration mission at Venus so far. The highly elliptical ($250 \times 66,000$ km) near-polar 24-h orbit was specifically chosen to combine global monitoring with close-up views of the planet. The orbit enabled the instruments to observe almost the entire planet over a full Venusian day (243 Earth days). Venus Express became the first ESA spacecraft to perform aerobraking reducing the orbital period from 24 h to just under 22 h 30 m. Venus Express performed innovative investigation of atmospheric densities in the polar

Venus Express,

Fig. 2 Sketch of the Venus Express orbit. Figures along the orbit show the time since pericenter passage (orbital time). (From Titov et al. 2008)



regions by measuring accelerations and torques exerted on the spacecraft at altitudes from 130 to 200 km during pericenter passes. This resulted in a large dataset over an extended period and has enabled sounding of the atmospheric structure in an altitude range not probed by conventional remote sensing (Fig. 2).

Spacecraft. The Venus Express spacecraft design was based on the successful Mars Express bus – a 600 kg three-axis stabilized platform $1.7 \times 1.7 \times 1.5$ m in size with two body-fixed telecommunication antennas. The spacecraft carried about 600 kg of fuel used for maneuvers, orbit insertion, and keeping. The spacecraft subsystems and payloads were mounted on its walls and on the panels inside the bus. The apertures of the optical instruments were located on +Z face pointing to the planet during observations (Fig. 3).

Payload. The scientific payload of Venus Express, summarized in the table below (Table 1), comprised seven instruments. Four of

these were reused “as is” or slightly modified versions from Mars Express, and three of them were adapted from ESA’s Rosetta mission. The PFS instrument was not operational due to a failure of the pointing mechanism.

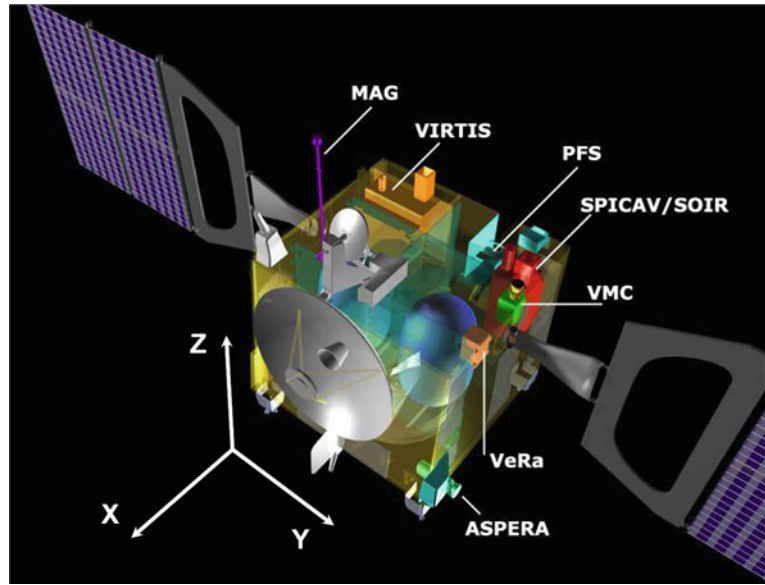
Key Research Findings

Venus Express provided observations of the atmosphere and plasma environment from 2006 to 2014 making breakthroughs in many science topics.

Atmospheric vertical structure. The vertical structure of the lower thermosphere through the upper troposphere (160–40 km) was studied by a combination of radio and solar occultation, thermal emission spectroscopy, and drag experiment (Limaye et al. 2018a). The mesospheric thermal field is characterized by a general temperature decrease with altitude and presence of a “cold

Venus Express,

Fig. 3 Semitransparent view of the Venus Express spacecraft with science instruments shown. (From Svedhem et al. 2007)



Venus Express, Table 1 Science payload of Venus Express

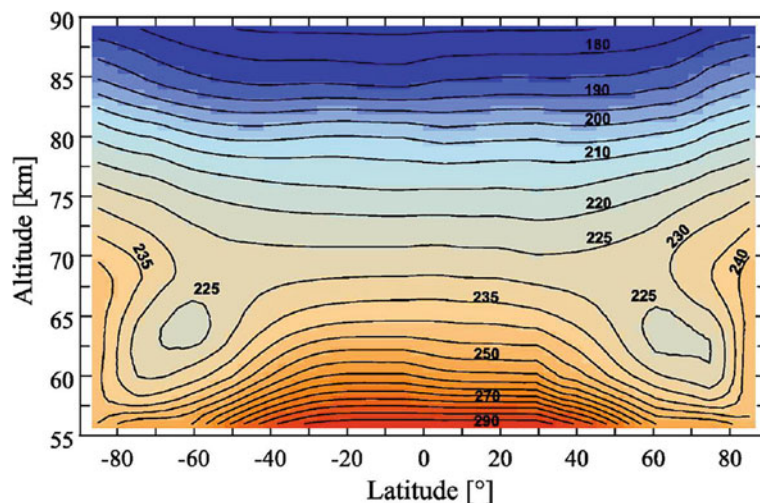
Instrument	Objective	Principal investigator
Analyzer of Space Plasma and Energetic Atoms (ASPERA-4)	Neutral and ionized plasma analysis	S. Barabash (IRF, Kiruna, Sweden)
Magnetometer (MAG)	Magnetic field measurements	T. Zhang (OAW, Graz, Austria)
Planetary Fourier Spectrometer (PFS)	Atmospheric vertical structure and composition	V. Formisano (IFSI CNR, Frascati, Italy)
Spectrometer for investigation of the characteristics of the atmosphere of Venus (SPICAV)	Atmospheric composition and structure by nadir, star, and solar occultation spectroscopy	J.-L. Bertaux (SA/CNRS, Verrières-le-Buisson, France)
Venus Radio science investigation (VeRa)	Vertical structure of the neutral atmosphere and ionosphere by radio-occultations	B. Häusler (Universität der Bundeswehr, München, Germany) & M. Pätzold (RIUUK, Cologne, Germany)
Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)	Dynamics and composition of the atmosphere, cloud morphology, and surface mineralogy by imaging spectroscopy	P. Drossart (CNRS/LESIA & Observatoire de Paris, France and G. Piccioni (IASF-CNR, Roma Italy)
Venus Monitoring Camera (VMC)	Atmospheric dynamics, cloud morphology, and surface properties by narrow-band imaging	W. Markiewicz (MPAe, Katlenburg-Lindau, Germany)

collar” – an annulus of cold air surrounding the planet at 50–75° latitude and about 65 km altitude in both hemispheres previously discovered by Pioneer Venus and Venera-15, -16 (Fig. 4). This region is characterized by strong temperature inversions at the cloud top. The temperature field showed significant local time variability.

Venus Express performed unique measurements of atmospheric density and temperature in the lower thermosphere (160–100 km) discovering a very cold layer at ~125 km and a strong variability at these altitudes. More than 800 radio occultations revealed fine details of the atmospheric structure at 40–90 km at few 100 m

Venus Express,

Fig. 4 Average temperature latitude–altitude cross-section of the Venus mesosphere derived from VIRTIS-M dataset. (From Limaye et al. 2018a)



vertical resolution indicating, in particular, that the region below the cloud base is convectively unstable in polar regions (Ando et al. 2020).

Morphology and structure of the clouds and hazes. Venus Express made significant progress in our understanding of the clouds and hazes by exploiting imaging instruments covering a spectral range from UV through thermal IR, spectroscopy in solar and stellar occultation geometry enhanced by the long duration of the mission and its highly elliptical polar orbit (Titov et al. 2018). The upper haze extending from the cloud top (70 km) to ~90 km is rather uniform over the planet and has scale height $H_a = 2.8 \pm 1.2$ km at $20\text{--}80^\circ\text{N}$ with a trend to increase to 4.4 ± 1.0 km at the pole. The aerosol population consists of sulfuric acid particles of up to $1\text{ }\mu\text{m}$ in radius. Below 75 km the scale height increases to 4–5 km at low and middle latitudes, while in polar regions the cloud top is very sharp ($H_a < 1$ km). Spectroscopic observations by VIRTIS and SPICAV found the cloud top at ~72 km in low-to-middle latitudes descending to ~64 km at the poles (Fig. 5).

Venus Express was the first orbiter exploiting near-infrared spectral transparency “windows” on the nightside that provided indirect constraints on the properties of the deep cloud. The cloud base in high latitudes was found to extend down to ~45 km (Oschlisniok et al. 2021), much lower than in the low and middle latitudes, with much greater total opacity at high latitudes.

Morphology of the upper clouds is the most prominent at UV wavelengths (Fig. 6). The observed contrasts reach ~30% due to nonuniform distribution of an unknown absorber in the upper cloud. The low latitudes are on average much darker than polar regions. Total opacity variations mainly formed in the deep cloud (~50 km) produce the features seen in the near-IR images on the nightside. Global cloud pattern at all altitudes indicates vortex-type circulation with air masses spiralling from equator to poles.

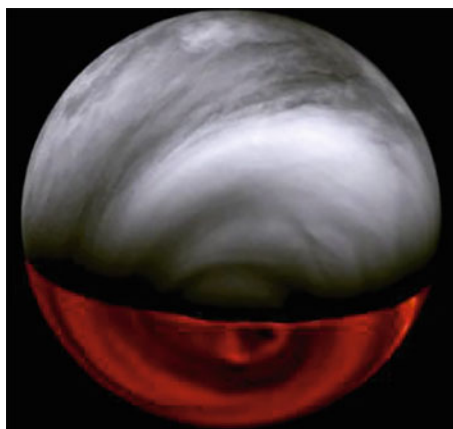
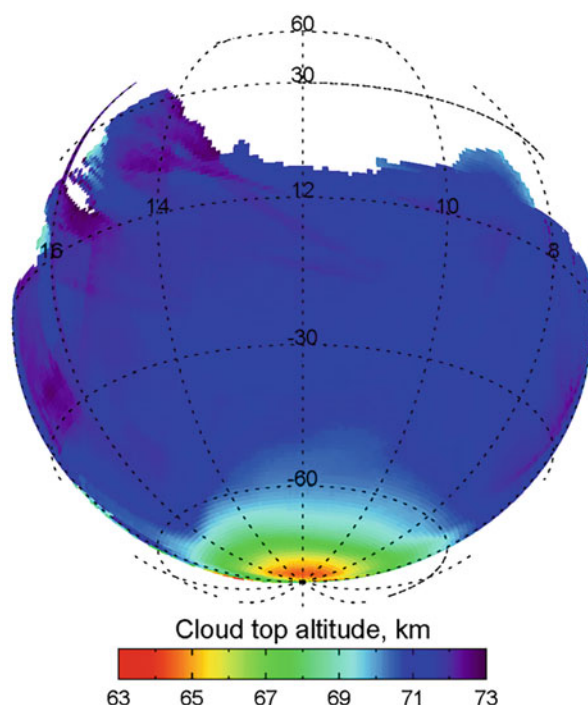
Figure 7 shows the structure and main properties of the Venus cloud and haze system.

Atmospheric circulation and dynamics. Several cameras on board Venus Express continuously imaged the planet in different spectral ranges on both day and nightside that allowed monitoring of the cloud motions at different altitudes thus providing “tomography” of the atmospheric circulation (Sánchez-Lavega et al. 2017).

The mesosphere and troposphere (0–100 km) are dominated by fast zonal retrograde (westward) motions called super-rotation (Fig. 8). In the low-to-middle latitudes ($0^\circ\text{--}55^\circ$) the zonal winds are weakly dependent on latitude but significantly change with altitude indicating a vertical wind shear of 2–3 m/s/km. Poleward of $\sim 60^\circ$ the zonal wind subsides. The apparent convergence of the wind profiles in Fig. 8 (upper panel) suggests either absence of a vertical wind shear or, more likely, a much denser aerosol media (Titov et al. 2018) that results in sounding of almost the same

Venus Express,

Fig. 5 Mean cloud top altitude in the Southern Hemisphere. (From Titov et al. 2018)



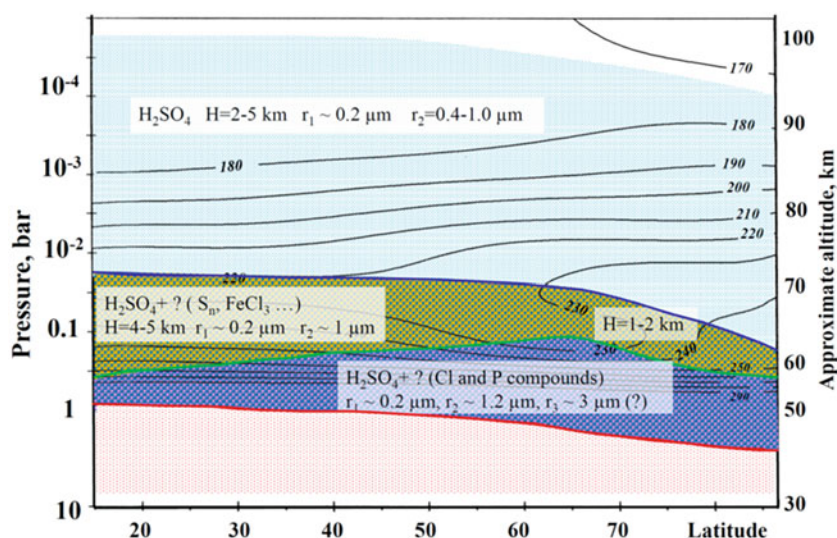
Venus Express, Fig. 6 Venus false color view consisting of VMC UV (365 nm) (grey) and VIRTIS near-IR (1.7 μ m) (red-black) images simultaneously taken on the day and nightsides. (From Titov et al. 2018)

altitude levels at all wavelength from UV through near-IR. The meridional winds (Fig. 8, lower panel) show a poleward velocity of 5–10 m/s at the cloud tops and a return flow in the deep cloud, thus indicating a Hadley cell encompassing the cloud layer at least in the low-to-middle latitudes.

Venus Express elliptical polar orbit with its apocentre above the Southern pole (Fig. 2) was very well suited for characterization of the polar dynamics that was not explored by the previous missions. The latitudes above 60° feature a polar vortex – a highly dynamic whirl-pool-like structure centered within few degrees from the pole and rotating with the period of 2–2.5 days shorter than the super-rotation of the atmosphere at low-to-middle latitudes. The vortex region is characterized by a very low cloud top (~62 km) and relatively high temperatures (Fig. 9).

Long-term monitoring of the atmospheric motions by Venus Express revealed variabilities in the circulation pattern at different temporal and spatial scales. They include thermally driven acceleration of the zonal winds by 5–15 m/s at the cloud top at low latitudes in the afternoon, signs of a planetary 4-day Kelvin and 5-day Rossby waves, and annual acceleration of the zonal circulation likely related to large-scale surface topography.

Venus provides a unique example of a slowly rotating planet that makes Coriolis force and its impact on atmospheric dynamics negligibly



Venus Express, Fig. 7 Sketch of the Venus clouds latitude-altitude structure: upper haze (light blue), upper cloud (yellow “droplets”), middle and lower clouds (blue “droplets”), and lower haze (red “droplets”). Black contours show isolines of the Venera-15 temperature field.

Blue, green, and red solid lines mark the cloud top ($\tau = 1$ level), the tropopause, and the cloud base, respectively. Composition and mean microphysical parameters of the cloud layers are shown in semitransparent inserts. (From Titov et al. 2018)

small. The general circulation of the Venus atmosphere, and in particular zonal super-rotation, is controlled by so-called cyclostrophic balance – approximate equality between centrifugal and pressure gradient forces. Thus, the zonal wind field is strongly correlated with pressure and temperature.

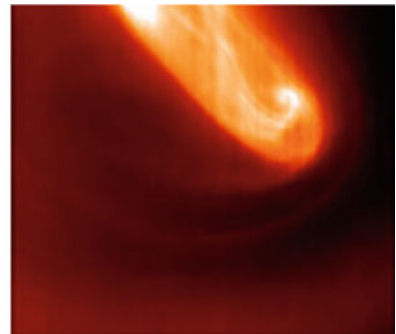
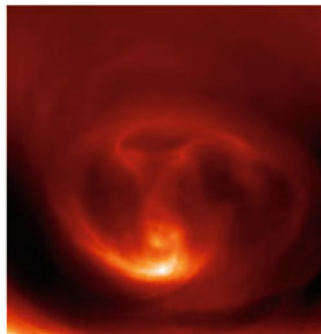
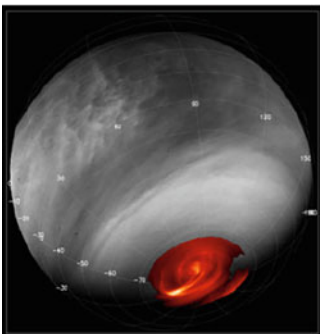
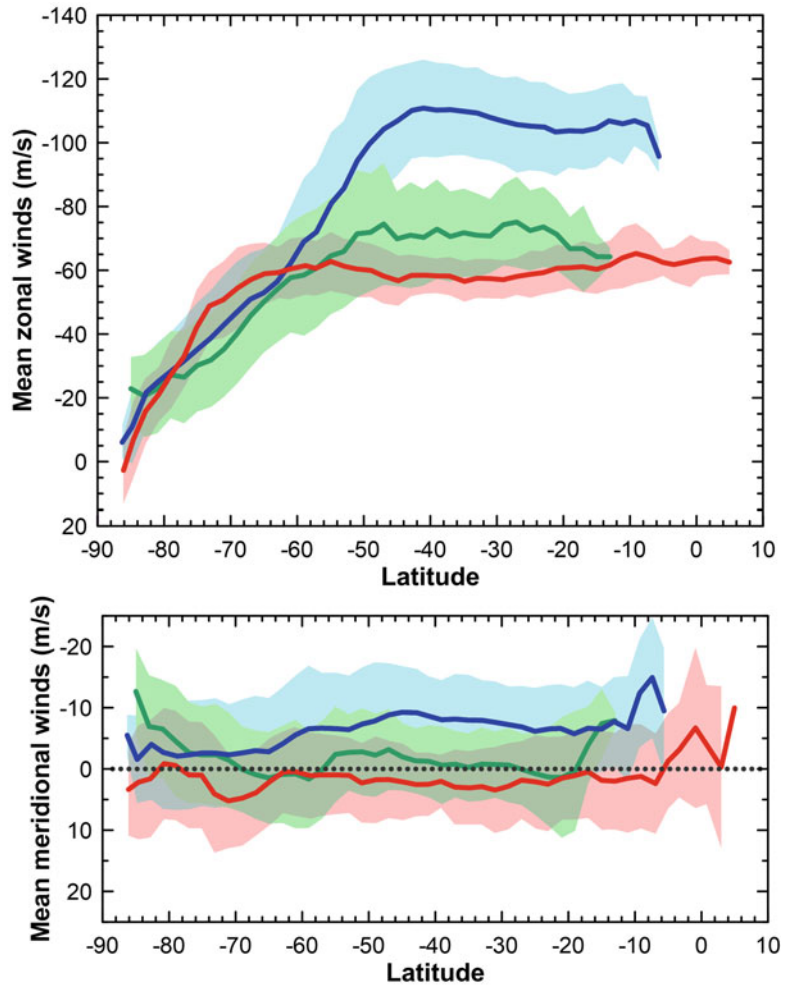
Composition and chemistry. Venus Express delivered pioneering results on the composition of the mesosphere and troposphere due to extensive exploitation of high-resolution spectroscopy in solar occultations and use of the novel technique of sounding the atmosphere below the clouds in spectral transparency “windows” on the nightside (Marcq et al. 2018; Chamberlain et al. 2020).

Figure 10 shows the summary of the Venus Express composition measurements. They revealed strong decrease by one to two orders of magnitude of the sulfur dioxide (SO_2) and water vapor (H_2O) abundance through the clouds resulting from the photochemical formation of sulfuric acid at the cloud tops. Furthermore, the abundance of SO_2 above the clouds was found to vary over two to three orders of magnitude. The mean abundance exhibited a fourfold rise during

the first year of Venus Express observations, and a tenfold decrease during subsequent years, a pattern which could be due to active volcanism or to intrinsic dynamics. Carbon monoxide (CO) shows the opposite trend of increasing mixing ratio with altitude due to photochemical production of this molecule above the clouds. Gaseous sulfuric acid (H_2SO_4) was sounded in the radio-occultation experiment at the cloud bottom where cloud droplets evaporate. Venus Express provided measurements of halides (HCl and HF) in the mesosphere that play an important role in chemical processes. Simultaneous measurements of H_2O and its heavy isotope HDO showed an even larger D/H ratio in the mesosphere than that measured before in the lower atmosphere: 240 ± 25 relative to the ratio on Earth. Strong enhancement of the Venus atmosphere with heavy isotope suggests presence of much larger amount of water on the planet in the past. The composition measurements indicated strong spatial and temporal variations of minor species pointing to various chemical and dynamical processes that will be understood in extensive simulations of the Venus atmospheric chemistry.

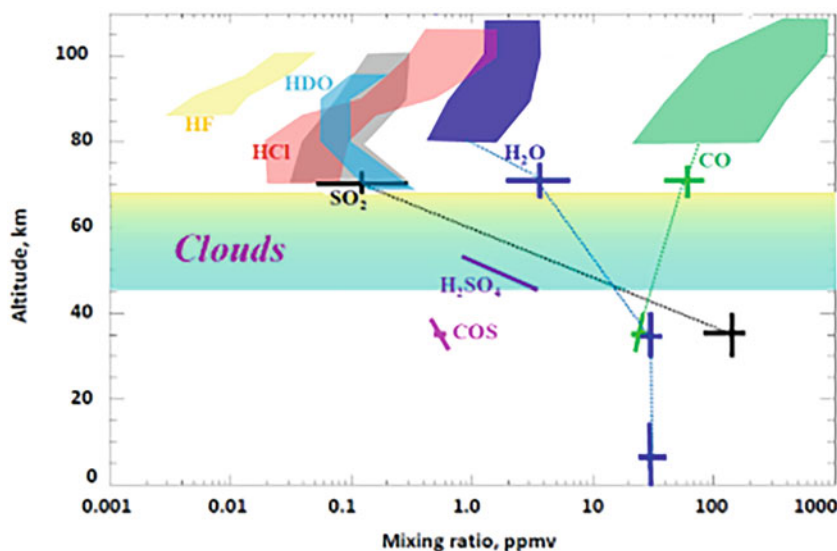
Venus Express,

Fig. 8 Global mean zonal (upper panel) and meridional (lower panel) winds measured in UV (blue), visible (green), and 1.74 μm (red) that correspond approximately to 70, 62, and 55 km at least in the low-to-middle latitudes. (From Sánchez-Lavega et al. 2017). The negative (positive) meridional winds correspond to poleward (equatorward) motions. The shaded areas show variability of the wind profiles. (Credit: R. Hueso, private communication)



Venus Express, Fig. 9 Morphology of the “eye” of the polar vortex: left – sketch of the vortex “eye” (red) over-plotted on top of a VMC/VEX UV image (grey), middle and right – original images of the polar “eye” taken by

VIRTIS/VEX at 5 μm . The color approximately represents the cloud top temperature with about 50 K difference between dark and bright areas. (From Titov et al. 2018)



Venus Express, Fig. 10 Summary of the Venus Express composition measurements. Colors mark different trace gases. The shaded areas above the cloud show results of the solar occultation measurements and include all kinds of

variabilities. Solid bars show nadir soundings. Dotted lines are linear extrapolations between different types of measurements

Aeronomy and ionosphere. Venus Express collected a wealth of data about the thermosphere and ionosphere of the planet. The mission mapped the nonthermal emissions (airglow, nightglow, and fluorescence) from the upper atmosphere with high spectral resolution from UV through middle-IR range that allowed characterization of the atmospheric structure and dynamics at 150–90 km, the altitude range poorly sampled before. Mapping of the O_2 nightglow at $1.27\ \mu\text{m}$ revealed its vertical structure peaking at ~ 100 km and spatial distribution (Fig. 11). The latter implies that the at this altitude the thermospheric circulation that supplies oxygen ions from the day side is almost entirely subsolar-antisolar. However, similar observations of NO emission that peaks at ~ 115 km show the shift of the emission peak by several hours local time likely suggesting significant super-rotation component of the circulation. Venus Express observations in Lyman- α confirmed that the planet's hydrogen corona is dominated by the nonthermal population at high altitudes.

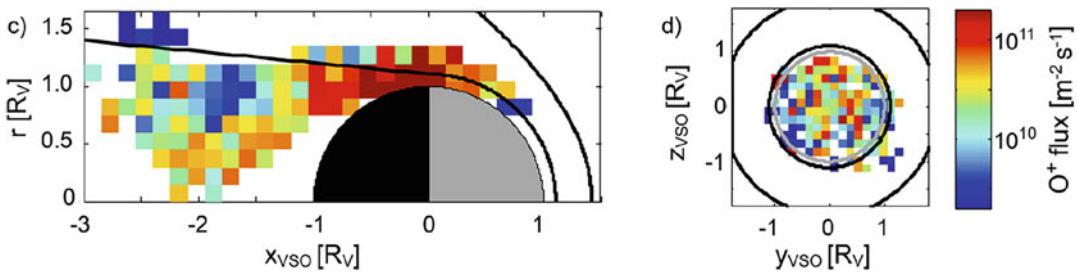
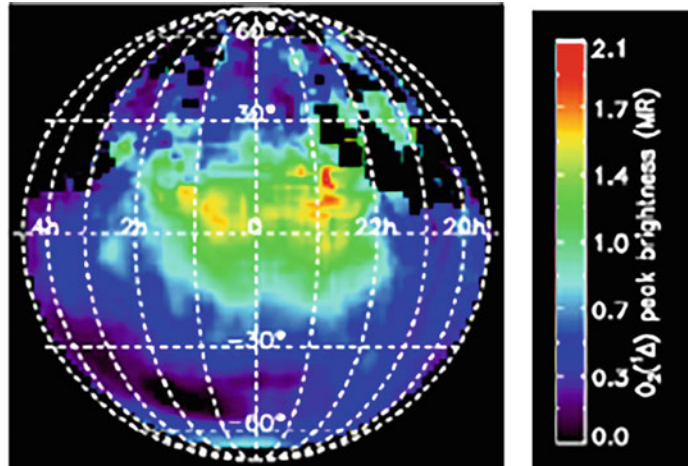
More than 800 radio-occultations by Venus Express allowed detailed characterization of the ionosphere and its variability with solar activity, local solar time, and latitude.

Plasma environment and escape. Venus Express was equipped with an ion and neutral particle spectrometer ASPERA-4 to characterize the plasma population in situ and a magnetometer MAG to measure the magnetic field (Futaana et al. 2017). The mission carried out unique investigations of plasma environment in the polar and terminator regions down to altitudes of ~ 250 km through a long and deep solar minimum, and probed the magnetic field to ~ 130 km as it made its final entry. For the first time it probed the plasma tail, the region hosting dynamic processes that lead to plasma energization and escape of ions to space. Venus Express studied topology of the plasma boundaries and response of the magnetospheric system to the solar wind conditions on different time scales. The first-ever energetic neutral atom measurements revealed the neutral exosphere and solar wind plasma interaction near Venus. A plethora of waves was identified by the magnetometer: proton cyclotron waves upstream of the bow shock, mirror mode waves in magnetosheath, and whistler mode waves, possibly generated by lightning discharges.

Venus Express found that planetary ion escape with energy of ~ 10 eV to ~ 10 s of keV occurs in

Venus Express,

Fig. 11 Map of the O₂ nightglow intensity. Antisolar point (midnight at equator) is in the middle of the planet disc. (From Gérard et al. 2017)



Venus Express, Fig. 12 Spatial distribution of the heavy ion flux. (From Futaana et al. 2017)

the solar wind wake and adjacent magnetosheath (Fig. 12). Ion mass separation capability allowed the ASPERA-4 particle instrument to determine that H⁺ and O⁺ ions escape in stoichiometric ratio of the water molecule, implying that water is still lost by the Venus atmosphere at a rate of (3–6) 10²⁴ molecules/s in the solar minimum epoch. The flux is almost doubled during high solar activity events (e.g., coronal mass ejection). It is notable that the escape flux at Venus appears to be smaller than that from Earth, despite Venus' proximity to the Sun and its lack of a magnetic field; this finding challenges the common assumption that planetary magnetic fields provide a shielding effect reducing atmospheric loss. These results are of great importance for comparative planetology since Venus is a nonmagnetic Earth-size planet.

Surface and activity. Although Venus Express was not specifically designed for surface

investigations, some observations provided important evidences of surface mineralogy and recent geological activity (Gilmore et al. 2017). VIRTIS and VMC cameras were capable of mapping weak nightside emissions around 1 μm leaking from the hot surface though the thick atmosphere. Low surface emissivity on tesserae, different from that observed on basaltic plains, was found consistent with felsic rocks, showing similarities to Earth's continental crust. VIRTIS also discovered regions with relatively high surface emissivity spatially associated with coronae, volcanoes, and lava flows indicating low weathering and thus geologically young (0.25–2.5 MYears) units. Transient high thermal emission events were detected by the VMC camera in the Ganiki Chasma rift zone indicating surface-elevated temperatures consistent with fresh lava flows (Shalygin et al. 2015). These observations indicating geologically recent and

even ongoing geological activity paved a way for future investigations by ESA's EnVision and NASA's VERITAS and DAVINCI+ missions to Venus.

Habitability. The proximity and similarity of Venus to Earth make the planet a very attractive target in terms of astrobiological exploration. Limaye et al. (2021) has recently presented a case for the exploration of Venus as an astrobiology target using four lines of argumentation: (1) likelihood that liquid water existed on the surface in the past; (2) existence of the habitable zones within Venus' present-day clouds; (3) theoretical investigations into how active aerobiology may impact the radiative energy balance of Venus' clouds and Venus-like atmospheres; and (4) application of these investigative approaches toward better understanding the atmospheric dynamics and habitability of exoplanets.

Several results of Venus Express addressed the history of water on Venus. The SPICAV experiment found the D/H ratio above the clouds to be 240 ± 25 times higher than Earth's (Marcq et al. 2017) implying a significant loss of water to space over time. The discovery of low $1 \mu\text{m}$ emissivity in highland regions, as described above, indicates an iron-rich (felsic) composition of the highlands, interpreted as being potentially consistent with a water-rich past environment (Gilmore et al. 2019). Persson et al. (2020) used in situ ion measurements by ASPERA-4 to quantify the escape rates of oxygen ions at different conditions. Extrapolation of the current escape rates back in time led to the conclusion that the total amount of water loss was only 0.02–0.6 m of a global equivalent layer, suggesting that present-day ion escape alone cannot account for the loss of an historical Earth-like ocean.

As to present habitability, Venus Express significantly contributed to our understanding of the Venus clouds, where relatively benign environmental conditions are found. In the upper clouds, one of the long-standing mysteries is the identity of the UV absorber which is responsible for absorption of a large fraction of the solar energy absorbed by the planet (Titov et al. 2018; Limaye et al. 2018a). Limaye et al. (2018b) presented an interesting hypothesis suggesting that cloud-

based microbial life could be contributors to the spectral signatures of Venus' clouds, building upon previous suggestions of the possibility of life in the clouds of Venus relying on the origin of life on Venus occurring when it presumably had liquid water oceans (Schulze-Makuch and Irwin 2002). Venus Express conducted detailed mapping of the spatial distribution of the UV absorption, and measured variations in the refractive index of the cloud top, by measuring the phase function which describes how it reflects light. This showed greater variability than could be explained by sulfuric acid clouds alone, leading investigators to suggest minority cloud constituents including FeCl_3 and elemental sulfur (Titov et al. 2018). However, a detailed measurement of cloud composition is not possible from orbit and will require future measurement in situ.

Applications

In several respects Venus Express was a pioneering mission that for the first time applied novel observation techniques. The mission provided global monitoring of the composition of the lower atmosphere from orbit using spectroscopy of weak emissions leaking from the lower atmosphere on the nightside. It also exploited very-high-resolution spectroscopy in solar occultation geometry to scrutinize composition of the mesosphere above the clouds. Imaging in a broad spectral range as well as extensive use of the radio-occultation sounding significantly advanced our understanding of the atmospheric dynamics and cloud morphology. Surface mapping at thermal wavelengths led to the discovery of surface emissivity anomalies suggesting geologically young features and even evidence for active volcanism today. The 3D ion mass analyzer, high-energy resolution electron spectrometer, and energetic neutral atom imager supported by a magnetometer allowed for the first time to study plasma environment and escape at Venus. And finally, Venus Express was the first ESA spacecraft to perform aerobraking at Venus, thus paving a way to future missions (e.g., EnVision). Future missions to Venus will strongly benefit

from the novel observation and mission-enabling techniques validated and extensively used by Venus Express.

Future Directions

Despite many successful spacecraft missions to Venus many fundamental questions remain unanswered. We still do not understand Venus tectonics, mechanisms of heat release from the interiors, surface composition, formation of geological features, and whether the planet is still volcanically active. The mechanisms driving atmospheric super-rotation, composition, and chemical cycles that form the clouds and its interaction with the surface are still poorly understood. Important details of the processes in the upper atmosphere and especially those responsible for atmospheric escape are still missing. However, many of the investigations and results from Venus Express have informed and inspired plans for follow-up investigations. Many of the findings from Venus Express are now being investigated in more detail by JAXA's Akatsuki orbiter, in particular in the fields of atmospheric dynamics and cloud morphology (Nakamura et al. 2018). Venus Express surface and atmosphere observations will be further developed by missions recently selected for implementation in the next decade: ESA's EnVision and NASA's VERITAS orbiters, NASA's DAVINCI+ entry probe, and possible future landers and cloud-level balloons.

Cross-References

- Absorption Spectroscopy
- Abundances
- Atmosphere, Structure
- Atmospheric Circulation
- Atmospheric Processes, Escape
- Emissivity
- EnVision
- ESTEC
- European Space Agency
- Greenhouse Effect
- Imaging

- Mesosphere
- Planet Characterization: High-Resolution Spectroscopy
- Plasma
- Spectroscopy
- Venus
- Venus Clouds, Potential for Life
- Wavelength

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Venus Missions (History of)

Michel Viso
Innovaxiom, Paris, CX, France

History

To date, 46 missions or spacecraft have been launched toward Venus, 40 of them aim to fly by, orbit, impact, or land on Venus. Out of 29 missions launched by the Soviet Union between 1961 and 1989, 14 have been successful or almost successful. The second mission Venera1, launched on February 12, 1961, was the first spacecraft to fly by another planet. Seven missions have been launched by the United States: One failed, and the others have been successful. The operational success does not mean that each time the science reward was at the level of the expectancy. One of the 3 Japanese missions,

Akatsuki, failed its insertion in Venus orbit on December 6, 2010. The JAXA developed a recovery plan, and the probe was inserted in the orbit on December 7, 2015, and is still operational in 2022. Venus Express is the sole mission to Venus launched by ESA (November 9, 2005) and was operational during almost 9 years. In 1984, Vega 1 and Vega 2 have been launched 1 week apart in December 1984 to deliver landers while the spacecrafts continue to achieve flybys of the comet 1PHalley in 1986.

Six missions have been launched toward Venus to benefit of a gravity assist to accelerate toward the gaseous giant planets (Galileo to Jupiter and Cassini to Saturn), to be directed toward Mercury (Messenger and BepiColombo), or to change the inclination of the probe orbit around the sun (Parker Solar Probe and Solar Orbiter).

Six missions are under development in United states (3), India (1), Europe (1), and Russia (1) slated to be launched between 2023 and 2029.

Several scientists' plea to explore Venus as a target of interest for astrobiology (Limaye et al. 2021) considering that the planet could have had liquid water on the surface in its early history, allowing the possible development of a form of life. Some clouds of the planetary atmosphere could be considered, presently, as potentially habitable. Finally the investigations about the energy balance and the dynamic evolution of the planet atmosphere are of interest to prepare the study of potential Venus-like and telluric exoplanets.

Cross-References

- Venus
- Venus Clouds
- Venus Clouds, Potential for Life
- Venus Express

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VeRa

► [Venus Express](#)

Vernadsky

Stéphane Tirard

Faculté des Sciences et des Techniques de Nantes,
Centre François Viète d'Histoire des Sciences et
des Techniques EA 1161, Nantes, France

History

Vladimir Ivanovitch Vernadsky (1863–1945) was a Russian geochemist scientist born in Saint Petersburg, who introduces the new concept of biosphere. In 1926, he wrote an important book, entitled precisely *The Biosphere*, formulating new ideas related to Earth as a global dynamic system. The concept of biosphere describes the relationships between living beings and the physical chemical and energetic aspects of the environment.

Vernadsky's contributions were broadly transdisciplinary with geology, chemistry, biology, and physics (notably with thermodynamics). His work constituted an important step to the ecology history.

Vernal Point

Daniel Rouan

LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

The vernal point is one of the two equinoctial points on the celestial sphere. The ► [celestial equator](#) and the ► [ecliptic](#) plane intersect at those two points which are crossed by the Sun at each ► [equinox](#). The vernal point is the one

corresponding to the spring equinox. The vernal point is the origin of the ► [right ascension](#) coordinate in the equatorial system of coordinates used by astronomers.

Cross-References

- [Coordinate Systems](#)
- [Ecliptic](#)
- [Equinox](#)
- [Right Ascension](#)

Very Large Telescope

- [VLT](#)

Very Long Baseline Interferometry

- [VLBI](#)

Vesicle

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A vesicle in biology is a small organelle within a cell consisting of fluid enclosed by a membrane that can store or transport substances. When prepared artificially they are generally called liposomes. They can be formed from a wide variety of surfactants including simple fatty acids and

mixtures of fatty acids and fatty alcohols. In living organisms, most vesicles have specialized functions depending on what materials they contain. Vesicles are used in the cell to store, transport, or break down cellular products and waste. The membrane enclosing the vesicle is similar to that of the ► [cell membrane](#), and vesicles can fuse with the plasma membrane to release their contents outside of the cell, in a process known as exocytosis. Vesicles can also fuse with other organelles within the cell.

Cross-References

- [Cell Membrane](#)
- [Lipid Bilayer](#)
- [Membrane](#)

Vesta

Stefano Mottola
German Aerospace Center (DLR), Institute of
Planetary Research, Berlin, Germany

Keywords

Asteroids

Definition

► [Asteroid](#) (4) Vesta is the second most massive and third largest object in the ► [main asteroid belt](#). It has an orbit with moderate ► [eccentricity](#) (0.09°) and ► [inclination](#) (7°). The length of its semimajor axis is 2.36 AU and the orbital period is 3.62 years. It is one of the very few asteroids occasionally visible to the naked eye. The International Astronomical Union (IAU) is presently considering whether to include Vesta in the newly defined class of ► [dwarf planets](#). Dawn, the NASA Discovery mission, has been orbiting Vesta from July 2011 to September 2012, mapping its surface and gravitational field.

History

Vesta was discovered on March 29, 1807, by Heinrich Wilhelm Olbers from the German city of Bremen and named after the Roman goddess of the hearth. It was the fourth object discovered in the main belt – after (1) ► [Ceres](#), (2) Pallas, and (3) Juno – and is the brightest one. Therefore, Vesta was also long thought to be the largest asteroid, until in 1900 E.E. Barnard showed by directly measuring the size of the disk of the first four asteroids that the higher brightness of Vesta was due to its high ► [albedo](#).

Overview

The shape of Vesta is approximately that of an oblate spheroid with semiaxes of 285 and 229 km, respectively. It shows a complex and substantial topography, with a relief-to-size ratio of about 15%. Vesta's shape is dominated by a giant impact basin located at the south polar region, named Rheasilvia, with a central mound. The Rheasilvia event obliterated preexisting craters in the southern region, thereby producing a North-South dichotomy, with the two hemispheres showing differences in terms of crater density, colors, and albedo. A system of concentric equatorial troughs that encircle the entire body is also thought to be associated with the Rheasilvia and a similarly large preexisting basin – Veneneia. Already Earth-based spectral observations (McCord et al. 1970) had shown that Vesta has a basaltic surface, which implies that the body experienced igneous ► [differentiation](#). This is thought to imply the formation of a basaltic ► [crust](#), an olivine-rich ► [mantle](#), and a metallic core. This finding has been confirmed by the Dawn measurement of the J_2 gravitational moment, which is compatible with the presence of a metallic core of about 110 km in radius.

The surface of Vesta is highly variegated, with a broad range in albedo. Dark regions are generally, but not always, associated with impact craters and can have albedos as low as 10%. It has been suggested that these dark spots are of exogenic origin and represent the remnants of carbon-rich impactors. The brightest regions can have an

albedo as high as 67%, are in general associated with crater walls, and probably represent underlying brighter material exposed as a result of surface processes.

It is believed that a class of meteorites found on ► [Earth](#), the Howardite, Eucrite, and Diogenite, or HED ► [meteorites](#), originated from Vesta, possibly from the Rheasilvia region. With the discovery of a class of asteroid (Vestoids) sharing the same surface spectral properties as Vesta, and spanning the gap between Vesta's ► [orbit](#) and the 3:1 mean motion resonance with ► [Jupiter](#) that provides a viable route to Earth, this hypothesis has been widely accepted by scientists.

Vesta was among the first bodies that formed in the ► [Solar System](#). Radioisotope chronology from the HED meteorites suggests it accreted in only 5–15 million years. Vesta is therefore one of the few original objects in the main asteroid belt that has escaped collisional destruction.

Cross-References

- [Albedo](#)
- [Albedo Feature](#)
- [Asteroid](#)
- [Asteroid Belt, Main](#)
- [Ceres](#)
- [Core, Planetary](#)
- [Crater, Impact](#)
- [Crust](#)
- [Differentiation](#)
- [Dwarf Planet](#)
- [Eccentricity](#)
- [Inclination \(Astronomy\)](#)
- [Jupiter](#)
- [Mantle](#)
- [Meteorites](#)
- [Orbit](#)
- [System Solar Formation, Chronology of](#)

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VEX

- [Venus Express](#)

Viability

- [Survival](#)

Viking

François Forget
Institut Pierre Simon Laplace, Laboratoire de
Météorologie Dynamique, Université Paris 6,
Paris, France

Keywords

Mars · NASA

Definition

Viking is the name of two missions launched by ► [NASA](#) in 1975 to explore ► [Mars](#). Each mission consisted of an orbiter and a landing probe. The two missions were successfully inserted in orbit around Mars and the surface probes landed successfully.

History

Emboldened by the success of Mariner 9 in 1971, NASA set itself the goal of placing a module on

the surface of Mars. Engineers at the Jet Propulsion Laboratory (► [JPL](#)) were conscious that, although the Soviets had been successful with their missions to Venus, an apparently far more inhospitable planet, their Mars effort had seen far fewer rewards.

Overview

With this in mind, NASA's preparations for their Viking missions were exhaustive: two identical spacecraft, weighing 3527 kg each, were launched on August 20 and September 9, 1975. They consisted of a Mariner-type orbiter, coupled with a lander weighing more than 1 t. This would be one of the most complex and costly explorations ever undertaken by NASA. The precautions were worthwhile: the ten-month journey to Mars went without a hitch. Viking 1 entered Mars orbit on June 19, 1976. Its instruments (cameras, infrared radiometer, and water vapor detector) were deployed, searching for an ideal landing site: "not too high, not too windy, not too sloping, not too rocky, not too dusty, not too near the pole." It was almost impossible to find such a site from orbit, and NASA had to delay the landing (originally planned to coincide with the American Bicentennial on July 4; national pride was

eventually satisfied, however, in 1997, when Mars Pathfinder landed on that date). Viking 1 finally touched down in triumph on July 20 (the eve of Belgium's National Day!), on Chryse Planitia, at latitude 22 °N. It just missed, by a few meters, a large boulder that could have ended the mission there and then. Images of Mars as seen from its surface became front-page news, but the primary objective of the mission was the search for life. As the days went by, the scientists overseeing the Viking experiments pieced together their conclusions: officially, "no life," but unanimity was lacking. Like its sister ship, Viking 2 landed unhindered, this time on the other side of the planet on the plain of Utopia, at latitude 48°N. The results of its experiments were the same. Nevertheless, the Viking mission was counted a success: The expected working lifetime of the modules was 90 days, but they continued to render loyal service for more than 6 years. The last contact, with Viking 1, took place on November 13, 1982 (Figs. 1 and 2).

Basic Methodology

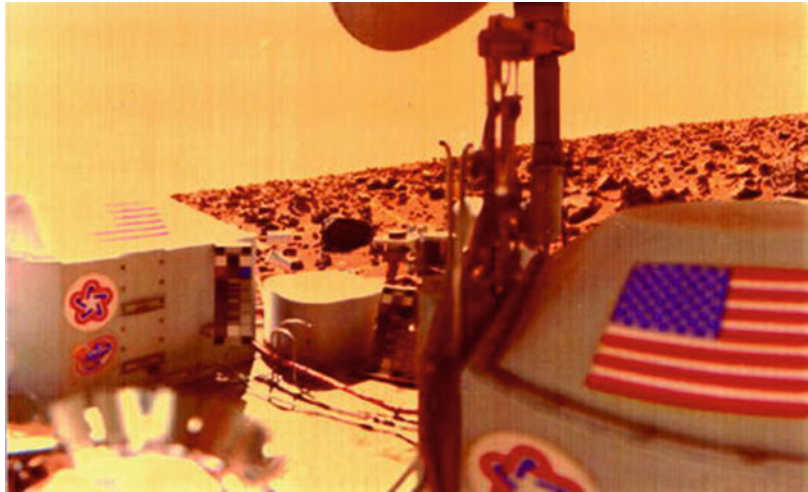
The Viking Landers

Before landing, the Viking landers passed through the Martian atmosphere at more than 4 km/s,

Viking, Fig. 1 Viking lander in its bio-shield ready to be heated up to 111.7 °C for 30 h



Viking, Fig. 2 Viking 2 lander color image looking south of spacecraft and Utopia Planitia



protected and decelerated by its heat shields. At 6000 m, a giant 18-m-wide parachute, suitable for Mars' thin atmosphere, was deployed. As happened earlier with the lunar modules, retro-thrusters slowed the lander during the last few hundred meters of its descent, autopiloted by the onboard radar. Before leaving Earth, the two probes had been carefully sterilized, so that Mars should not be contaminated, in accordance with the outer space treaty (OST). On the surface, a plutonium-based radioactive source provided energy for the module. A parabolic antenna was used for communications with Earth, either direct or relayed via the orbiters. As well as cameras and the necessary equipment for biological experiments, the Viking landers also had meteorological instruments, a mass spectrometer, and an X-ray fluorescence spectrometer for chemical analysis and a seismometer.

The Viking Orbiters

The orbiters monitored the surface and the atmosphere of ► [Mars](#) until July 25, 1978 (orbiter 2), and August 7, 1980 (orbiter 1). They were using color cameras (the highest resolution obtained was 7.5 m), the Mars Atmospheric Water Detectors (MAWD), and the Infrared Thermal Mappers (IRTM) which mapped the surface and the atmospheric temperature as well as the surface ► [Albedo](#) and thermal inertia.

Key Research Findings

The Viking Landers' Search for Life. The detection of life on the Martian surface was one of the main objectives of the Viking probes. An articulated arm, capable of digging into the surface, gathered samples of Martian soil. The samples were subjected to three investigations: the pyrolytic release, gas exchange, and labeled release experiments:

- The *pyrolytic release* experiment was designed to check if possible Martian organisms would assimilate carbon dioxide, as certain terrestrial organisms do (photosynthesis). No such activity was detected.
- The *gas exchange* experiment was designed to detect gas produced by microorganisms having digested organic matter. Quite a lot of oxygen was detected, but as it was still being produced after sterilization by heating the sample to 145 °C, it was concluded that the oxygen came from the chemical oxidization of the material. Rather than detecting life, the experiment showed that the surface of Mars is an oxidizing and sterilizing milieu, rather like some medical disinfectant.
- The *labeled release* experiment was designed to detect, by radioactive marking, the transformation of organic matter into carbon dioxide.

The result proved positive: There was indeed a transformation, which ceased as soon as the sample was heated – exactly what one might expect if bacteria were present.

- In case of the *GCMS*, however, the verdict was finally negative, because another instrument, *a gas chromatograph coupled with a mass spectrometer*, capable of detecting organic molecules at a concentration below one part per billion, found nothing, to the surprise of all concerned.

In the light of the other experiments, most of the experts, though not all, concluded that the labeled release experiment was evidence of the chemistry of inorganic processes in an oxidizing environment. The surface of Mars seems to have been completely purged of all natural organic matter by ultraviolet radiation and oxidization.

More recently, the Viking GCMS measurements have been re-analyzed in light of the Phoenix lander and Curiosity rover observations. Evidence for chlorobenzene have been found (Navarro-González et al. 2010; Guzman et al. 2018) like with Curiosity, and it has been suggested that the oxidation by Martian perchlorates during pyrolysis could explain why Viking did not detect more organic molecules.

Cross-References

- [Mars](#)

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Vinyl Cyanide (CH₂CHCN)

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Synonyms

[2-propenenitrile \(IUPAC name\)](#); [Acrylonitrile](#); [CH₂CHCN](#); [Cyanoethane](#)

Definition

Under standard conditions in the laboratory, vinyl cyanide is a colorless liquid that is highly flammable and toxic. It is commonly observed by radio astronomers in the “hot cores” of interstellar clouds, which are the sites of the formation of massive stars, and it has also been detected at lower abundance in cold interstellar clouds and in the envelopes of evolved, carbon-rich stars. Observations at millimeter wavelengths detect the pure rotational transitions in the ground vibrational state and in low-lying vibrational states; 13-carbon isotopic species have also been detected in molecular clouds (Müller et al. 2008).

History

Interstellar vinyl cyanide was first detected in the interstellar medium by Gardner and Winnewisser (1975). It has also been observed in the atmosphere of Saturn’s satellite Titan (Cordiner et al. 2018).

Cross-References

- [Hot Core](#)
- [Interstellar Medium](#)
- [Isotope](#)
- [Molecules in Space](#)
- [Titan](#)

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the modified host cell membrane. In most animal and plant virus families, non-enveloped or “naked” virions show either icosahedral or helical symmetry. In turn, enveloped virions as well as those that infect bacteria and archaea usually show complex shapes. Virions typically range in size from about 20 to 300 nm, although certain viral families that infect amoebas produce larger virions.

Cross-References

- [Virology](#)
- [Virus](#)

Viral Metagenome

- [Metavirome](#)

Viral Particle

- [Virion](#)

Virion

Carlos Briones
Consejo Superior de Investigaciones Científicas,
Centro de Astrobiología (CSIC/INTA), Madrid,
Spain

Synonyms

[Viral particle](#)

Definition

A virion is an entire virus particle. A virion can also be defined as the extracellular infective form of a virus. It consists of an RNA or DNA genome surrounded by a protein capsid and, in some virus families, an external lipid envelope derived from

Viroid

Ricardo Flores
Instituto de Biología Molecular y Celular de
Plantas (UPV-CSIC), Universidad Politécnica de
Valencia – Consejo Superior de Investigaciones
Científicas, Valencia, Spain

Keywords

Catalytic RNAs · Early replicons ·
Hammerhead ribozymes · High mutation rate ·
Small RNAs

Definition

Viroids are independently replicating circular RNAs of small size (246–401 nucleotides), with compact secondary structure, without protein-coding capacity, and capable of infecting and causing disease in plants. Viroids bear some resemblance with other two replicons: (1) viroid-like satellite RNAs, often called virusoids, which are structurally similar to viroids but dependent on coinfecting helper viruses for replication and transmission, and (2) human hepatitis delta virusRNA, which is also circular and highly structured, but with a size fourfold larger than that of

the largest viroid, coding for a protein in the antigenomic polarity and depending on hepatitis B virus for assembly and transmission.

Overview

Viroids are the minimal RNA replicons characterized so far – their [▶ genome](#) is tenfold smaller than that of the smallest known virus RNA – and, therefore, they can be regarded as the frontier of life (Diener 1972; Gross et al. 1978). Despite being only composed by a small nonprotein-coding RNA molecule, viroids contain sufficient information to infect some plants, to manipulate their gene expression for producing a viroid progeny, and to incite in most cases specific diseases (Diener 2003). In contrast to viruses, which can be essentially considered as parasites of the translation machinery of their host, viroids parasitize their host [▶ transcription](#) machinery.

The approximately 30 known viroid species are grouped into two families, *Pospiviroidae* and *Avsunviroidae*, the members of which replicate and accumulate in the nucleus and the chloroplast, respectively. As opposed to viruses, which encode in their genomes proteins that mediate their replication, movement, and suppression of host defense, viroids depend exclusively on host factors for these purposes. Viroids replicate through an RNA-based rolling circle mechanism with three steps that, with some variations, operate in both polarity strands (Branch and Robertson 1984): (1) synthesis of longer-than-unit strands catalyzed by a host RNA polymerase that reiteratively transcribes the incoming circular template; (2) processing to unit length, which remarkably is mediated by hammerhead ribozymes in the family *Avsunviroidae* (Hutchins et al. 1986; Flores et al. 2000); and (3) circularization resulting from the action of an RNA ligase or from self-ligation.

Certain viroid properties, including their size, circularity, structural periodicity, and lack of protein-coding capacity and, specially, the presence of hammerhead [▶ ribozymes](#) in the family *Avsunviroidae*, support the idea that they may have a very ancient evolutionary origin

independent of viruses. In line with this view, the mutation or error rate of a hammerhead viroid is the highest reported for any biological entity (Gago et al. 2009). Viroids, which therefore propagate in their hosts as populations of closely related sequence variants ([▶ quasispecies](#)), may tolerate such elevated mutation rates owing to their small genome size (Eigen and Schuster 1977). Given their genomic simplicity and catalytic activity, hammerhead viroids are reminiscent of the postulated [▶ RNA world](#) replicons (Gilbert 1986; Diener 1989), for which an extremely error-prone replication has also been assumed. The high-error rate of precellular replication may have promoted the emergence of polyploid genomes, with the mechanism of viroid replication (reiterative transcription of a circular template) providing an efficient channel for genome duplication. Additionally, evolution of complexity in the early history of life must have entailed emergence of replication fidelity mechanisms.

Cross-References

- [▶ Error Rate](#)
- [▶ Genetics](#)
- [▶ Genome](#)
- [▶ Quasispecies](#)
- [▶ Replication \(Genetics\)](#)
- [▶ Ribozyme](#)
- [▶ RNA](#)
- [▶ RNA World](#)
- [▶ Transcription](#)
- [▶ Virology](#)
- [▶ Virus](#)

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Virology

Carlos Briones

Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

Definition

Virology is the discipline of biology which studies viruses and subviral pathogens such as ► [viroids](#) and ► [prions](#). Different research areas are identified in current virology. Basic virology is interested in the structure of the viral particle and its constituents, as well as in the genetics, evolution, and taxonomy of viruses. Applied virology uses either whole viruses or parts of them – capsids, nucleic acids, or proteins of viral origin – for biotechnological or biomedical applications. Research in clinical virology includes the study of viral pathogenesis and epidemiology, as well as the development of antiviral drugs and vaccines. As a result, since the 1940s, many of the basic concepts and tools of ► [genetics](#) and molecular biology have been derived from the study of viruses and the viral replication cycle within the host cell.

Cross-References

- [Genetics](#)
- [Genome](#)
- [Prion](#)
- [Quasispecies](#)
- [Viroid](#)
- [Virus](#)

VIRTIS

- [Venus Express](#)

Virus

Kenneth Mark Stedman

Department of Biology, Center for Life in Extreme Environments, Portland State University, Portland, OR, USA

Keywords

Archaea · Bacteria · Eukarya · Genome · Life · Nucleic acid · Origins · Parasite · Virion

Synonyms

[Capsid encoding organism](#)

Definition

“Viruses are entities whose ► [genomes](#) are elements of ► [nucleic acid](#) that replicate inside living cells using the cellular synthetic machinery and causing the synthesis of specialized elements that can transfer the viral genome to other cells” (Luria et al. 1978). Viruses are infectious obligate intracellular parasites that can enclose their nucleic acid genome in a protein capsid and persist extracellularly. Viruses can be considered “bags” of nucleic acid.

Overview

Viruses have been termed the ultimate parasite. To replicate, viruses must release their genome composed of either DNA or RNA (either single or double stranded, or in rare cases both), inside a cellular host. This release process, or infection, occurs by disassembly of the extracellular virus particle, the virion. Once inside the cell, viruses require cellular ► [translation](#), in particular the ► [ribosome](#), for viral protein production. Some viruses can replicate their genome using exclusively viral proteins, but some require cellular proteins, often including DNA or RNA polymerases. After virus genomes and proteins are made, virions are assembled in a process unique to viruses. In the absence of a host cell, viruses do not undergo ► [metabolism](#), but when inside a host, they can drastically modify host metabolism. Viruses can infect archaeal, bacterial, or eukaryotic organisms. On Earth, viruses outnumber cellular organisms by orders of magnitude and are much more genomically complex. The origin and antiquity of viruses are unclear and hotly debated (Koonin et al. [2006](#)).

Key Research Findings

History of Virology

Before the discovery of ► [bacteria](#), all infectious diseases were known as “viral,” since the Latin for poison is *virus*. Only after the introduction of filters that did not allow the passage of bacteria in the late nineteenth century were viruses discovered to be separate infectious entities. Viruses infecting bacteria, also known as bacteriophages or phages, were discovered in the early twentieth century. Until recently, viruses were always associated with disease (Luria et al. [1978](#)).

Viruses Are Everywhere

Now practically all organisms are known to have viruses, many benign; some viruses even appear to have viruses of their own (Claverie [2006](#)). Massive numbers of viruses have been discovered in all ► [ecosystems](#), including oceans (Suttle [2005](#)), soils (Srinivasiah et al. [2008](#)), and extreme

environments (Prangishvili et al. [2006](#)). The number of viruses on Earth is calculated to be an astronomical 10^{31} , with genetic diversity swamping that of cellular ► [life](#). If all of the predicted oceanic viruses were lined up end to end, they would be 50 million light-years long. Viruses play a critical role in global nutrient cycles (Suttle [2005](#)) as well as in the ► [lateral gene transfer](#) between organisms. From 8% to 40% of the human genome is viral or virus derived (Lander et al. [2001](#); Venter et al. [2001](#)). Other sequenced genomes have similar virus content (e.g., Casjens [2003](#)).

Virus Classification Is Problematic

Animal and plant viruses are named by the diseases that they cause, for example, herpesviruses, *Tobacco mosaic virus*, etc. Viruses of Bacteria and ► [Archaea](#) have abstract or descriptive names such as T4, fuselloviruses, etc. Most named viruses infect animals, fewer infect plants, and even fewer infect microbes. However, the latter is by far the largest and most diverse group. Standard virus classification is based on genome (DNA or RNA, single stranded or double stranded), shape of the virion, and whether it has a lipid envelope or membrane (Fauquet et al. [2005](#)). However, there are a number of exceptions, whereby clearly related viruses are not grouped together. Thus, other methods have been proposed. One is based on shared structures, which indicate that viruses infecting Bacteria, Archaea, and ► [Eukarya](#) have a ► [common ancestor](#) (Krupovic and Bamford [2008](#)). Attempts have been made to classify viruses based on their genome sequences, but this has not been successful mostly due to a lack of conserved genes (Hendrix et al. [1999](#)). On the other hand, viruses are often defined as “small”. The *Mimivirus*, however, is visible in the light microscope and contains a genome larger than many Bacteria and Archaea. The *Mimivirus* genome lacks a ribosomal RNA gene but contains many otherwise “cellular” genes (Raoult et al. [2004](#)). Since the late 1960s, the International Committee on Taxonomy of Viruses (ICTV) develops and maintains a universal virus ► [taxonomy](#). A recent virus genome was found that appears to have arisen by

a fusion between RNA and DNA viruses, further confusing classification (Diemer and Stedman 2012).

Applications

Starting in the 1940s, researchers led by Max Delbrück and Salvador Luria used bacterial viruses to study fundamental aspects of biology. This approach was successful beyond all expectations. These studies led to the discovery of mRNA and the conclusive determination that DNA was the genetic material, that genes are linear, that the genetic code is triplet, etc. (Cairns et al. 1992). The study of animal viruses was critical for the discovery of DNA splicing, DNA replication, ► [transcription](#), etc. The study of the archaeal virus SSV1 showed that archaeal and eukaryal transcription mechanisms are closely related (Reiter et al. 1988). Most of the advances in molecular biology and biotechnology have been derived from research on viruses. As self-assembling nanoparticles, viruses are of great interest for nanotechnology (Mao et al. 2009). They are also promising gene therapy vectors.

Future Directions

Are Viruses Alive?

Researchers and students alike debate whether viruses are alive. The question is really semantic, since it depends on the definition of ► [life](#) or what it means to be alive. Viruses evolve, replicate, mutate, persist in many environments, and are large and critical parts of extant ecosystems (Suttle 2005). On the other hand, viruses are inert when not inside a host cell, they lack metabolism, and they can be crystallized and chemically synthesized (Wimmer et al. 2009). Viruses modify organism's metabolism, even though they have none as a virion. Striking examples are viruses of marine ► [cyanobacteria](#) that reprogram their host's energy-generating photosystem (Clokic and Mann 2006). Viruses may also have been involved in some major transitions in cellular life, such as the split of Bacteria, Archaea, and

Eukarya and the development of DNA as the genetic material from an ► [RNA world](#) (Forterre and Prangishvili 2009). Research on viral ► [quasispecies](#) has shown the great adaptive potential of current RNA viruses and has provided interesting clues on possible replicative strategies during the ► [RNA world](#) (Domingo 2007).

Where Do Viruses Fit in the "Tree of Life"?

Universal molecular phylogenies depend on conserved genes, often ribosomal. Since no virus genomes found to date contain ribosomal RNA genes, analysis of these genes cannot determine viruses' relationships to cellular organisms. No genes are completely conserved in virus genomes, but a number of viral "hallmark genes" are found only in virus genomes (Koonin et al. 2006). However, many other genes in virus genomes are cellular in origin, and vice versa. Viruses are agents of lateral or horizontal gene transfer; they must release their genomes into host cells, and newly replicated virus genomes are packaged in host cells. Thereby, viruses can either acquire or deliver genes to their hosts. Therefore, it is difficult to construct molecular phylogenies for viruses. In addition, many virus genes have no known homologues, making tree construction problematic. Recent attempts to determine virus phylogeny have concentrated on structural instead of sequence similarity (Krupovic and Bamford 2008). Based on the *Mimivirus* genome, some authors have proposed that viruses are a fourth domain of life equivalent to Bacteria, Archaea, and Eukarya (Raoult et al. 2004). More recently, it was proposed that viruses should be called "capsid-encoding organisms" (CEOs) while cellular life should be called "ribosome-encoding organisms" (REOs) (Raoult and Forterre 2008). Both of these proposals are controversial (Moreira and Lopez-Garcia 2009).

Unique Viruses in Extreme Environments

Viruses from extreme environments, some of them off-Earth analog environments, are particularly interesting because their genome sequences and virion structures are unique. Viruses of thermoacidophilic Archaea are particularly striking, ranging from spindle shaped to filamentous

and longer than the host cell. Some of them have no genes in their genomes with any homologues in any other (viral or cellular) genome. Nonetheless, some of these viruses are clearly closely related. Even though some of them have lipid membranes, others do not, contradicting one major tenet of virus classification (Prangishvili et al. 2006). The thermoacidophile virus STIV may provide a “missing link” between viruses infecting Bacteria, Eukarya, and Archaea (Hendrix 2004).

Antiquity of Viruses?

How old viruses are is an open question. There are no reported viruses in the rock record, but work is ongoing to determine if virus biosignatures can be preserved. “Paleoviruses” have been reconstructed and indicate that some current human retroviruses are at least 44 million years old (Emerman and Malik 2010). The oldest direct indication of viruses is the particles observed in ca. 100-million-year-old amber inclusions (Poinar and Poinar 2005).

Indirect evidence from the study of virion protein structures in bacterial, archaeal, and eukaryal viruses indicates a common viral ancestor present at the split of the three host lineages, billions of years ago (Hendrix 2004). Some have proposed that the eukaryotic nucleus is derived from a virus (Claverie 2006). Based on molecular phylogeny, the lack of cellular homologues to many virus genes and that some viruses use RNA as their genetic material, Eugene Koonin and colleagues have postulated that viruses predated cellular life and are a remnant of the RNA world (Koonin et al. 2006). Again, some of these ideas have been rejected by other researchers (Moreira and Lopez-Garcia 2009).

Viruses Relevance for Astrobiology

On Earth, viruses outnumber all other organisms by orders of magnitude. If an extraterrestrial were to collect a “representative” sample from Earth, seawater, there would be far more viruses in that sample than any other biomarkers. Viruses also require a cellular host to replicate; thus, if viruses or biomarkers thereof are found on other planets, this would strongly indicate the presence of

cellular life. Viruses are clearly involved in lateral gene transfer; this is how they replicate. Lateral gene transfer appears to have been critical in the evolution of life on Earth. If viruses are remnants of the RNA world and may even have predated cellular life, it is critical to study them to understand this fundamental stage in the development of life on Earth and possibly beyond.

Cross-References

- ▶ [Acidophile](#)
- ▶ [Archaea](#)
- ▶ [Bacteria](#)
- ▶ [Common Ancestor](#)
- ▶ [Cyanobacteria](#)
- ▶ [Ecosystem](#)
- ▶ [Eukarya](#)
- ▶ [Evolution, Biological](#)
- ▶ [Extreme Environment](#)
- ▶ [Extremophiles](#)
- ▶ [Genome](#)
- ▶ [Hot Spring Microbiology](#)
- ▶ [Hyperthermophile](#)
- ▶ [Lateral Gene Transfer](#)
- ▶ [Life](#)
- ▶ [Metabolism](#)
- ▶ [Metavirome](#)
- ▶ [Nucleic Acids](#)
- ▶ [Photosynthesis](#)
- ▶ [Quasispecies](#)
- ▶ [Ribosome](#)
- ▶ [RNA World](#)
- ▶ [Taxonomy](#)
- ▶ [Thermophile](#)
- ▶ [Transcription](#)
- ▶ [Translation](#)
- ▶ [Viroid](#)
- ▶ [Virology](#)

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VIS

► Visible Light

Viscosity

Avi M. Mandell
NASA Goddard Space Flight Center, Greenbelt,
MD, USA

Definition

Viscosity is the physical parameter that describes the resistance of any medium in general and of astrophysical fluids in particular to shear stress. In a ► [protoplanetary disk](#), the stress can be caused by differential orbital velocity of material. Viscosity in a protoplanetary disk causes the gaseous component of the disk (the bulk of the mass in a primordial disk) to lose gravitational energy to heat, causing the material to heat up (known as “viscous heating”) and causing orbital decay and infall of material onto the central star (known as “viscous accretion”). Viscosity in astrophysical fluids can be generated by a number of different mechanisms (i.e., molecular viscosity, magnetorotational instability), and the type and magnitude of the viscosity in protoplanetary disks are unknown, but observations of gas accretion onto young stars support the existence of viscosity which is larger than the molecular one.

Cross-References

► Accretion, Stellar

Viscous Stirring

Rory Barnes
Astronomy Department, University of
Washington, Seattle, WA, USA

Definition

In planet formation theory, viscous stirring corresponds to the transfer of orbital energy of a single particle into kinetic energy of other particles. For example, a large particle (relative to the typical-sized particle) in a ► [protoplanetary disk](#) can increase the velocity of a smaller body as it passes by due to its stronger gravity. When this acceleration occurs, the larger particle transfers a fraction of its energy to the smaller object. This situation is not to be confused with ► [dynamical friction](#), in which the random motion of the large particle decreases as a result of the excess of particles focused behind it.

Cross-References

- [Dynamical Friction](#)
- [Planetesimals](#)

Visible

- [Visible Light](#)

Visible Light

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[VIS](#); [Visible](#)

Definition

The term visible designates the domain of electromagnetic waves that is perceptible to the human eye. The response of an average human eye is between the wavelengths 390 nm (limit of ultraviolet) and 750 nm (limit of infrared). Until the mid-twentieth century and the advent of radio astronomy and of the spaceborne instrumentation for the gamma-ray, X-ray, UV, and infrared domains, observing in the visible was the unique way for astronomers to get information on the universe. The domain is often abbreviated by the term VIS. The photometric filter V at 550 nm stands for visible.

Cross-References

- [Electromagnetic Radiation](#)
- [Johnson UBV Bandpasses](#)
- [UV Radiation](#)

Vitalism

Charles T. Wolfe
Département de philosophie, Université de
Toulouse Jean-Jaurès, Toulouse, France

Keywords

Life · Materialism · Medicine · Ontology ·
Organism

Synonyms

[Holism](#); [Organicism](#)

Definition

Vitalism is typically presented as the belief – scientific, metaphysical, poetic, and other – in the uniqueness of life, presented as a “substance,” “force,” or “principle.” As such, it is a frequently

criticized theory, often in caricatural forms, where a model of organism, embryo development, or forms of nonmechanical causality, is called “vitalist” – a label applied to various theories which have little in common with each other, with entirely different empirical bases and/or metaphysical commitments. In fact, the historical and conceptual significance of the category of vitalism for biological thought lies in its perpetual challenge to justify the autonomy of biological entities.

Overview

In a recent review of the status of theoretical biology, we are told that “in vitalism, living matter is ontologically greater than the sum of its parts because of some life force (‘entelechy,’ ‘élan vital,’ ‘vis essentialis,’ etc.) which is added to or infused into the chemical parts” (Gilbert and Sarkar 2000). As such, it is also usually opposed to ► [materialism](#), which is often understood as a strictly “mechanistic” and/or physicalistic account of matter. While this is a correct description of ideas dating back to the late nineteenth century, particularly the vitalism put forth by the embryologist Hans Driesch, it is incorrect about vitalism in general. Driesch derived from experiments on sea urchin embryos a metaphysical theory of what he called “entelechies,” entities which somehow existed apart from the causal, space-time world studied by natural science (Driesch 1914). In contrast, eighteenth-century vitalism, notably as defined and practiced by physicians such as Bordeu, Ménuret de Chambaud, and Barthez at the Montpellier Faculty of Medicine (where the word is first used to describe a medical doctrine), is not a metaphysical claim about a mysterious life force (Cimino and Duchesneau 1997; Rey 2000; Williams 2003). It is a more practical, heuristically oriented medical and philosophical program that uses functional, Newtonian-inspired models of organism to discuss temporal, dynamic, and sometimes subjective dimensions of embodiment – disease, crisis, pulse, nosology, etc. (Wolfe 2008). In addition, Montpellier vitalism is “materialism friendly,” denying the existence of the soul

other than as an organic entity, and believing that higher functions are explainable in terms of arrangements of living matter – as one can also see with the vitalist Bordeu’s inclusion as a (positively presented) character in Diderot’s philosophical novel *D’Alembert’s Dream* (1769). It is important to distinguish between this earlier, medically based vitalism and a later, more metaphysically oriented vitalism, even if the latter begins with embryological (developmentalist) work. In addition to these two forms of vitalism – *ontological* (Driesch) and *functional* (the Montpellier School) – in the twentieth century, thinkers such as Kurt Goldstein and Georges Canguilhem developed a *projective* or *attitudinal* vitalism, in which it is presented as an *attitude* living beings necessarily adopt toward other such beings (Goldstein 1934/1995; Canguilhem 1965/2008; Wolfe 2011; Huneman and Wolfe 2010). It is interesting to observe that has been termed here “functional vitalism” is quite hard to distinguish from twentieth- (and twenty-first) century organicism, inasmuch as it is less a metaphysically founded set of claims about the uniqueness of biological entities and more an attempt to describe their uniquely relevant “systemic” functional properties (an approach that is very well articulated in Claude Bernard’s approach to what he called “organic machines”: Canguilhem 1989). In that sense, vitalism, or the “problem of vitalism,” directly interrogates the status quo of a kind of back-and-forth between reductionist and anti-reductionist approaches, and not necessarily as the most extreme anti-reductionist view (Chen 2018). In sum, vitalism comes in different forms, some of which seem well beyond the pale for mainstream biological thought, others which can serve as useful heuristics or correctives in attempting to deal with the question of the ontological status of living entities (Normandin and Wolfe 2013, Wolfe 2019, 2020, 2021).

Cross-References

- [Chance and Randomness](#)
- [Diderot’s Conception of Origins of Life](#)

- [Materialism](#)
- [Physicalism](#)
- [Reductionism](#)

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Vitreous Carbon

- [Amorphous Carbon](#)

VLBI

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Synonyms

[Very Long Baseline Interferometry](#)

Definition

Very Long Baseline Interferometry (VLBI) is a variant of the radio interferometry technique currently used in astronomy, but combining the signals of extremely distant telescopes. VLBI provides observations of an object with an exquisite angular resolution, equivalent to that of a telescope whose size is the separation between the distant telescopes. This distance can reach thousands of km (transcontinental VLBI), thus allowing measurement of details as small as 10 milli-arcsec (mas), i.e., one hundred times finer than with a conventional telescope in visible light. To achieve VLBI observations, the radio signal is locally recorded together with time stamps of an atomic clock and later the different data from all antennas are correlated using digital electronics and computers to produce the resulting image.

Cross-References

- [Interferometry](#)
- [Radio Astronomy](#)

VLT

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Keywords

Astronomy · Instruments · Observatory ·
Telescope · Interferometry

Synonyms

Very Large Telescope

Definition

The Very Large Telescope (VLT) is the main facility for European ground-based optical astronomy. It consists of four Unit Telescopes (UTs) with primary mirrors of 8.2-m diameter and four movable 1.8-m-diameter ► [telescopes](#), situated in the north of Chile. It features a very complete suite of instruments, large-field imagers, ► [adaptive optics](#)-corrected cameras and spectrographs, as well as high-resolution and multi-object spectrographs, and the VLT covers a broad spectral region, from ultraviolet (300-nm) to mid-infrared (24- μ m) wavelengths. It is also able to work in recombined or interferometric mode. This is the world's most important facility for visible/infrared astronomy.

Overview

The Very Large Telescope array (VLT) is operated by an international organization, the European Southern Observatory (ESO). Located on Cerro Paranal in Northern Chile (70° 24' 11" W; 24° 37' 31" S) at an altitude of 2635 m, it operates at wavelengths ranging from 0.3 to 25 μ m. It is the world's largest optical instrument, consisting of four Unit Telescopes with main mirrors of 8.2-m diameter and four movable 1.8-m-diameter telescopes (Auxiliary Telescopes: see Fig. 1), able to

work in a collaborative way (interferometric mode). The first of the Unit Telescopes, "Antu," was commissioned on April 1, 1999. Today, all four Unit Telescopes and all four Auxiliary Telescopes (ATs) are operational.

The telescopes can be optically linked when working in the interferometric mode (VLTI), or the 8.2-m-diameter Unit Telescopes can be used individually.

The 8.2-m-diameter telescopes are housed in compact, thermally controlled buildings, which rotate synchronously with the telescopes, thus limiting the disturbing effects of air turbulence in the telescope tube. The VLT Unit Telescope has an altazimuth mount. In such a mount, the telescope tube moves around a horizontal axis (the elevation axis), and the two bearings that support the tube are mounted on a fork rotating around a vertical axis (the azimuth axis), thus enabling the telescope to point over the entire sky.

The VLT Unit Telescope optical layout is of the Ritchey-Chrétien type. Each of the four ► [telescopes](#) can operate in either Cassegrain, Nasmyth, or coudé focus. The light is collected by the primary mirror (M1) and then concentrated by the combination of the primary and the secondary mirror (M2), either directly to the Cassegrain focus located below the primary or to one of the two Nasmyth foci. The coudé focus is obtained by transferring one Nasmyth focus to another location in the telescope basement by means of an optical relay system. From the coudé focus, the light is sent to the interferometric focus. Due to the low ratio between their thickness and diameter, the VLT monolithic primary mirrors are rather flexible, thus requiring permanent control of their optical shape through active optics. This consists in applying controlled forces to the primary mirror and in moving the secondary mirror in order to cancel out the optical errors. The system essentially compensates for static or slowly varying deformations such as thermal effects, low frequency components of wind buffeting, and gravitational deformation due to telescope inclination.

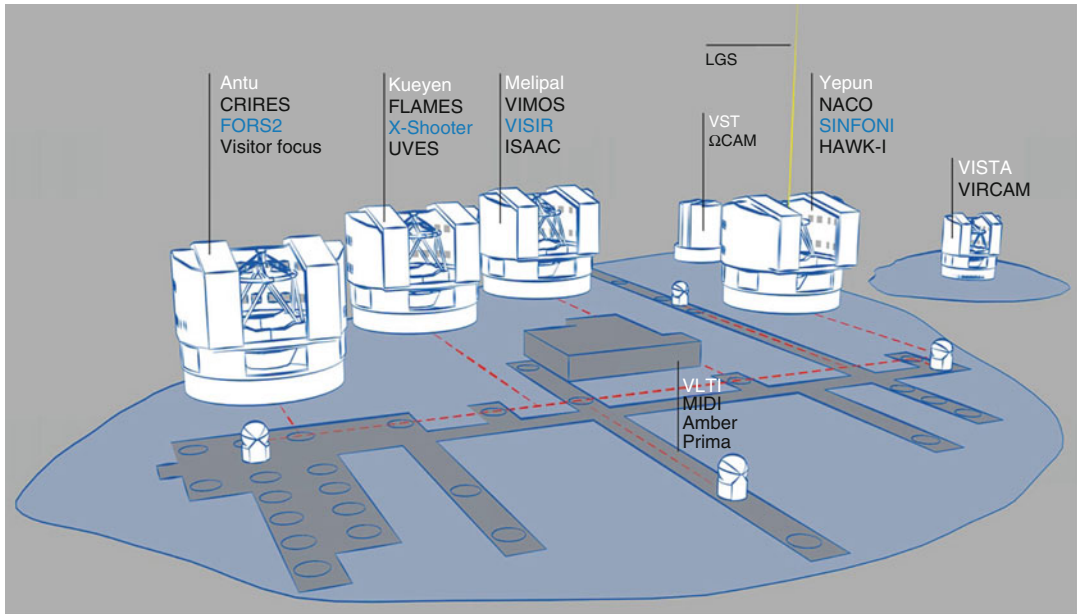
The four 8.2-m Unit Telescopes are mostly used for individual observations, thanks to an ambitious instrumentation program. It includes



VLT, Fig. 1 A view of the Very Large Telescope (VLT) at night. One can see three smaller Auxiliary Telescopes in the foreground and the four enclosures of the large Unit Telescopes

large-field imagers, ► [adaptive optics](#)-corrected cameras and spectrographs, as well as high-resolution and multi-object spectrographs and covers a broad spectral region, from ultraviolet (300-nm) to mid-infrared (24- μm) wavelengths. The suite of instruments is as follows (Fig. 2):

- FORS1 and FORS2 (FOcal Reducer and low dispersion Spectrograph) are a visible light camera and multi-object spectrograph with a 6.8-arcmin field of view.
- ISAAC (Infrared Spectrometer And Array Camera) is a near-infrared imager and spectrograph.
- UVES (Ultraviolet and Visual Echelle Spectrograph) is an ultraviolet and visible light spectrograph.
- FLAMES (Fibre Large Area Multi-Element Spectrograph) is a multi-object fiber feed unit for UVES and GIRAFFE, the latter allowing simultaneous ► [spectroscopy](#) of a 100 objects at moderate spectral resolution in the visible.
- NACO (NAOS-CONICA, NAOS meaning Nasmyth Adaptive Optics System and CONICA meaning COudé Near-Infrared CAmera) is an ► [adaptive optics](#) facility, which produces infrared images as sharp as if taken in space and includes spectroscopic, polarimetric, and coronagraphic capabilities.
- VISIR (VLT spectrometer and imager for the mid-infrared) provides diffraction-limited ► [imaging](#) and ► [spectroscopy](#) at a range of resolutions in the 10- and 20- μm mid-infrared (MIR) atmospheric windows.
- SINFONI is a medium resolution, near-infrared (1–2.5- μm) integral field spectrograph fed by an adaptive optics module.
- CRILES (CRYogenic InfraRed Echelle Spectrograph) is adaptive optics assisted and provides a resolving power of up to 100,000 in the infrared spectral range from 1 to 5 μm .
- HAWK-I (High-Acuity Wide-field K-band Imager) is a near-infrared imager with a relatively large field of view.
- VIMOS (VISible Multi-Object Spectrograph) delivers visible images and spectra of up to 1000 galaxies at a time in a 14×14 -arcmin field of view.
- X-Shooter, the first second-generation instrument, a wide-band [UV to near infrared]



VLT, Fig. 2 The four Unit Telescopes (*UTs*) and the four Auxiliary Telescopes (*ATs*) that form the VLT. The various instruments available at the different foci are indicated

► **spectrometer** designed to explore the properties of rare, unusual, or unidentified sources.

The telescopes can also work together, in groups of two or three or even more, to form a giant “interferometer,” the ESO Very Large Telescope Interferometer, allowing astronomers to capture details up to 25 times finer than with the individual telescopes. The light beams are combined in the VLTI using a complex system of mirrors in underground tunnels where the light paths must be kept equal to distances less than 1 μm over 100 m. The VLTI can reconstruct images with an angular resolution of milliarcseconds.

The 8-m UTs are used for interferometric observations for a limited number of nights every year, but four smaller, dedicated, Auxiliary Telescopes (ATs) are available to allow the VLTI to observe interferometrically every night. The ATs are mounted on tracks and can be moved between precisely defined observing positions from where the beams of collected light are combined in the VLTI. The ATs are dedicated ► **telescopes**, self-contained in their ultracompact protective domes,

and travel with their own electronics, ventilation, hydraulics, and cooling systems. Each AT has a transporter that lifts the ► **telescope** and moves it from one position to the other.

The VLT is the most productive individual ground-based facility in the world, and results from the VLT have led to the publication of an average of more than one peer-reviewed scientific paper per day.

Cross-References

- **Adaptive Optics**
- **Imaging**
- **Interferometry**
- **Spectroscopy**
- **Telescope**

References and Further Reading

<http://www.eso.org/projects/vlt/>

The VLT white book – European Southern Observatory

VMC

► [Venus Express](#)

Volatile

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Definition

In planetary science, volatiles are chemical elements and compounds with low boiling points typically associated with a planet's or Moon's crust and/or atmosphere. Some examples include nitrogen (N or N₂), water, carbon dioxide, ammonia, hydrogen (H or H₂), methane, and sulfur dioxide. These compounds or elements, in the solid state, are often significant components of the crusts of moons and planets. Planetary scientists often classify volatiles with exceptionally low melting points, such as hydrogen and helium, as gases, while those volatiles with melting points above about 100 K are classified as ices. Here, the terms “gas” and “ice” can be applied to compounds that may be solids, liquids, or gases. Thus, Jupiter and Saturn are referred to as “gas giants,” and Uranus and Neptune are referred to as “ice giants,” even though the majority of the “gas” and “ice” in their interiors is liquid. The Earth's Moon has a very low volatile content. Its crust contains oxygen chemically bound in the rocks, but negligible amounts of H, N, or C. In contrast, those elements and compounds with high boiling points are known as refractory substances.

Scientists working on planetary interiors apply the term volatile to elements that are gaseous at magnetic temperatures (>1300 K). Typical

volatiles are gases such as H₂O, CO₂, CH₄, but also Hg, Zn, Pb, S, and alkali elements.

Cross-References

► [Refractory Molecule](#)

Volcanic Mountain

► [Tholus](#)

Volcaniclastic Sediment

Nicholas Arndt
Emeritus Professor, ISTerre, University Grenoble
Alpes, Grenoble, France

Definition

A *volcaniclastic sediment* is a sediment (regardless of the average grain or clast size) composed primarily of debris of effusive ► [igneous rocks](#) (volcanic material). This volcanic material may be pyroclastic (fragments derived from explosive volcanism) or hyaloclastic (fragments formed by thermal shock when hot lava comes in contact with cool sea or lake water). Undisturbed clastic deposits of volcanic materials are called volcanoclastic; the term sediment is added when the material has been reworked and redeposited by water, wind, or gravity. Volcaniclastic sediments have a wide range of compositions, from ► [basalt](#) (rarely ► [komatiite](#)) to rhyolite. They may display sedimentary features familiar from siliciclastic sediments, such as graded or cross bedding (i.e., cross-stratification, when layering is produced within a sediment stratum and with an angle respect to the main bedding plane). Commonly, volcanoclastic sediment undergoes metasomatism or diagenetic changes, including carbonatization or silicification, for example, by hydrothermal fluids.

Cross-References

- [Chert](#)
- [Igneous Rock](#)
- [Metasediment](#)
- [Sedimentary Rock](#)

Volcano, Planetary

Daniele L. Pinti

GEOTOP Research Center for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Definition

Volcanoes are structures (constructional volcano edifices) created by the accumulation of erupted molten lava or solid, fragmental pyroclastic rocks (or pyroclasts). Volcanoes range in size from small cones a few tens of meters high to enormous shields hundreds of km in diameter. Most volcanoes on Earth and other planets are cone shaped. The morphology of the volcano edifice depends basically on the type of volcanic material which erupted. When the lava is relatively fluid, such as ► [basalt](#), volcanic edifice has low-angle slopes creating a so-called ► [shield](#) volcano. When the lava consists of very viscous rhyolite, the extrusion of pasty lava tends to form a dome, or the explosive eruption of the highly viscous material and fragmental material will form a steep-sided structure called stratovolcano. Volcanoes are commonly present on Earth as a result of ► [plate tectonics](#) processes and on other telluric planets of our Solar system, namely Mars and Venus, and on Jupiter moon Io. Constructional volcano edifices can be also be produced by eruption of glaciated material (cryovolcanism on Titan and Enceladus moons) or eruptions of mud (mud volcanism on Earth and possibly on Mars).

Overview

Volcanoes are the superficial expression of planetary tectonics. On Earth, volcanoes are mainly distributed along convergent margins of tectonic plates, where they form insular (i.e., Japan) or continental (i.e., Andes) arcs and at the apex of mantle plumes (i.e., Hawaii or Tahiti). At convergent margins, hydrated sediments are subducted together with the basaltic seafloor back to the mantle. Dehydration of the subducting sediments and incorporation of water at the mantle wedge (i.e., the triangular-shaped region of mantle which lies above the subducting plate and below the overriding plate) lowers the mantle melting point allowing magmas to form and to reach the surface. The occurrence of water and associated volatiles and the relative high viscosity of the formed magmas (from andesitic to rhyolitic in composition) provoke at the surface the phenomenon of *magma fragmentation*. *Magma fragmentation* is the breakup of molten rock into discrete pieces, called pyroclasts. Magma contains bubbles of compressible magmatic volatiles. If the magma is highly viscous, resistance to bubble growth will instead lead to excess gas pressure and the magma will deform viscoelastically by fracturing like a glassy solid, resulting in the formation of a violently expanding gas-pyroclast mixture, which provokes explosive eruptions (Gonnermann 2015). Volcanic chains as Hawaii are the surface expression of a mantle plume rising from the core-mantle boundary or from the bottom of the ► [asthenosphere](#). Magmas are generally low in viscosity (basalts). In this case, gas bubbles can expand freely, and the eruption is reduced to lava flows, or, in case of high gas content, to lava fountains. The type and nature of erupted material control the morphology of volcanoes, with large shield volcanoes produced by low-viscosity lava flows and stratovolcanoes from alternances of pyroclastic material and lavas. Yet the morphology can be further complicated by the migration of the position of the erupting vent with time, creating complex nested edifices (typical is the Colima stratovolcano in Mexico; the Piton des Neiges-Piton de la Fournaise in Reunion Island,

or the Somma-Vesuvius, Italy). Secondary processes related to partial emptying of the magma chamber beneath a volcano edifice or lateral eruptions can create partial collapses of the edifice (Mt. St Helens in 1980). During cataclysmic eruptions, the complete emptying of the magma chamber brings to the total collapse of the edifice with the creation of a typical caldera, a large cauldron-like hollow (Yellowstone is the most known).

The presence of volcanoes usually indicates magmatism, the opposite is not always true. Indeed, the largest volume of magma on Earth (80% of the total) is erupted at the ► [mid-ocean ridges](#), where oceanic crust is formed, and the majority of volcanic material is emitted through fractures (fissural volcanism). Accumulating basaltic flow along the mid-ocean ridges create long “mountainous” chains but no single constructional volcano edifices. On Earth, fissural volcanism is also responsible for the continental flood basalts (CFB) or ► [Trapps](#) which are characterized by voluminous step-like basaltic sequences (Trapps means “stairs”). This is also the case on other telluric planets of the Solar system. For example, Mercury is covered by a volcanic crust, and numerous are the evidence of lava flows, but not indication of constructional volcanic edifices (Wright et al. 2018), except for 11 volcanic domes detected on its surface. It is likely that most of the past volcanic activity of Mercury was related to fissural volcanism. Venus, Mars, the Moon, and Jupiter’s satellite Io show volcanic edifices. Venus shows numerous volcanic structures and the highest density of volcanoes of any other planet or moon in the Solar system (around 1000). They are mainly shield volcanoes (such as the 8 km height Maat Mons) indicating emission of low viscosity molten rocks such as those emitted by the Hawaiian hot spot volcanoes. High thermal emissions detected by the Venus Express spacecraft suggest that volcanic activity could be recent, less than 2.5 Ma ago (Smrekar et al. 2010). The Moon has volcanoes typically in the form of small domes and cones that form large volcanic complexes and isolated edifices. Calderas are exceptionally rare. Volcanism was active from 4.2 to 1.2 Ga ago, though new volcanic

features discovered in the far side of the Moon suggest more recent limited volcanic activity not older than 50 Ma (Watters et al. 2012). Mars is dominated by the largest volcanoes on the Solar system, mainly shield volcanoes as those concentrated in the Tharsis Volcanic Province (Ascraeus Mons, Pavonis Mons, and Arsia Mons collectively named as Tharsis Montes). These three huge shield volcanoes are aligned NE-SW. Off axis, on the NW of the Tharsis Montes there is the highest shield volcano of the Solar system, Olympus Mons (21 km above Martian datum with 4–5° slopes for a 71 x 92 km diameter). In addition to the large shield volcanoes, Tharsis region contains smaller volcanoes called *tholi* and *paterae*. *Tholi* are dome-shaped edifices with flanks that are much steeper than the larger shield volcanoes. Their central calderas are also quite large in proportion to their base diameters. *Paterae* (a Latin word indicating a shallow drinking bowl) appears to be morphologically like the *tholi*, except for having larger calderas. It is believed that these two structures represent the summit of buried larger shield volcanoes. The volcanic activity on Mars was mainly concentrated between the Noachian (3.7 Ga ago) and Amazonian (500 Ma ago) though there are speculation that much recent volcanic activity resurfaced some areas of the Tharsis region (Hauber et al. 2011). The fifth moon of Jupiter, Io, has the largest volcanic activity among the planetary bodies of the solar system. The surface is splotched with lava lakes and floodplains of molten lava, and 150 active volcanoes have been detected, but the total number could reach more than 400. Volcanic activity is accompanied by sulfur and sulfur dioxide plumes that can reach 300 km altitude in the Io’s atmosphere.

Constructional volcanic edifices are not only produced by emission of molten rock but by other fluids such as mud and ice (Hargitai et al. 2014). Mud volcanism is the extrusion at the surface of Earth of mud and water driven by gases such as methane in hydrocarbon-bearing basins (Mazzini and Etiope 2017). These extrusions normally create relatively small, pitted cones and mounds but in Pakistan the largest ones can reach 100 m in

diameter and up to 700 m height. Pitted cones and mounds at the surface of Mars could be derived by mud volcanism (Skinner Jr and Mazzini 2009). Cryovolcanism, namely “the extrusion of liquids and vapors of materials that would be frozen solid at the planetary surface temperatures of the icy bodies of the outer solar system” (cf. Geissler 2015), is believed to produce constructional volcanic edifices, particularly on Saturn’s moon Titan (Doom Mons). The majority of cryovolcanic activity observed in the Solar system, particularly on Saturn’s moon Enceladus, is limited to geysers.

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Cross-References

- [Basalt](#)
- [Enceladus](#)
- [Mars](#)
- [Mud Volcanism](#)
- [Plate Tectonics](#)
- [Titan](#)
- [Trapps](#)
- [Triton](#)
- [Venus](#)

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Vortex, Vortices

Sean N. Raymond
 Laboratoire d’Astrophysique de Bordeaux,
 CNRS, Université de Bordeaux, Bordeaux,
 France

Definition

In the context of gaseous protoplanetary disks, vortices are spinning regions that undergo anticyclonic rotation. The existence and longevity of vortices in planet-forming disks is still debated. If vortices do exist, they could accelerate the process of planet formation by providing regions where solids are accumulated, which would speed up the process of planetesimal growth.

Cross-References

- [Planetesimals](#)
- [Planet Formation](#)
- [Protoplanetary Disk](#)

Vostok, Subglacial Lake

Sergey Bulat¹ and Jean-Robert Petit²
¹NRC ‘Kurchatov Institute’-Petersburg Nuclear Physics Institute, Gatchina, Russia
²Univ. Grenoble-Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France

Keywords

Accretion ice · Antarctic ice sheet · Chemolithoautotrophs · Extreme environment · *Hydrogenophilus thermoluteolus* · Life detection · Psychrophiles · Subglacial environments

Synonyms

Subglacial Antarctic Lake Vostok

Definition

The subglacial Lake Vostok (Russian, “east”) is the largest, deepest, and most studied lake among more than 400 subglacial lakes (water features) inventoried through airborne radio-echo sounding and satellite altimetry surveys (Siegert et al. 2016; Wright and Siegert 2012). It is located beneath the Russian Vostok Antarctic research station, and it has already been unsealed in triple (Bulat 2016). The naturally refrozen lake water, or accretion, ice collected by deep drilling and used as a proxy for the lake water has proved to be exceptionally clean, though much diluted, leading to controversial biological and chemical analyses. Nevertheless, the likely indigenous DNA fingerprint of a chemolithoautotrophic thermophile along with some other bacteria seems to fit with the lake’s extreme environment.

Overview

Subglacial lakes are water bodies formed at the base of the 3–4 km thick Antarctic ice sheet due to the geothermal heat flux, which melts basal ice layers. The meltwater accumulates in bedrock troughs with long residence times (Bell et al. 2002). It may be periodically discharged through a subglacial hydrologic network (Wingham et al. 2006), depending on geological and bedrock relief settings.

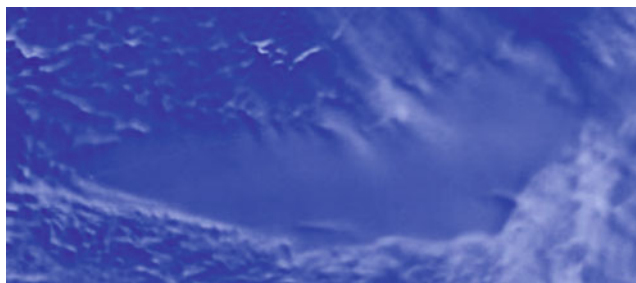
The subglacial Lake Vostok was discovered by radio-echo sounding in the late 1960s (Oswald and Robin 1973). It was mapped in detail by radar altimetry in the 1990s (Ridley et al. 1993) and defined as a lake after seismic ground studies in 1996 (Kapitsa et al. 1996). It is the largest and deepest subglacial lake located beneath the Vostok station (78° S, 106° E, elevation 3488 m, ~1300 km from the coast, mean surface annual temperature -55.1°C) under the ~3750–4200 m thick central East Antarctic ice sheet (Fig. 1).

The subglacial Lake Vostok is the best-studied water feature in Antarctica (Petit et al. 2005). It is crescent-shaped and extends northward from Vostok station for more than 275 km in a deep trough and has a surface area of $\sim 15,000\text{ km}^2$, similar to that of Lake Ontario in North America. It is 65 km wide and $\sim 400\text{ m}$ deep on average with a volume of $\sim 6100\text{ km}^3$ (Popov et al. 2011). There are two separate basins, one with a trough as deep as 1650 m in the southern region (Masolov et al. 2001, 2006; Studinger et al. 2003). Lake Vostok is a tectonically controlled subglacial lake with minor recently recorded tectonic activity (Studinger et al. 2003). The lake has likely been isolated from the surface for ~ 14 million years, the time of the major East Antarctica glaciation (Bo et al. 2009).

The overlaying glacier flows at $\sim 2\text{ m/year}$ across the lake. From the South (Vostok region) to the North, the ice thickness increases from 3750 to 4200 m because of the deepening bedrock trough. This imposes a tilted interface between the lacustrine water and the overlying ice. As the melting point changes with pressure, the glacier’s base melts on the thick side (Northern region) supplying the lake. Water also refreezes in the upper layers of the lake in the Southern region, and the so-called *accretion ice* is exported by the glacier’s movement out of the lake. This leads to the replacement of the lake water every $\sim 40\text{--}80\text{ ka}$ (Bell et al. 2002; Petit et al. 2005).

The subglacial lake environment is characterized by high pressure ($\sim 400\text{ bars}$) and in situ temperatures close to the freezing point of water ($\sim -2.6^{\circ}\text{C}$). Energy resources are seriously limited as there is complete darkness and an ultralow dissolved organic carbon content ($\text{DOC} \leq 0.010\text{ mg/L C/L}$) (Preunkert et al. 2011). The lake water is likely highly saturated with air, particularly molecular oxygen, released over long periods from the continuous ice melting (upper limit 815–1300 mg/L for dissolved O_2 concentration) (Lipenkov and Istomin 2001; Lipenkov et al. 2016; McKay et al. 2003). The accretion ice is also enriched in radiogenic ^4He originating from the bedrock and degassed through deep faults (Petit et al. 2005; Jean-Baptiste et al. 2018).

The accretion ice is composed of two distinct layers: the uppermost ice (from 3539 to 3608 m)



Vostok, Subglacial Lake, Fig. 1 The subglacial Lake Vostok as seen from space by ice-penetrating radar (RADARSAT, <http://svs.gsfc.nasa.gov/vis/a000000/a000900/a000996/>).

The Russian Vostok station location (tiny white dot, most left) and tractor traverse track (tiny white thread) were recorded as well

containing millimeter size mica-clay inclusions (accretion ice I) and the deeper ice (below 3608 m), which is transparent and very clean (accretion ice II). Various groups have studied the biological content of accretion ice samples. The nature of the samples, the integrity of microbes, the possibility of contamination from the drilling and recovery process, the introduction of nonindigenous materials, and the sparse microbial populations all suggest that caution should be taken when interpreting the results. Not unexpectedly, these limitations have led to differing opinions and, in some cases, contradictory results (Priscu et al. 1999; Christner et al. 2006 vs. Bulat et al. 2004). For example, measured microbial populations in ice range from thousands of cells per ml (up to 36,000, Priscu et al. 1999; Christner et al. 2006; Abyzov et al. 2001) to only a few (1–10) cells/mL (Bulat et al. 2004, 2009). Such a significant variation (three orders of magnitude) may be caused by differences in methodology used to decontaminate, retrieve, and process the samples. Some microbes may originate from external contamination during ice coring with drilling fluids (Alekhina et al. 2007).

From the recent studies, for which chemical and biological contamination is better documented and controlled, the Lake Vostok ice appears very clean and much diluted with respect to chemical and biological content. The lake water (at least the uppermost layer) appears almost entirely lifeless. Only a few bacterial phylotypes were identified in accretion ice, which were not related to contamination (Bulat et al. 2004, 2009; Bulat 2016). The confidently recorded DNA fingerprint

of the chemolithoautotrophic thermophile *Hydrogenophilus thermoluteolus* suggests the presence of a deep biosphere within the bedrock (Bulat et al. 2004; Petit et al. 2005; Lavire et al. 2006), while the expected high oxygen stress of the water may be very restrictive for biology (Bulat et al. 2004).

Basic Methodology

Stringent decontamination procedures have to be applied in order to remove the outer part of the ice core contaminated by heavy drilling operations with kerosene-based drilling fluid. The protocol consists of scraping off the outer surface, washing off the kerosene with special solutions followed by ozone treatment, and a series of washes with ultra-pure low-DOC content water in certified cleanroom conditions. The chemical composition of the ice has first to meet the reference profiles imposed by clean working conditions. Microscopic observations, flow cytometry assays, and culturing trials were implemented to assay the biomass. Finally, DNA-based techniques including very sensitive DNA amplifications were applied. To validate the DNA results, a contaminant library was established (Bulat et al. 2004; Bulat 2016).

Key Research Findings

Life in Lake Vostok

Referring to Bulat et al.'s (2009) data, cell concentrations would not exceed 19–24 cells/mL in

both accretion and glacial ice, respectively, values comparable to those found in other works (D'Elia et al. 2008). The chemical content is very low in accretion ice II (less than 100 mg/L for total ions), suggesting the lake is poorly saline ($<0.1\%$ taking into account ion partitioning during freezing). At the same time, sulfate salts (gypsum) and carbonates are likely to present (up to 1 g/L) within the mineral inclusions in accretion ice I (De Angelis et al. 2004). Dissolved organic carbon (DOC) is present in less than 0.010 mg C/L imposing ultra-oligotrophic conditions (Preunkert et al. 2011). The accretion ice has a total gas volume content two to three orders of magnitude lower than the glacier ice, imposing anaerobic conditions. No light is available for photosynthesis.

The overall environmental conditions in the lake and accreted ice would restrict any possible biota to chemoautotrophs. Possible redox couples seem to be limited to hydrogen and/or sulfides as electron donors and sulfates and oxygen (in sediment inclusions) as electron acceptors. The carbon dioxide or carbonate from sediments could serve as a carbon source. Therefore, if life is present, one may expect to discover anaerobic chemoautotrophic piezophilic psychrophiles in accretion ice as a special habitat and the same forms, but with a high oxygen tolerance in the lake water which is highly likely supersaturated with oxygen.

Sequencing microbial 16S rRNA genes, constrained by numerous contaminant controls and criteria, showed that the accretion ice is essentially free of microbial DNA. Bulat et al. (2004) and Lavire et al. (2006) have recorded the only confidently identified DNA signature in accretion ice of the ► [chemolithoautotroph](#) thermophile *Hydrogenophilus thermoluteolus*. The niche for this thermophile was suggested to be within deep faults of the bedrock encircling the lake (Fig. 2), where the environmental conditions of warm, anoxic, CO₂-rich sediments along with probable hydrogen emission due to water radiolysis would support this type of organism. Sporadic seismotectonic activity (Staudinger et al. 2003) might have flushed some material from the veins into the lake and the accretion ice

I (Bulat et al. 2004; Petit et al. 2005). Despite the Lake Vostok was unsealed in a triple, the water has not yet been cleanly sampled for the study. However, it is expected that the main water body of the lake could be microbe-free or contain unusual “oxygenophilic” (“extraterrestrial”) life forms.

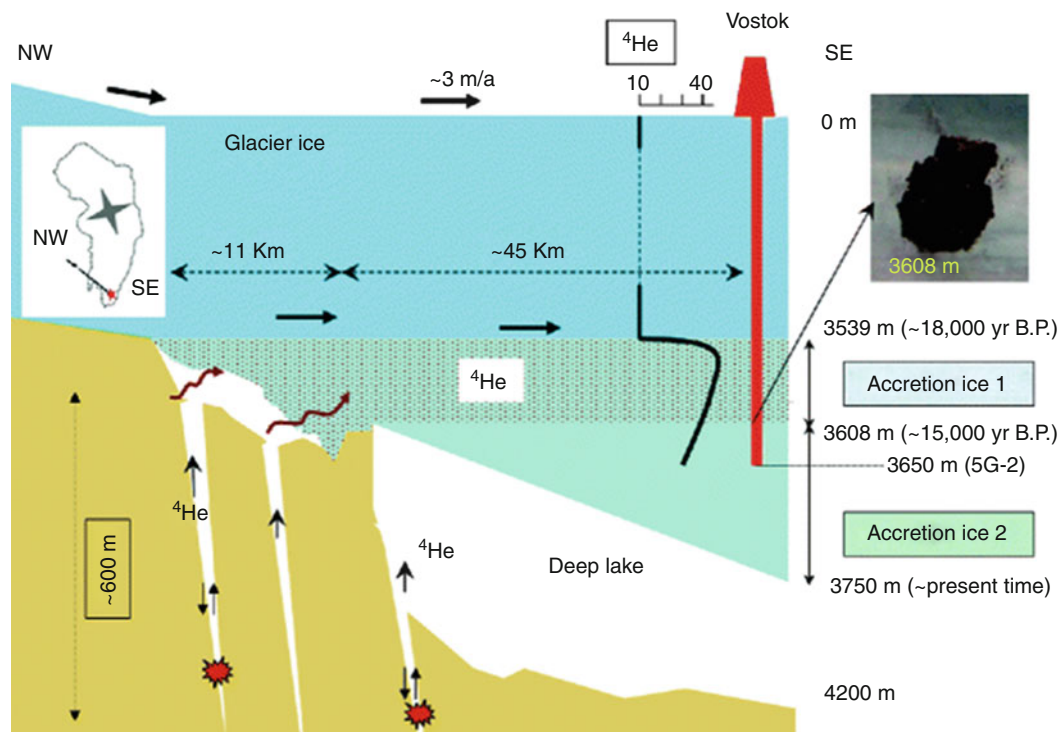
Excepting the thermophile discovered in natural accretion ice, the present-day bacterial finds (passed all possible contamination precautions) in lake water poured into the borehole following lake unsealing (dubbed “technogenic,” i.e., contaminated lake water) include hitherto-unknown and phylogenetically unclassified phylotype w123-10 likely belonging to *Parcubacteria* Candidatus *Adlerbacteria*, the phylotype 3429v3-4 showing below genus-level similarity with *Herminiimonas glaciei* of *Oxalobacteraceae* (*Beta-Proteobacteria*) and 3698v46-27 being conspecific with several species of *Marinilactobacillus* of *Carnobacteriaceae* (*Firmicutes*). The fourth recently discovered phylotype 3721v34-24 has remained taxonomically unidentified – 87.7% (below family-level) similarity with *Mucilaginibacter daejeonensis* NR_041505 of *Bacteroidetes* (*Sphingobacteriaceae*) (Bulat et al. 2020).

Applications

Since the subglacial Lake Vostok may be viewed as the only extremely clean (microbe-free) giant aquatic system on the Earth, it provides a unique test area for searching for life on icy worlds such as Jupiter's moon Europa or Saturn's moon Enceladus. Confirmation of life living in Lake Vostok would strengthen the prospect for the possible presence of life on icy moons and planets.

Future Directions

Explorations of Antarctic subglacial lakes are entering an active phase with variable technological completion depending on the ice thickness to penetrate before reaching the water body. For lakes buried under more than 3000 m of ice, two



Vostok, Subglacial Lake, Fig. 2 Sketch of the glacier and lake basement along the Vostok ice flow line. The rock basement is represented by escarpments where deep faults allow water to seep in-depth and circulate. Fault activity and radiogenic ^4He degassing from the rocks are depicted

by a symbol of explosion and vertical arrows, respectively. A sketch of down core ^4He concentration suggests ^4He contribution from shallow depth area upstream Vostok. On the top right is shown a sediment inclusion within the ice at 3608 m depth. (Modified from Bulat et al. 2004)

major Subglacial Antarctic Environments (SAE) programs are established and ready-to-implement: Subglacial Lake Vostok (Russia) (partly done) and Subglacial Lake Ellsworth (UK) (suspended due to technological failure). In the Ross Ice shelf region (ice streams), shallow lakes (a few dozen meters under a thousand meters of ice) have been successfully reached by using a hot water system – the Lake Whillans (Mikucki et al. 2016) and the Lake Mercer (Priscu et al. 2021). Because individual lakes may have different origins and geological histories, the limnological conditions, the age, the source of founder microbes, the time of isolation, and the populations of extant microbes, if they exist, may vary from location to location. Thus, the findings in Lake Vostok will not necessarily be typical of other lakes and stream sediments like it came up with the Lake Whillans and the Lake Mercer (Mikucki et al. 2016; Priscu et al. 2021).

The subglacial Lake Vostok is a unique reservoir of genetic material evolving in cold darkness under high oxygen stress isolated from another biota for the last 14 million years and may contain organisms with distinctive adaptations. As for the Lake Vostok program, the first entry into the lake was performed at the depth of 3769.3 m on February 05, 2012. The water rose into the borehole up to 363 m and froze. During the following season, 2012–2013, drillers re-cored the fast-frozen lake water and obtained only 32 m of the ice core. Further drilling operations of re-coring this frozen lake water have been biased from the old borehole and went out into the pristine glacial ice. The second entry into the lake occurred at a depth of 3769.15 m 3 years later, on January 25, 2015. The water rose again into the borehole to the level of about 70 m and was left to freeze. In four days, drillers re-cored the icy “cork” and obtained about 12 m of a new fast-frozen lake

water core before the water came up again into the borehole and finally froze at the level of 65–67 m above the ice/water interface. However, although the Russians were the first to enter a subglacial Antarctic lake at such a great depth (3769 m) and were able to perform the lake entry twice, the drilling technology used (electromechanical drill along with kerosene drilling fluid with the use of foranes as densifier) proved to be inappropriate to collect the liquid water in general and clean samples in particular. More technological developments are needed to face such a challenge including the development of sophisticated systems consisting of well-sealed transport module preventing the contamination of in-module-encapsulated devices/samplers with the drilling fluid as well as the use of thermal drill just before the next lake unsealing.

Cross-References

- [Biomarkers](#)
- [Chemolithoautotroph](#)
- [Extreme Environment](#)
- [Mars Analogue Sites](#)
- [Subglacial Environments](#)

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Voyager 1

► [Voyager, Spacecraft](#)

Voyager 2

► [Voyager, Spacecraft](#)

Voyager, Spacecraft

Michel Viso
Innovaxiom, Paris, CX, France

Synonyms

[Voyager 1](#); [Voyager 2](#)

Definition

The Voyager mission was designed to take advantage of a rare geometric arrangement of layout of ► [Jupiter](#), ► [Saturn](#), ► [Uranus](#), and ► [Neptune](#), which occurs about every 175 years. This allowed for a four-planet tour for a minimum of propellant and trip time. The flyby of each planet bends the spacecraft's flight path and increases its velocity

enough to deliver it to the next destination. Using this “gravity assist” technique, the flight time to Neptune was reduced from 30 to 12 years.

Both spacecraft were launched from Cape Canaveral: Voyager 2 was launched first, on August 20, 1977; and Voyager 1 was launched on a faster, shorter trajectory on September 5, 1977.

Overview

The prime mission to Jupiter and Saturn brought Voyager 1 to Jupiter on March 5, 1979, and Saturn on November 12, 1980, followed by Voyager 2 to Jupiter on July 9, 1979, and Saturn on August 25, 1981. Voyager 1’s trajectory, designed to send the spacecraft close to Titan and behind Saturn’s rings, bent the spacecraft’s path northward out of the ecliptic plane. While Voyager 2 was aimed to fly by Saturn at a point that would direct the spacecraft toward Uranus, Voyager 2 encountered Uranus on January 24, 1986, returning detailed photos and other data on the planet, its moons, magnetic field, and dark rings. Following Voyager 2’s closest approach to Neptune on August 25, 1989, the spacecraft flew

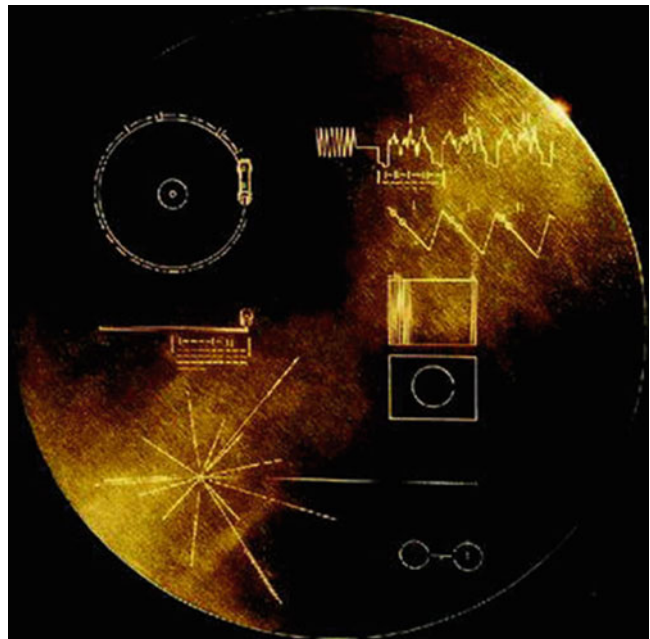
southward, below the ecliptic plane, and onto a course that will take it, too, to interstellar space. Voyager 1, meanwhile, continues to press outward, conducting studies of interplanetary space. Since September 2013, it is announced that Voyager 1 is in the interstellar space more than 19 billion kilometers (or 127 AU) from the Earth. NASA announced in December 2018 that Voyager 2 entered also the interstellar space.

The energy production by the radio-isotopic thermoelectric generator based on the nuclear decay of plutonium is regularly decreasing. The instruments are then progressively turned off to maintain sufficient power margins. The energy supply is supposed to last up to 2025.

The spacecraft reach, in 2022, more than 44 years of continuous operations. In April 2022, both spacecraft are sending data from their respective locations about the physical border between the solar system and the interstellar space. Voyager 1 travels at about 21 light hours (23,27 billion of km) from the Earth at almost 61,000 km/h and 4 instruments out of 10 are “On”: the Cosmic Ray telescope, the Low Energy Charged Particle experiment, the Magnetometer, and the Plasma Wave experiment. Voyager 2 travels at about 18 light hours (19,48 billion

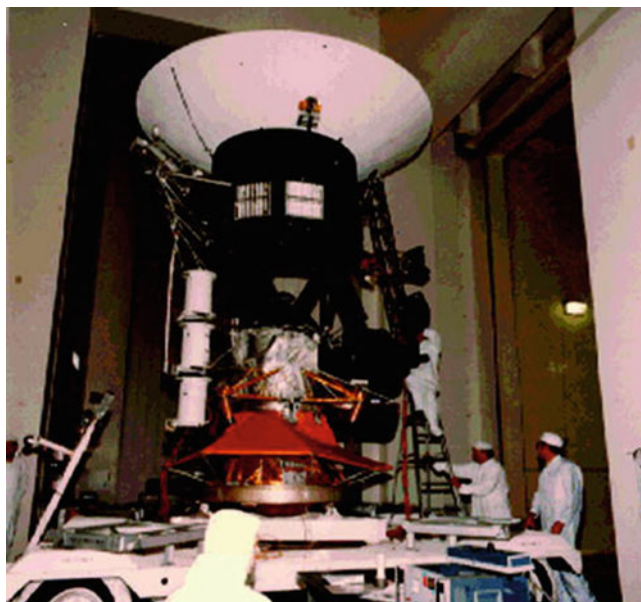
Voyager, Spacecraft,

Fig. 1 The golden record disk engraved with figures related to the position of the Earth. (Photo NASA)



Voyager, Spacecraft,

Fig. 2 The Voyager spacecraft at the environmental test laboratory. Note the three *white* cylinders representing the RTGs



km) at about 55,000 km/h from the Earth with the same four instruments “On” plus the Plasma Spectrometer.

According to the Jet Propulsion laboratory, Voyager 1 will pass the Oort cloud, getting out of the zone of attraction of the Sun, within 14,000 to 28,000 additional years. . .

As the Pioneer 10 and 11 spacecraft, while they are leaving the solar system, both Voyager spacecraft are loaded with a gold-plated record disk, initiated by Carl Sagan, that contains pictures and sounds from the Earth as well as greetings from human beings (Figs. 1 and 2).

explosion. It is currently in a state characterized by substantial mass loss from its surface, which creates a dense circumstellar envelope, with a complicated morphology, which is rich in primarily oxygen-bearing species and cosmic dust (most likely in the form of silicates). The oxygen-rich nature of its circumstellar matter (i.e., the abundance of oxygen is higher than that of carbon) limits somewhat the chemical complexity, but more than 20 circumstellar molecular species have been detected. Noteworthy is the presence of aluminum, phosphorus, and titanium oxides.

Cross-References

- [Circumstellar Chemistry](#)
- [Interstellar Dust](#)
- [Molecules in Space](#)

VY CMa

Hans Olofsson
Department of Earth and Space Sciences,
Chalmers University of Technology, Gothenburg,
Sweden

Definition

VY Canis Majoris is a massive, red, supergiant star, which is evolving toward a supernova

Warm Season Flows

- [Slope Lineae, Recurrent](#)

Warrawoona Group

Martin J. Van Kranendonk
School of Biological, Earth and Environmental
Sciences, University of New South Wales,
Sydney, NSW, Australia

Definition

The 3.52–3.43 Ga-old Warrawoona Group is a ~12 km-thick succession of dominantly volcanic and minor sedimentary rocks forming the base of the Pilbara Supergroup in the Pilbara Craton, Western Australia. It is famous for hosting the world's oldest evidence of life, as ► [stromatolites](#), ► [microbially induced sedimentary structures](#) and molecular remnants in bedded sedimentary rocks of the ca. 3.49 Ga Dresser Formation, probable ► [microfossils](#) in chert-barite hydrothermal feeder veins associated with the Dresser Formation, and other microfossils in bedded chert from the overlying ca. 3.47 Ga Mount Ada Basalt.

Cross-References

- [Apex Basalt, Australia](#)
- [Apex Chert](#)
- [Apex Chert, Microfossils](#)
- [Archaean Traces of Life](#)
- [Microfossils](#)
- [North Pole Dome \(Pilbara, Western Australia\)](#)
- [Pilbara Craton](#)
- [Stromatolites](#)

WASP

Coel Hellier
Keele University, Keele, UK

Keywords

Exoplanets · Exoplanet transits · Hot Jupiters ·
Transit surveys

Acronyms

WASP Wide Angle Search for Planets

Definition

WASP: A ground-based survey covering most of the sky looking for exoplanet transits.

History

After trials with a single-camera “WASP0” prototype, the first WASP survey instrument was installed in 2003 at the Observatorio del Roque de los Muchachos on La Palma (Pollacco et al. 2006). It operated during 2004 as a manned facility, equipped with 5 cameras based on Canon 200-mm, f/1.8 lenses backed by 2x2k CCDs. Data acquired led to the first three WASP planet discoveries: WASP-1b, WASP-2b, and WASP-3b (Collier-Cameron et al. 2007; Pollacco et al. 2008). A companion facility, WASP-South, was then constructed at the Sutherland station of the South African Astronomical Observatory. From 2006 onwards, both WASP-South and the upgraded La Palma “SuperWASP” ran as robotic, eight-camera facilities. In 2012, WASP-South switched to 85-mm, f/1.2 lenses in order to survey brighter stars. The WASP facilities continued operating until 2014. Overall, the WASP project has led to the discovery of over 190 gas-giant exoplanets transiting stars brighter than visual magnitude $V \sim 13$.

Overview

The WASP survey (Wide Angle Search for Planets), which operated from 2004 to 2014, was one of a number of ground-based surveys aimed at surveying large regions of sky in order to detect the dips in stellar light-curves caused by transiting exoplanets. Similar projects, overlapping with WASP in both aims and timescale, included HATnet, the TrES survey, the XO project, the OGLE microlensing project, KELT-North and KELT-South, the Qatar survey, MASCARA, and the HATSouth project. Until the launch of the TESS spacecraft in 2018, the space-based transit surveys (first CoRoT, then Kepler, and Kepler’s

K2 extension) were limited to relatively small fields of view. Thus the ground-based projects were the first to survey much of the sky, and, while lacking the space-quality photometry needed to detect rocky planets, were capable of detecting the $\sim 1\%$ dips caused by transits of Jupiter-sized gas giants. In particular, the class of “hot Jupiters” were easy prey, partly because their short-period orbits mean that they transit often, and also because they are often bloated in size, owing to irradiation and tidal effects, and so produce deeper transit dips than a “cold” Jupiter. Indeed, the bloated radii of short-period gas giants meant that Saturn-mass and even Neptune-mass planets could be found. Since bloated, fluffy exoplanet atmospheres are the easiest to characterize with spectral analysis, many of the gas giants found by WASP and other ground-based surveys have become prime targets for the detailed study of exoplanets and their atmospheric compositions (e.g., Spake et al. 2018).

The WASP project operated two 8-camera arrays, SuperWASP on La Palma in the Northern hemisphere, and WASP-South in South Africa. They monitored sets of fields every clear night, observing each field every 10–15 mins. Between 2004 and 2014, they recorded seven million CCD frames, producing 580 billion photometric data points on over 30 million different stars. Automated searching followed by human assessment led to 2000 transiting-planet candidates. Only a tenth of these would prove to be real (the remainder being transit mimics, such as blended eclipsing-binary stars). Discovering the planets thus required a follow-up campaign involving hundreds of nights of telescope time. In the South, the CORALIE spectrograph on the 1.2-m Swiss/Euler telescope combined with photometry from the 0.6-m TRAPPIST telescope to pursue the WASP-South candidates (e.g., Hellier et al. 2012). In the North, the follow-up was mainly with the SOPHIE spectrograph at the Observatoire de Haute-Provence. In total, over 190 exoplanets have been discovered by WASP, most with host stars of visual magnitude between $V = 9$ and $V = 13$.

Notable WASP discoveries include: WASP-8b (Queloz et al. 2010; a hot Jupiter in a highly

eccentric orbit), WASP-12b (Hebb et al. 2009; with material boiling off its surface, and with an orbit showing tidal decay), WASP-17b (Anderson et al. 2010; discovered in a retrograde orbit, and bloated to 2 Jupiter radii), WASP-18b (Hellier et al. 2009; with the strongest planet-star tidal interaction of any known planet), WASP-19b (Hebb et al. 2010; the shortest-period hot Jupiter), WASP-30b (Anderson et al. 2011; the first transiting brown dwarf discovered), WASP-33b (Collier-Cameron et al. 2010; the first hot Jupiter found transiting an A-type star), WASP-43b (Hellier et al. 2011; the closest-orbiting hot Jupiter, and prime target for “phase curve” observations), WASP-47b (Hellier et al. 2012; which K2 found to have two rocky companion planets), WASP-76b (West et al. 2016; a prime target for atmospheric characterization, with “iron rain”), WASP-80b (Triaud et al. 2013; a hot Jupiter transiting an M-type star), WASP-107b (Anderson et al. 2011; a bloated, Neptune-mass planet where metastable helium was discovered), WASP-103b (Gillon et al. 2014; a planet on the edge of tidal disruption), WASP-121b (Delrez et al. 2016; an archetypical “ultra-hot Jupiter”), and WASP-166b (Hellier et al. 2019; a bloated, Neptune-mass planet transiting a bright star).

Cross-References

- [CoRoT 7b](#)
- [Exoplanets, Discovery](#)
- [HATnet](#)
- [Hot Jupiters](#)
- [Hot Neptunes](#)
- [Kepler](#)
- [TESS](#)
- [Transit](#)
- [Transiting Planets](#)
- [TrES](#)

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Water

Henderson James Cleaves II

Earth-Life Science Institute (ELSI), Tokyo

Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,

Washington, DC, USA

Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

Keywords

Solvent · Phase diagram · Hydrogen bonding

Definition

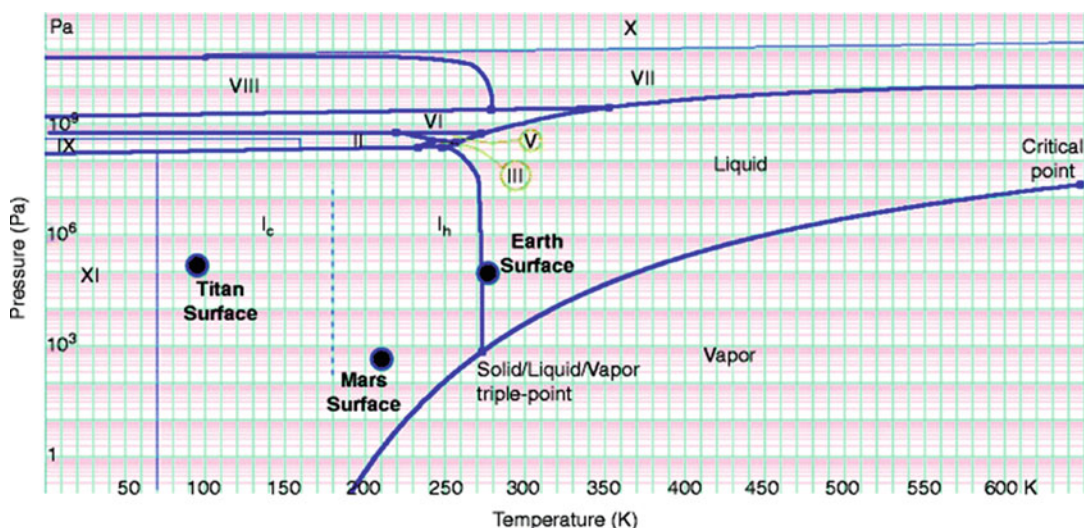
Water is a tasteless and odorless molecular compound formed from two atoms of hydrogen and one of oxygen (H_2O), being thus the oxide of hydrogen or the hydride of oxygen. As hydrogen and oxygen are themselves among the most abundant atoms in the Universe (#1 and #3, respectively), water is also an extremely abundant

molecule in the universe, being formed as a by-product in star-forming regions.

Overview

At standard atmospheric temperature and pressure (1 atm, 25 °C), pure water is a liquid. At the same pressure, water undergoes a phase transition to a solid (water ice) at 0 °C and a phase transition to a gas (water vapor) at 100 °C (see Fig. 1).

Liquid water, although it covers some 70% of the Earth's surface, and may occur in subsurface environments of other rocky planets such as Mars or some moons of the outer planets (e.g., Europa and Enceladus), and in the interiors of some asteroids and possibly transiently in comets where temperature and pressure conditions are sufficient to keep water in the appropriate region of its phase diagram, is rarely encountered in the universe (see ► [Water in the Universe](#)). Water occurs much more commonly in the gas phase in the interstellar medium, or as a solid in ices, either in icy planets or moons, comets and interstellar dust grains, or associated with hydrated mineral phases.



Water, Fig. 1 The pressure-temperature phase diagram of pure water. The various phases of water are indicated and Roman numerals used for some of the different possible phases of ice. Mean surface conditions on Mars, Earth,

and Titan are indicated. Under current atmospheric pressure, water ice on Mars' surface would sublime directly to the vapor

Due to the difference in electronegativity of the oxygen and hydrogen atoms, water molecules have a dipolar moment and are able to form intermolecular hydrogen bonds between molecules which contribute to its unusual properties, such as its high viscosity, boiling point, surface tension, heat of vaporization, specific heat capacity, and latent heat of fusion (see ► [Water, Solvent of Life](#)). These properties make water an especially good solvent for a wide range of molecules and contribute to its facilitation of chemical reactions and mineral weathering. Water's physical properties are also believed to contribute to the habitability of planets, as water is largely transparent in the visible region of the electromagnetic spectrum in which photosynthesis occurs, but considerably opaque in the UV and infrared regions, shielding organisms from radiation damage and contributing to the greenhouse effect that helps keep planetary surfaces warm, respectively.

Cross-References

- [Asteroid](#)
- [Enceladus](#)
- [Europa](#)
- [Greenhouse Effect](#)
- [Hydrogen](#)
- [Hydrogen Bond](#)
- [Ice](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Latent Heat](#)
- [Mars](#)
- [Water in the Solar System](#)
- [Water in the Universe](#)
- [Water, Solvent of Life](#)
- [Weathering](#)

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Water Activity

Victor M. Fernández

Institute of Catalysis, CSIC, Madrid, Spain

Keywords

Water · Vapor pressure · Temperature · Water availability

Synonyms

[Available water](#); [Free water](#)

Definition

Water activity, a_w , is a dimensionless parameter defined as the vapor pressure of water in a system (p) divided by that of pure water at the same temperature (p_o). It correlates with the proportion of water available for biological or chemical reactions and is related to the energy status of the water molecules in a given system (pure distilled water has $a_w = 1$).

Overview

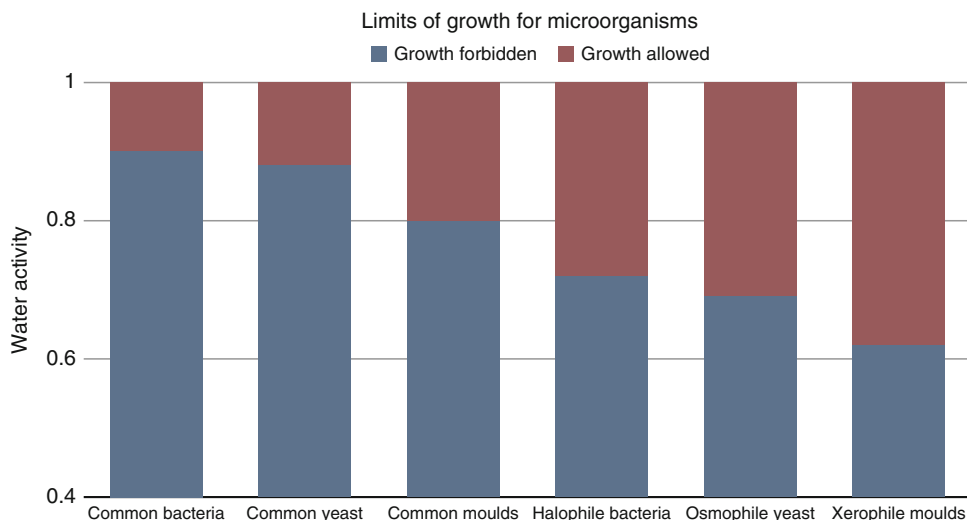
a_w measures how efficiently the water present in a system, including, for example, microbial cells, can take part in a reaction or in a physical process and is often also referred to as the “free” or “available water” in a system.

For an ideal solution,

$$a_w = \frac{n_1}{n_1 + n_2} = \frac{p}{p_0}$$

where n_1 refers to moles of water, n_2 refers to moles of solute, and p , p_0 refer to the vapor pressure of solution or solvent, respectively.

a_w is temperature dependent since it is associated with the amount of free, unbound water in the system and changes on the temperature of the system, which strongly affects parameters like



Water Activity, Fig. 1 Water activity limits for the growth of different microorganisms

water binding, water dissociation, and solubility of dissolved compounds. Water activity is related, in a nonlinear way, to moisture content at a given temperature, which is represented as a sorption isotherm.

a_w affects growth, sporulation, toxin production, and survival during storage of microorganisms. The bars in the figure indicate the limits of growth of microorganisms commonly present in foods. Common bacteria do not grow at water activities below 0.9, and no microbial growth occurs below 0.6. In some cases, when a_w limit for growth is reached, sporulation occurs. Therefore, water activity is an important parameter related to the control of bacterial growth and determines the shelf life of many foods. a_w values of foods are precisely measured with the help of capacitance hygrometers or dew-point hygrometers, both of which are commercially available.

At high a_w values, food substances tend to support more microorganisms; therefore, lowering the water activity by drying or salting foods is an important way to preserve food since plasmolysis occurs when cells are subjected to lower a_w as a result of an increase in osmotic pressure. In addition, low a_w can help to reduce the rates of adverse reactions to food preservation such as

browning, protein denaturation, fat oxidation, or vitamin degradation. Common solutes that decrease a_w are NaCl, KCl, glucose, sorbitol, fructose, and sucrose. In contrast, bacteria and mold can synthesize soluble compounds like amino acids, sugars, glycerol, or charged ions like K^+ that accumulate in the cytoplasm and contribute to an increase in a_w . However, the minimum a_w for growth is affected by other factors such as pH, temperature, nutrient availability, and presence of antimicrobial substances (Fig. 1).

Cross-References

► [Water](#)

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Water in the Solar System

Therese Encrenaz¹ and Tilman Spohn²

¹LESIA, Observatoire de Paris - Section de Meudon, Meudon, France

²International Space Science Institute, Bern, Switzerland

Keywords

Astrochemistry · Solar system · Water

Synonyms

H₂O

Definition

Water is ubiquitous in the Universe and also present in all kinds of solar-system objects. This molecule, made of two ► [hydrogen](#) atoms and one oxygen atom, has played a key role in the formation of solar-system bodies and in the evolution of the ► [terrestrial planets](#).

Overview

Water is one of the most abundant molecules of the Universe, which is a consequence of the high cosmic abundance of its two components, hydrogen and oxygen (see ► [Water in the Universe](#)). It is a major component in the solar system, especially in its outer parts where it is mostly in the form of ice. The ► [Earth](#) is presently the only place where water is present in substantial quantities in all of its three states: solid, liquid, and vapor. Water vapor and ice can be found on ► [Mars](#); on the Moon and Mercury, water ice may be present in permanently shaded craters near the poles. Water can also be present as a minor constituent in rock both on the surface and the interior. In a planetary interior, water may have

a major effect on the rheology and the heat transfer mechanism and rate. For the upper Earth mantle, the concentration may differ from that in the Earth's lower mantle. The concentration of water in the interior of the terrestrial planets is not well known but has been speculated to possibly reach values similar to the Earth mantle at least for Mars.

Apart from its high abundance, water has specific chemical properties that explain its key role in astrochemistry. Due to its large dipole moment, liquid water is a very good solvent, which makes possible the development of complex chemical reactions. In addition, water is liquid over a large temperature range, as compared to other molecules. In a ► [protoplanetary disk](#), as in the protosolar disk, water is the first simple molecule to condense as the temperature decreases (beyond the ► [snow line](#)). Another interesting property is the density of water ice which is lower than that of liquid water; as a consequence, a liquid ocean can be protected by an icy upper layer if the temperature drops below the water freezing point at the surface.

Water has several isotopes (HDO, D₂O, H₂¹⁷O, H₂¹⁸O). The most interesting one is HDO ("heavy water"), observations of which are used in the outer solar system to probe the temperature of the medium where the molecule has been formed. Indeed, as observed in the ► [interstellar medium](#) and as studied in the laboratory, at low temperatures, HDO is enriched versus H₂O with respect to their protosolar abundances, as a result of ion-molecule or molecule-molecule reactions. In the case of terrestrial planets, the ► [D/H \(deuterium/hydrogen\) ratio](#) is also a diagnostic of an early atmospheric escape.

Another interesting property of water is linked to its two states, ortho and para, associated to the spin directions of its two hydrogen atoms. The two states have slightly different spectroscopic transitions, which can be used to determine the ortho/para ratio (OPR) of the molecule. This provides another diagnostic of the formation temperature of the molecule; such measurements have been made in the case of comets.

The Formation Scenario of the Solar System

It is generally accepted that the solar system was formed after the collapse of an interstellar rotating cloud that gravitationally fell into a disk. The proto-Sun was formed at the center from the accretion of the surrounding matter. In the turbulent disk, particles accreted through mutual collisions; some ► [planetesimals](#) grew and formed planets, attracting by gravity the neighboring particles.

Within the protosolar disk, the amount of solid matter available to form planetesimals depends upon the temperature. Near the Sun, at temperatures of a few hundred kelvin, only heavy elements (silicates, metals) are in solid form. Because these elements are formed by stellar nucleosynthesis, their abundance is very small, as shown by the table of cosmic abundances. Planets formed at these heliocentric distances are dense and relatively small: they are the terrestrial planets, also called rocky planets. In contrast, at larger heliocentric distances, where the temperature drops below about 200 K, more abundant molecules start to form ices. The first (and also the most abundant) one is water. Other simple molecules (NH_3 , H_2S , CO_2 , CH_4 , etc.) condense at larger heliocentric distances. Rock-ice cores are formed, with a mass that can reach 10–15 terrestrial masses. Above this threshold, the gravity field of these cores is sufficient to capture the surrounding gas, mostly made of hydrogen and helium. This process leads to the formation of ► [giant planets](#), with a huge mass and volume but a low density. It also explains the presence of the regular satellites, found in the equatorial plane of the giant planets.

In the planetary formation process, water plays a key role, as the distance where the molecule condenses marks the limit, at about 180 K, between the terrestrial and giant planets. This limit, called the snow line, was at about 3–4 AU from the Sun at the time of the planet's formation. Presently, after the cooling of the protosolar disk, the limit is closer to about 2 AU, as observed from the water outgassing of comets.

Water in Comets

The volatile content of comets can amount to about 80% of water by mass. The study of water is very informative for cometary research. The analysis of the water rotational or rotational-

vibrational transitions at high spectral resolution allows the study of the kinematics and the physical properties of the inner coma. In addition, as mentioned above, the measurement of D/H and the ortho/para in comets brings information about their formation temperature. The ortho/para ratio, measured in a few comets originating from the ► [Oort cloud](#), indicates a low formation temperature, typically around 30 K or below. The D/H ratio, also measured so far on a few Oort cloud comets, is 3×10^{-4} , that is, 15 times the protosolar value and 2 times the terrestrial value. The large enrichment, as compared to the protosolar value, is a consequence of the ► [deuterium](#) enrichment in the ice at low temperatures. The enrichment with respect to the terrestrial value is an important diagnostic, as it shows that Oort cloud comets cannot be the only reservoir for the terrestrial water. The D/H ratio in the terrestrial oceans is actually close to the D/H ratio measured in the outer edge of the main asteroid belt, which could be the main reservoir for the water on Earth. An alternate hypothesis was brought in 2012 with the measurement of D/H in a Kuiper belt comet, 103P/Hartley 2, by the Heterodyne Instrument for the Far Infrared (HIFI) heterodyne spectrometer of the Herschel Space Observatory. The inferred D/H ratio was found equal to the terrestrial value, which suggests that Kuiper Belt comets might be, at least partly, at the origin of the ocean water.

Water in the Giant Planets

Water is present both in the interior and the upper stratospheres of the ► [giant planets](#). Water vapor has been detected in the lower ► [tropospheres](#) of ► [Jupiter](#) and ► [Saturn](#) by infrared spectroscopy around 5 μm (a spectral window where the radiation comes from deep levels) and, in addition, by the Galileo probe in the case of Jupiter. In the case of ► [Uranus](#) and ► [Neptune](#), tropospheric water vapor cannot be detected because H_2O is in the form of ice at observable levels (a few bars).

A surprising discovery was the detection of water vapor in the upper ► [stratospheres](#) of giant planets and ► [Titan](#) by the ISO satellite, in 1997. The water emission lines were later analyzed in more detail by the Herschel Space Observatory, in operation between 2009 and 2013. The thermal vertical profiles of the giant planets all exhibit a

tropopause where the temperature, ranging between 50 and 110 K, is always below the water freezing temperature. As a result, the water observed in their stratospheres cannot come from their interior, as the tropopause acts as a cold trap. Thus, the stratospheric water of the giant planets and Titan must be of external origin. This origin could be local (rings, satellites) or interplanetary (comets, micrometeorites). Following the Herschel observations, it appears that the origin of stratospheric water in Jupiter is probably the result of the collision of comet Shoemaker-Levy 9 with the planet in 1994. In the case of Saturn, the detection and analysis of the water torus of Enceladus by Herschel indicates that this torus is the most plausible source for stratospheric water on Saturn but not on Titan.

Water in the Rings and Outer Satellites

All ring systems of the giant planets are mostly made of water ice, with the exception of the tenuous ring of Jupiter, fed by inner satellites. In the case of Uranus and Neptune, the rings are dark, probably as a result of a hydrocarbon deposit due to their irradiation by high-energy particles (see ► [Planetary Rings](#)).

The Galilean satellites Ganymede and Callisto have major shares of water, about one-third by mass for both. ► [Europa](#) has a relatively thin water layer of 150 km thickness, equivalent to about 8 wt.%. No water ice has been found on ► [Io](#), Jupiter's closest satellite, which is subject to strong tidal forces and exhibits active volcanism. Europa, the next satellite in distance from Jupiter, is of particular interest for astrobiology, as it is almost certain to have an internal ocean of saltwater in contact with a rocky crust at its bottom. Ganymede and Callisto also are likely to have internal oceans, but these are sandwiched between ice layers thus probably limiting the supply of nutrients. In addition, the ice shell above the ocean is likely to be around 100 km or thicker, while for Europa the ice shell is only a few tens of kilometers thick on average. Some models even have an ice shell only a few kilometers thick for Europa. Water ice is the main constituent of most outer satellites as indicated by their average densities close to $1,000 \text{ kg m}^{-3}$. In the case of ► [Titan](#), water ice is also present in its interior

and at its surface, as the boulders shown by the images of the ► [Huygens](#) probe are most likely made of water. Another interesting outer satellite is ► [Enceladus](#), which probably feeds the E-ring of *Saturn*, where active ► [cryovolcanism](#) (mostly driven by water) has been discovered by the ► [Cassini](#) orbiter. As mentioned above, the water torus of Enceladus was detected for the first time by the Herschel Space Observatory.

The Role of Water in the Evolution of Terrestrial Planets

The atmospheres of ► [Venus](#), the Earth, and Mars show remarkable differences in their physical conditions, with surface temperatures and pressures ranging from 730 K and 90 bars (Venus) to about 230 K and 0.06 bar (Mars). In between, the Earth, with a surface temperature of 288 K and a pressure of 1 bar, has the capability of keeping water in the form of liquid oceans. Still, the primitive atmospheres of the three planets probably had a similar composition, with a large fraction of CO_2 , a small percentage of N_2 , and, possibly, substantial amounts of water. It has been suggested that Venus and Mars had a large initial water content based on two pieces of evidence. First, the D/H ratio of these planets is, with respect to the terrestrial value, substantially enriched in the case of Venus (by a factor at least 120) and still significantly enriched in the case of Mars (a factor 5). This has been interpreted as the signature of massive early water outgassing, especially in the case of Venus, although other interpretations are possible. The second diagnostic is, in the case of Mars, the evidence from the surface relief and mineralogy (detection of phyllosilicates and sulfates) that liquid water has been present at the Martian surface in its early history.

Why did the terrestrial planets evolve toward so different states? Water may have played a major role in these divergences. Indeed, the surface temperature of these planets now is such that water has to be in the form of vapor on Venus and solid + vapor on Mars (although it could be liquid for some time before it evaporates) but is mostly liquid on the Earth. In the past history of Venus, water may have been liquid at its surface, due to the fainter radiation of the young Sun. As the solar radiation increased to reach its present level, water

would have evaporated. The atmosphere, with both water vapor and ► [carbon dioxide](#), would have experienced a huge ► [greenhouse effect](#) which led to the present conditions.

In the case of Mars, another factor must be considered: the mass of Mars is about one-tenth of the terrestrial mass. Due to the lower internal energy and a smaller gravity field of the planet, the primitive atmosphere of Mars must have been more tenuous than those of Venus and the Earth. Still, it must have been thicker than today and also warmer to allow the presence of liquid water and account for the enriched D/H ratio. The Martian atmosphere may have escaped when the internal activity ceased to supply water vapor to the atmosphere and the internal dynamo ceased to supply a global magnetic field. The atmosphere might also have lost the water as a consequence of a major impact.

In the case of the Earth, atmospheric water condensed very early to form the oceans, as shown by the presence of zircons in Archaean rocks in Western Australia. The atmospheric carbon dioxide was trapped in the oceans in the form of calcium carbonate, which led to a moderate greenhouse effect and allowed the temperature to stay more or less constant over the planet's history. The Earth probably experienced phases of almost complete glaciations, especially at the beginning of its history when the solar radiation was fainter; however, the planet's internal energy must have been sufficient to warm the atmosphere through volcanism.

Conclusions and Open Questions

There are many open questions regarding water in the solar system. In the case of comets, what is the D/H ratio for ► [Kuiper belt](#) comets? In the case of the giant planets, what is the O/H value below the clouds? In the case of Jupiter, the Galileo probe entered a dry region of subsidence and its O/H measurement was not representative of the whole planet. In the case of Mars, the search of water is an ongoing challenge for future space missions.

The special role of water in the formation and evolution of the solar system must be the consequence of its unique physical and chemical properties; we can thus expect water to play a similar key role in extrasolar planetary systems.

Cross-References

- [Carbon Dioxide](#)
- [Cassini](#)
- [Comet](#)
- [Cryovolcanism](#)
- [Deuterium](#)
- [Deuterium/Hydrogen Ratio](#)
- [Dynamo, Planetary](#)
- [Earth](#)
- [Enceladus](#)
- [Europa](#)
- [Giant Planets](#)
- [Greenhouse Effect](#)
- [Heat Transfer, Planetary](#)
- [Huygens](#)
- [Hydrogen](#)
- [Interstellar Medium](#)
- [Io](#)
- [Isotope](#)
- [Jupiter](#)
- [Kuiper Belt](#)
- [Mars](#)
- [Neptune](#)
- [Oort Cloud](#)
- [Phyllosilicates, Extraterrestrial](#)
- [Planetary Rings](#)
- [Planetesimals](#)
- [Protoplanetary Disk](#)
- [Protostars](#)
- [Rheology, Planetary Interior](#)
- [Satellite or Moon](#)
- [Saturn](#)
- [Snow Line](#)
- [Terrestrial Planet](#)
- [Titan](#)
- [Uranus](#)
- [Venus](#)
- [Water in the Universe](#)

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Water in the Universe

Cecilia Ceccarelli

Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), Université Grenoble Alpes, CNRS, Grenoble, France

Keywords

Astrochemistry · Interstellar medium

Synonyms

H₂O

Overview

► **Water** is one of the most abundant molecules in the Universe. This is not surprising, as water is made up by two of the most abundant elements in the universe, hydrogen and oxygen. Water is widespread in the molecular phase of the ► **interstellar medium** (see also ► **Molecular Clouds**). It is found in both the coldest and warmest regions of space. A very important fraction ($>1/3$) of all elemental oxygen not trapped into the refractory component of the interstellar grains is locked into water molecules, either as ice mantles on the interstellar grains or in the gas phase.

► **Water** in the solar system is covered in a separate entry.

Water as Ice and Gas

In the interstellar medium, water molecules are found in the following states:

1. In cold (≤ 100 K) molecular clouds, oxygen and hydrogen atoms stick onto the dust grain surfaces and form water ices around the refractory component of the grains (composed by silicates and carbonaceous material; see ► **Interstellar Ices**). These ices are also called grain mantles. It is estimated that about one-third or more of the elemental oxygen is locked into the grain mantles.
2. In warm (≥ 100 K) regions, usually associated with star-forming regions (see also ► **Star Formation: The Observations**), ices are sublimated and the water molecules are released into the gas. Important regions where this phenomenon occurs are the ► **hot cores** and ► **hot corinos**, regions surrounding new forming stars.
3. Water molecules can also be sputtered from the grain mantles in mild to violent (<100 km/s) shocks (see also ► **Shock, Interstellar**). The amount of water molecules released into the gas phase depends on the shock velocity, and it can reach a substantial fraction (10% or more) of that contained in the grain mantles. If extremely violent, the shock can destroy completely the grains, and molecules from the whole mantle would be, in this case, released into the gas phase.
4. Another mechanism thought to release the frozen water molecules from the grain mantles to the gas phase is the ► **photodesorption** of the ices. Ultraviolet (UV) photons, usually those emitted by young stars, hit the grains and lift off water molecules at the surface of the ice coating. The mechanism can be relatively efficient in the presence of strong UV fields.
5. In very warm (≥ 220 K) regions, reactions forming water in the gas phase become very efficient and water molecules can contain all the oxygen in the gas phase not locked into the CO molecules. Typical regions where this phenomenon occurs are (some) hot cores, hot corinos, and shocks.

How water is formed in the various situations, following which formation and destruction pathways, is still a matter of debate and will not be further described here. Both the excitation and the chemistry of water in various astronomical

environments are discussed by van Dishoeck et al. (2014).

Deuterated Water, HDO

The chemistry associated with the formation of the water isotopologue HDO, where a deuterium atom substitutes one of the two hydrogen atoms, is particularly relevant in the astrobiology context for two reasons:

1. HDO lines are more easily observable than H_2O astronomically (see ► [Basic Methodology](#) below) and can, therefore, be used to probe the presence of water in different circumstances.
2. The HDO/ H_2O abundance ratio is a valuable probe of the conditions prevailing when water is formed: for example, observations of the HDO/ H_2O abundance ratio in ► [comets](#) and terrestrial oceans provide important clues on the solar system's history (see also Ceccarelli et al. 2014 and ► [Oceans, Origin of](#)).

In the Universe, there is one deuterium atom for about every 31,000 hydrogen atoms (see ► [Deuterium](#)). Therefore, HDO should be 62,000 times less abundant than H_2O . However, in a cold medium, the HDO/ H_2O ratio can be enhanced by several orders of magnitude and reach the level of a few percent. This is caused by a peculiar chemistry that takes place in cold ($\leq 20\text{--}30\text{ K}$) environments and is basically due to the difference in the quantum mechanical ground-state energy of a deuterated species relative to its nondeuterated equivalent (see ► [Isotopic Fractionation \(Interstellar Medium\)](#) and Ceccarelli et al. 2014). In practice, large ($>10^{-3}$) HDO/ H_2O ratios can only be produced in cold ($< \text{about } 20\text{--}30\text{ K}$) gas or in warm ($>200\text{ K}$) gas illuminated by a strong UV field. In addition, exchange of deuterium (in the two directions, from and to) with other deuterated species may also occur in the water ice on interstellar grain surfaces.

Observations provide upper limits to the degree of water deuteration in interstellar water ice: HDO is less than about 1% relative to H_2O . On the contrary, HDO has been observed

as high as a few percent in the gaseous phase, specifically in hot cores, hot corinos and protostellar molecular shocks (see also ► [Chemistry](#)). In most comets, the HDO/ H_2O ratio has been measured to be around $1\text{--}5 \times 10^{-4}$, i.e., more than ten times larger than the elemental deuterium/hydrogen ratio.

Water During the Formation of a Solar-Type Star and Associated Planetary System

It is worth summarizing the cycle of water during the star formation process and, in particular, during the formation of a solar-type star and its planetary system (see also [Star Formation](#); ► [Protoplanetary Disk](#), [Chemistry](#); and van Dishoeck et al. 2014 and Caselli and Ceccarelli 2012). The following points give a brief summary, beginning with the dense core in a molecular cloud that will form the star:

1. During the pre-collapse phase, water molecules are largely frozen onto the grain mantles and only a very small fraction remains in the gas-phase, with an abundance of $\text{H}_2\text{O}/\text{H}_2 < 10^{-9}$. Since the medium is very cold ($<10\text{ K}$), it is believed that the HDO/ H_2O ratio in the water ice is enhanced, but no observations can prove (or disprove) that, so far.
2. Once the collapse starts, matter falls from the envelope toward the central newborn star, releasing the gravitational energy as radiation. Matter in the innermost envelope heats up, and the grain mantles formed during the pre-collapse phase sublime. In the hottest regions, where the gas temperature exceeds about 250 K , water is also formed by gas-phase reactions (see above). Large abundances ($\text{H}_2\text{O}/\text{H}_2 > 10^{-5}$) have been measured, although the exact values need confirmation.
3. Simultaneously with the collapse, a relevant fraction of matter is ejected out from the center at large velocities ($>100\text{ km/s}$). When the outflowing gas hits the surrounding medium, various shocks are created, the gas is compressed and heated, and water is again either sputtered from the grain mantles or formed in the gas phase. The shocked gas cools down once the shock passes and again forms ices.

- In this case, the HDO/H₂O ratio of the ices is relatively small, as warm water condenses fast on the ices.
4. As time passes, the envelope surrounding the newborn star is dispersed and only the surrounding protoplanetary disk remains. The innermost regions are warm and water ice sublimates. However, a large fraction of the disk is cold and water is frozen onto the grain mantles. Here the intense UV field emitted by the newborn star plays a key role in releasing water into the gas phase (via photodesorption; see above) and also in enhancing the HDO/H₂O in the innermost, warm gas. Water vapor has been measured with large abundances, H₂O/H₂ ≤ 10⁻⁴, in the innermost regions of the disk, whereas only upper limits exist of the abundance in the outermost, cold disk, H₂O/H₂ < 10⁻⁶.
 5. Dust grains in the protoplanetary disks coagulate into the planetesimals that eventually will form larger bodies: the bulk of rocky planets, asteroids, and comets. In the disk midplane, the temperature is low and water is frozen again onto the grains. As in the pre-collapse phase, the HDO/H₂O ratio is thought to be greatly enhanced in the ice of the outermost disk. Finally, ices in the comet formation region of the disk may also have enhanced HDO/H₂O ratios caused by reactions between neutrals involving OH and OD. So far, no observations exist of the HDO/H₂O in disks.

Water in the Distant Universe

Water has been detected in several external galaxies, notably by observation of the water maser line at 22 GHz and, in fewer cases, by observations of water thermal (non-masing) lines. The most distant galaxy where water has been detected so far lies at a redshift of 4.7.

Basic Methodology

With the exception of in situ experiments, namely, probes sent to the Moon or Mars or comets, water in the universe is detected and measured indirectly by the photons that it absorbs or emits, as for any

other molecule in space. What photons, namely, at what wavelengths, are emitted or absorbed depends on the water status, whether in the gas phase or as solid ices. Water ice has specific bands in the near infrared (see also ► [Infrared Spectroscopy](#)), which are typically a fraction of a micron wide. On the contrary, gaseous water has lines in the millimeter to infrared wavelength range that are much narrower, typically a few megahertz wide. Since water is present in the Earth's atmosphere, the detection of water in the universe usually requires observations from space telescopes. So far, there have been a few telescopes that have provided observations of water in space: the ► [Infrared Space Observatory](#) (ISO), the Submillimeter Wave Astronomy Satellite (SWAS), the Odin telescope, the ► [Spitzer Space Telescope](#), and the Herschel Space Observatory. In addition, a few water ► [maser](#) lines can be observed with ground-based telescopes, notably the 22 GHz line in the radio spectral region. In this context, the isotopologue of water, HDO, which has several lines accessible with millimeter and submillimeter ground-based telescopes, provides a very precious pathway to probe the presence of water. Similarly, the even rarer isotope D₂O has transitions observable with ground-based telescopes.

In general, water ice is observed in absorption, whereas gaseous water can be in absorption or emission, depending on the temperature and density of the gas and dust. Water ice (whose bands are at about 3, 6, and 13 μm) can only be observed when a bright infrared source lies behind the gas cloud. The same applies also in the case of water in cold gas: the photons emitted by the bright source behind (usually emitted by the dust) are absorbed by the water molecules between the infrared or submillimeter source and the telescope, with the result that the spectrum shows a dip at the wavelengths of the water bands or lines.

The intensity of the water lines in emission, but also in absorption, depends on the gas (and dust) temperature and density, in addition to the abundance of the water. In practice, estimating the abundance of gaseous water from observations is a relatively complex problem, which critically depends on our knowledge of the microphysics

of the water molecule and its mixing with dust. It involves computing exactly how the energy is passed by collisions from the H₂ molecules to the internal energy of the H₂O molecule and vice versa as well as the radiative pumping from dust photons. The former is a complex problem of quantum mechanics that only recently has been correctly solved and addressed.

- [Protoplanetary Disk, Chemistry](#)
- [Shock, Interstellar](#)
- [Spitzer Space Telescope](#)
- [Star Formation, Observations](#)
- [Water](#)
- [Water in the Solar System](#)
- [Water, Delivery to Earth](#)
- [Water, Solvent of Life](#)

Future Directions

Since space telescopes are required to observe water lines, a lot still remains to be understood about water in the Universe: its chemistry and role during the star formation process and, in general, in the ► [interstellar medium](#), both galactic and extragalactic. In the near future, the James Webb Space Telescope, launched in the winter 2021, will provide new data on the water ices as well as the water vapor abundance and status in the warmest regions of weak, very young protostars and protoplanetary disks. We will know much more about the cycle of water, in particular during the star formation process, including how water is formed and destroyed during each phase. Ultimately, this will help us to understand the heritage received by the Earth from the very first phases of formation of our solar system.

Cross-References

- [Comet](#)
- [Europa](#)
- [Herschel Mission](#)
- [Hot Core](#)
- [Hot Corino](#)
- [Infrared Astronomy](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Mars](#)
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- [Oceans, Origin of](#)
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Water Planet

- [Ocean Planet](#)

Water World

► Ocean Planet

Water, Delivery to Earth

Reika Yokochi^{1,2} and Avi M. Mandell³

¹Department of Geophysical Sciences, The University of Chicago, Chicago, IL, USA

²Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL, USA

³NASA Goddard Space Flight Center, Greenbelt, MD, USA

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Comets · Hydrodynamic escape · Impact degassing · Isotope fractionation · Missing xenon · Primitive meteorites · Planetary accretion · Solar nebula

Synonyms

H₂O

Definition

The origin of the Earth's water is one of the most important questions in determining the prerequisites for a habitable planet. Calculations of the temperature of protoplanetary material at the Earth's orbital radius have suggested that the Earth's original water content may have been very low. The primitive Earth may therefore have needed a mechanism to deliver water-rich material from the outer Solar System. Current theory suggests that contributions from inward-scattered water-rich asteroids during formation could provide the necessary water, but other models for water delivery cannot be currently ruled out.

Overview

Hydrogen and oxygen forming water molecules on the present-day Earth could have been delivered in several different forms during the planetary accretion. Because there is no direct evidence of water delivery to the Earth, the origin of water can only be addressed by indirect approaches. Astrophysical models and observations of extrasolar protoplanetary disks provide information on possible processes occurring during planetary accretion. The actual processes that were significant to the evolution of the Earth need to be identified based on the chemical and isotopic records obtained from meteorites, cometary comae, interplanetary dust particles (IDPs), planetary atmospheres and the Sun, as well as the Earth itself.

In a star-forming gas disk, condensation of the nebula gas separates gaseous volatile elements from refractory elements depending on the heliocentric distance (thus on the temperature of the region). A condensation front for water ice called “snow line” was located around 2.7 AU in the early solar system. The condensates were “rocky” (dry) near the Earth's orbit because water remained in the vapor phase, whereas “icy” (water-rich) objects such as ► [comets](#) develop outside the snow line. Volatile-rich rocky materials, such as phyllosilicate minerals (i.e., hydrated clay minerals), occupy the intermediate region. The dust grains coagulated and accreted to form planetesimals, asteroids, and eventually planets while the nebula gas dissipated. As the protoplanet grew in size, the impact velocity of accretion increased. This caused volatilization of the colliding objects. The volatiles released at the surface of the accreting planet were lost to the space until the gravitational energy of the planet exceeded the kinetic energy of gas constituents. If the latter condition was fulfilled before the dissipation of the Solar nebula, the planet also captured hydrogen-dominated nebula gases. Hydrostatic stability of the proto-atmosphere could be disturbed by events such as large impacts and intense UV radiation from the T-Tauri phase of the young Sun, which resulted in erosion of the early water- or hydrogen-bearing atmosphere.

Numerous physical parameters remain unconstrained in this context, such as the feeding zone of the Earth, the rate of protoplanet growth, and the relative timing of the events. Being volatile, the behaviors of water and hydrogen are sensitive to physical and chemical conditions that are controlled by these factors. Moreover, the presence of water can significantly affect the fate of the planet. Deciphering the delivery and origin of water on Earth therefore involves detailed understanding of planetary evolution, which is essentially an identical problem to the origin of terrestrial atmosphere. Further discussion on the origin of water on Earth can be found in Morbidelli et al. (2000), Dauphas et al. (2000), Abe et al. (2000), Drake (2005), Marty and Yokochi (2006), and Mottl et al. (2007).

Basic Methodology

There are three categories of approaches for studying the origin of water on Earth: (1) numerical simulation that tracks the fate of condensed solid in the early solar system (Morbidelli et al. 2000; Ciesla and Lauretta 2005; Gomes et al. 2005), (2) modeling of the proto-atmosphere aimed to reveal the fate of volatile elements on accreting planets (Zahnle et al. 1990; Abe et al. 2000; Ikoma and Genda 2006), and (3) comparative isotopic and elemental studies of terrestrial and extraterrestrial materials, as well as mass balance constraints based on them (Pepin 1991; Dauphas et al. 2000).

Key Research Findings

Source of Water and Heliocentric Migration of Objects

In the absence of water in a solid phase within the region of the Earth's orbit, it is necessary either to capture water in gas phase or to bring in a water-bearing phase from the outer Solar System. Dynamical simulations of planetary accretion in the Solar System demonstrated that a few large, hydrous planetary embryos that grew in asteroidal belt could have migrated inward and delivered water to Earth, whereas the mean collision

probabilities of cometesimals with the Earth are too small to account for the delivery of water presently existing on our planet (Morbidelli et al. 2000). Due to gas drag, smaller (1 m size being the most efficient) phyllosilicate-bearing bodies could also be drifted inward during the early stage of accretion (Ciesla and Lauretta 2005). Both processes result in the delivery of carbonaceous chondrite-like materials to the Earth; thus, it would be difficult to distinguish these processes by chemical or isotopic records.

Finally, there are two possible ways of incorporating local (i.e., near the Earth's orbit) water in the Earth so that the heliocentric migration is not required. Stimpfl et al. (2006) showed that between one and three Earth ocean masses of water vapor from ambient solar nebula could be adsorbed into forsterite at temperatures of 500–700 K, which would subsequently be incorporated into planetesimals (Stimpfl et al. 2006; Drake 2005). The other possibility is a gravitational capture of hydrogen-dominated solar nebula gas as discussed below (Hayashi et al. 1979; Ikoma and Genda 2006).

Behavior of Water on the Earth During Planetary Accretion

As the size of the accreting body increases, both the impact velocity and the impact pressure of the projectile increase. Results of shock-loading experiments indicate that impact degassing of water from porous hydrous minerals starts at around 20 GPa, corresponding to the proto-Earth radius of 1500 km or 1.3% of its present mass (e.g., Lange and Ahrens 1982; Tyburczy et al. 2001). In order to retain the degassed water, the gravitational energy of the planet needs to exceed the kinetic energy of the water vapor. The kinetic energy of gas depends on the temperature, whereas the surface temperature of the accreting planet is controlled by the gravitational energy from accretion and radiative heat balance. These peculiarities are functions of the accretion rate, opacity, and blanketing effect of the atmosphere (Abe et al. 2000), which remains one of most enigmatic part of Earth's history. The same condition applies to the occurrence of gravitational capture of solar nebula. Ikoma and Genda (2006) set constraints on the mass of a planet with water

of nebular origin to be >0.3 of the Earth's mass based on a detailed model of the proto-atmosphere.

Giant impact and intense UV radiation from the Sun during its T-Tauri stage are currently recognized processes that could have disturbed the hydrostatic stability of the atmosphere, causing a substantial loss of the proto-atmosphere to the space (Kasting et al. 1984). Hydrodynamic escape can result in isotopic and elemental fractionations of gas species, and clear evidence of such event is recorded in the isotopic composition of ► [noble gases](#) in the atmosphere (► [Earth's Atmosphere, Origin and Evolution of](#)). The implications of this event to water delivery on Earth are as follows: (1) the current abundance of hydrogen (or water) represents only a small fraction of what had been once brought to the Earth, and (2) the D/H ratio of terrestrial hydrogen could have been significantly modified. A model investigation of D/H fractionation during hydrodynamic escape suggested that this ratio could be fractionated by up to a factor of 9 (Genda and Ikoma 2008). This result warns that direct comparison of this ratio to potential precursors could be misleading.

Elemental and Isotopic Constraints

The D/H ratios of potential precursors vary significantly, from the Solar nebula value (25×10^{-6}) to that of three comets from the Oort cloud (370×10^{-6}), whereas ► [carbonaceous chondrites](#) have intermediate bulk D/H ratios within $130\text{--}180 \times 10^{-6}$ (see Marty and Yokochi 2006 for review). This value is comparable to that of the Earth's ocean at 153×10^{-6} . This similarity is frequently used as a major argument for chondritic and against solar or cometary origin of water on the Earth. Given the possibilities of isotopic fractionation mentioned above, it merits further investigation.

The scenario of water delivery to Earth needs to be consistent with the observed abundances of other volatile elements on Earth. Noble gases in the atmosphere have two important characteristics that help understand the processes which affected volatile elements at the surface of the Earth: (1) the general enrichment in heavier isotopes and elements of noble gases compared to the Sun and (2) the “missing Xe” problem. Mars and

the Earth have a deficiency in Xe relative to other noble gases when compared to the meteoritic composition. Laboratory experiments simulating the formation of comets revealed that high concentrations of noble gases are trapped in amorphous water ice and exhibit a clear depletion in Xe relative to Kr (Bar-Nun and Owen 1998). Based on the low Xe/Kr ratio expected in comets, it has been suggested that the “missing Xe” problem of the terrestrial atmosphere could be a result of cometary contribution to the Earth (Owen et al. 1992). Note that the contribution of water from a comet could still be minor while significantly affecting the noble gas budget due to the high noble gas concentration in comets. Detailed modeling of mass balance and isotopic fractionation during hydrodynamic escape demonstrated that the cometary contribution could bring an exact outcome of noble gas elemental and isotopic composition of the terrestrial atmosphere (Dauphas 2003).

Future Directions

Several different approaches will further constrain the delivery processes of water to the Earth. Our knowledge of the D/H ratios and noble gas isotopic and elemental compositions in comets is limited at present, but is essential in order to estimate the cometary contribution to the terrestrial water budget. Investigating the volatile distribution of growing planets in extrasolar systems will help link the volatile budgets of potential precursors and the Earth and will provide useful constraints on dynamic modeling. Elemental and isotopic fractionation during the accretion and evolution of planets is a factor that should not be dismissed but has been little explored. A terrestrial inventory hydrogen including that present in the Earth's core is also indispensable for mass balance constraints.

Cross-References

- [Carbonaceous Chondrite](#)
- [Comet](#)
- [Deuterium/Hydrogen Ratio](#)
- [Earth, Formation, and Early Evolution](#)

- [Earth's Atmosphere, History of the Origins](#)
- [Hydrogen Isotopes](#)
- [Impact Degassing](#)
- [Late Heavy Bombardment](#)
- [Mantle Volatiles](#)
- [Noble Gases](#)
- [Oceans, Origin of](#)

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Water, Formation and Photodissociation

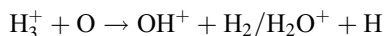
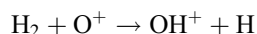
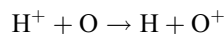
José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

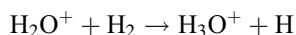
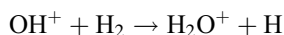
Synonyms

[H₂O](#)

Definition

Water vapor can be formed in gas phase and on the ice mantles of dust grains (see “► [Water in the Universe](#)”). Once formed, the molecule is mainly destroyed by photodissociation through the effect of UV photons. In gas phase the molecule can be formed in low-temperature ► [clouds](#) through the chain of reactions:





In this set of reactions, H_2 is formed on the surface of dust grains, and H_3^+ is the product of the reaction of H_2^+ and H_2 . All the intermediate species producing H_2O in gas phase, OH^+ , H_2O^+ , and H_3O^+ , together with H_2O itself, have been observed toward a large number of astronomical objects using the Herschel satellite (van Dishoeck et al. 2013, 2014). Water can be destroyed in the gas phase through reactions with HCO^+ and H_3^+ producing H_3O^+ , CO , and H_2 .

At low temperature, water can be also formed on the surface of dust grains (see “► [Water in the Universe](#)” and van Dishoeck 2013, 2014).

At higher temperatures, water vapor can be also formed from the reaction of OH and H_2 , and OH itself is formed from the reaction of O and H_2 .

The photodissociation of water in space is produced mainly from the absorption of photons with wavelengths between 175 and 200 nm from the ground state to the first excited electronic state producing OH and H . Photodissociation with more energetic photons (Lyman alpha or X-rays) could also produce H_2 and O (see van Dishoeck et al. 2013).

The Herschel satellite has provided an incredible amount of observations of water in interstellar and circumstellar clouds, and in external galaxies (see van Dishoeck et al. 2021).

Cross-References

- [H₂O](#)
- [Herschel Mission](#)
- [Interstellar Chemical Processes](#)
- [Interstellar Cloud](#)
- [Interstellar Ices](#)
- [Interstellar Medium](#)
- [Interstellar Molecule](#)
- [Maser](#)
- [Molecular Cloud](#)

- [Molecular Line Map](#)
- [Molecules in Space](#)
- [Water in the Universe](#)
- [Water, Related Interstellar Radicals and Ions](#)
- [Water, Vibrational and Rotational Transitions](#)

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Water, Related Interstellar Radicals and Ions

William M. Irvine

Department of Astronomy, University of Massachusetts, Amherst, MA, USA

Synonyms

H_2O^+ ; H_3O^+ ; HO_2 ; HOOH ; OH ; OH^+

Definition

Several radicals, ions, and neutral molecules whose chemistry is related to that of water have been found in the interstellar medium. These include water itself, hydrogen peroxide (HOOH), H_2O^+ , HO_2 , OH , OH^+ , and H_3O^+ . For many of these species, the pure rotational transitions are in the terahertz frequency range, so that their detections have followed the recent availability of high-altitude or space-based telescopes such as APEX and Herschel. Details of such recent observations may be found in the links from the table of interstellar and circumstellar

molecules in the entry ► [Molecules in Space](#). In contrast, the ► [hydroxyl radical](#) (OH) was the very first molecular species detected by radio astronomers, observing at wavelengths around 18 cm the lambda-doublet transitions which arise from interaction between the molecular rotation and the motion of the unpaired electron. These lines have traditionally been used to estimate the water abundance in comets, since cometary OH is mainly produced by photodissociation of H₂O. ► [Maser](#) emission is observed astronomically from OH in the Milky Way and in external galaxies, as well as from H₂O.

The surprisingly high abundance of molecular oxygen, O₂, found in comet 67P/Churyumov-Gerasimenko by the Rosetta mission has been linked to the formation of hydrogen peroxide (H₂O₂) in the cometary water ice followed by sublimation of the ice and self-reaction of H₂O₂ to form H₂O and O₂ (Dulieu et al. [2017](#)).

Cross-References

- [Comet](#)
- [Maser](#)
- [Molecules in Space](#)
- [Rosetta Spacecraft](#)
- [Water in the Universe](#)

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Water, Solvent of Life

Gilles Bruylants
Engineering of Molecular NanoSystems,
Universté Libre de Bruxelles, Brussels, Belgium

Keywords

Hydrophobicity · Origin of water on Earth · Prebiotic evolution

Synonyms

H₂O; [Hydrogen oxide](#)

Definition

Liquid water is a colorless liquid whose molecules associate extensively through hydrogen bonding.

Overview

The water molecule, chemical formula H₂O, is composed of two hydrogen atoms (H) covalently bonded to a single oxygen atom (O). Two of the six outer-shell electrons of the oxygen atom are involved in covalent bonds with the hydrogen atoms and the remaining electrons are organized into two nonbonding (or lone) pairs. The four electron pairs surrounding the oxygen adopt an approximately tetrahedral configuration with an H-O-H angle of 104.5°. The positive and negative charges on the molecule are not distributed uniformly due to the difference in the electronegativity of the oxygen and hydrogen atoms and the water molecule possesses an electric dipole moment of 1.85 Debye (Franks [1973](#); Chaplin [2009](#)).

Each of the two lone pairs of electrons of the oxygen atom and each of the two hydrogen atoms can be involved in a ► [hydrogen bond](#). Every water molecule can therefore be H-bonded with up to four other water molecules. Although hydrogen bonding is a relatively weak attraction compared to the covalent bonds within the water molecule itself, the hydrogen bonds that form between water molecules account for some of the unique properties of water in the condensed phase, such as its high cohesion energy density, its high surface tension, and its relatively high melting and boiling points. The extensive hydrogen-bonding network between the molecules also gives liquid water a large specific heat capacity (Franks [1973](#)).

Solid water (ice) can form, depending on the pressure and temperature, 1 of 15 known phases that are differentiated by their crystalline structure, ordering, and density. There are also

two metastable phases of ice under pressure (Salzmann et al. 2006).

Water molecules can interact efficiently with anions via hydrogen bonds and with cations via coordination between the lone pairs on the oxygen atom and empty orbitals of the cations. Polar species are also highly soluble in water. The poor solubility of apolar compounds in liquid water, described as “hydrophobicity,” is a direct consequence of the fact that water molecules form an infinite and dynamic network of hydrogen bonds in the liquid phase (Tanford 1980). Frank and Evans (1945) proposed a simple molecular interpretation for the poor solubility of apolar compounds in water. Their model, which is still generally accepted, suggests that the water structure is strengthened in the first hydration shell around an apolar solute (“hydrophobic hydration”) and explains the unusually large entropy loss encountered upon dissolution of a nonpolar compound in water. This term more than compensates the favorable enthalpy change, and consequently the transfer of an apolar solute from the gas phase (or from a nonpolar medium like its pure liquid phase) to a dilute water solution is characterized by a large and positive free-energy change.

The term “hydrophobic interaction” is commonly used to describe the interaction between nonpolar solutes in water (Ben-Naim 1980, 2002; Chandler 2005). The association of the nonpolar solutes in water is accompanied by a decrease of the entropy of the interacting partners which is overcompensated by an increase of the entropy of the water molecules as the total hydrophobic surface that the bimolecular, or polymolecular, complex offers to the water molecules is lower than the sum of the surfaces offered by the separated partners. Therefore, there is an global increase of entropy associated to the binding event linked to the dehydration of the apolar surfaces that are buried in the complex.

The Origin of Liquid Water on Earth

Until now, liquid water has only been found on Earth. It is highly unlikely that liquid water exists on the surface of any other body of our Solar System, but if it is present elsewhere in the Solar System, it could be present in the Martian

subsurface or below the icy crust of a Jovian satellite like Europa. Water vapor and solid water (ice) are of course abundant in the Solar System. Water vapor is present in the atmosphere of many planets and comets are described as “dirty snowballs.” Water is also present in the form of crystallization water in the mineral matrices of a class of meteorites called carbonaceous chondrites, which, in some cases, have a water content higher than 20% by weight.

The origin of water on Earth remains a subject of debate (Gargaud et al. 2001). It has been suggested that the young Earth was essentially formed by the accretion of planetesimals with a low water content. According to this scenario, water on Earth is the result of post-accretion delivery involving the impact of asteroids, meteorites, micrometeorites, and comets coming from the external parts of the Solar System that had a high water content. The young Earth, just after accretion, is described as a “hot and dry” body, heavily bombarded by large impactors. After this dramatic event, the bombardment by massive bodies was slowly replaced by a very important flux of micrometeorites characterized by a high content of volatiles like dinitrogen, carbon dioxide, and water.

Another scenario, called the endogenous scenario, is sometimes also evoked to explain the origin of liquid water on the Earth’s surface. It is associated with the degassing of the Earth’s crust and mantle. Even if this scenario is currently considered to be less plausible than the exogenous scenario, this does not exclude the possibility that a certain percentage of the water present on the surface of the young Earth was the result of the violent volcanism which was certainly taking place during the first hundreds of million years after the Earth’s formation. This endogenous scenario implies that the young Earth already had a non-negligible water content and therefore that planetesimals coming from the external part of the Solar System must have contributed to the first phase of the accretion.

Initially, water on the Earth was present as crystallization water in rocks or as water vapor in the atmosphere as the temperature and pressure conditions were incompatible with the existence of liquid water. Just after accretion the Earth was a

hot body but the cooling by radiative processes was very efficient and, after a few tens of million years, the solid crust was formed. Subsequently, various post-accretion phenomena took place and an atmosphere slowly surrounded the lithosphere. The radiative heat transfer between the hot planet and outer space was such that it can be estimated that the surface temperature of the young Earth would have quickly reached values too low for liquid water to be able to accumulate. Furthermore, the young Sun in its T-Tauri phase was most probably a “pale Sun” with a less intense electromagnetic spectrum than today at least in the near-UV/visible region of the spectrum (the amount of X-rays was probably much higher than today) (Gargaud et al. 2001). The light intensity in the near-UV/visible range was probably 25% lower than the present value. The only way to explain how liquid water managed to accumulate, and to solve what is often called the “faint solar paradox,” is to imagine the presence of an intense greenhouse effect, much more efficient than what occurs today (Sagan and Chyba 1997). An atmospheric pressure of few bars of carbon dioxide is one hypothesis to solve this paradox and explain how liquid water was present on the Earth’s surface 4.4 Gy ago (Gargaud et al. 2001). The presence of sedimentary rocks 4 Gy old and the existence of zircons, which seem to be 4.4 Gy old, are evidence suggesting that the oceans formed 4.4–4 Gy ago. This date gives the upper limit for what is frequently considered as the first steps of the process leading from non-living to living matter.

The Role of Water in Prebiotic Evolution

Today, the presence of life on Earth depends on the availability of liquid water. In living systems, water is ubiquitous and cannot be considered merely a diluent. It performs many functions: it transports, structures, stabilizes, lubricates, reacts, and partitions. It is widely appreciated that water molecules play an invaluable role in governing the structure, stability, dynamics, and function of important biomolecules such as proteins and nucleic acids (Ball 2008). Molecular water also plays a key role in the formation of the

association complexes (Ben-Naim 2002) and entropy-driven binding processes, as discussed above is a phenomenon widely encountered in molecular biology and plays a role in many processes of major importance in the living world. The finely tuned involvement of water in life processes is confirmed by the fact that heavy water is toxic to these processes in many organisms, although some microbes are able to tolerate almost complete isotopic substitution. Liquid water is a component of all living cells and its role is so important and fundamental that it is difficult to imagine any form of life without liquid water (Bruylants et al. 2010; Locci et al. 2002).

Research devoted to the processes by which matter evolved from “nonliving” to “living” must take into account the role of water. It seems impossible to imagine any primitive form of life in the absence of liquid water but, on the other hand, the possibility that life forms without DNA or proteins is conceivable; the “RNA world” being one example (Orgel 2004). In a way, water appears more important than DNA or proteins for prebiotic evolution!

The spontaneous formation of membranes may be one of the first steps in prebiotic evolution, not only because it separates an “in” and an “out” but also because membranes represent an apolar medium in which condensation reactions can take place (Luisi et al. 1999; Ourisson and Nakatani 1996). In water, the spontaneous formation of vesicles or liposomes is a well-known process governed by the entropy increase of water upon desolvation of hydrophobic surfaces. This suggests that, without liquid water, life based on cells separated from the external world by organic membranes could never have appeared on Earth.

The living world should be thought of as an equal partnership between proteins, nucleic acids, lipids, ions, and water. No other molecule abundant on the primitive Earth and abundant in the Solar System could have played this role. It is even highly probable that any other form of life in the universe, if it exists, is based on liquid water.

Cross-References

- ▶ [Earth's Atmosphere, Origin and Evolution of](#)
- ▶ [Evolution, Biological](#)
- ▶ [Hydrogen Bond](#)
- ▶ [Life](#)
- ▶ [Nucleic Acids](#)
- ▶ [Protein](#)

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Water, Vibrational and Rotational Transitions

José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Keywords

Astrochemistry · Molecules in space ·
Interstellar medium

Synonyms

H₂O

Definition

The electromagnetic spectrum of H₂O contains three different types of transitions, electronic (optical-ultraviolet), vibrational (infrared), and rotational (millimeter, submillimeter, far-infrared). Ro-vibrational transitions occur between the rotational levels of different vibrational modes.

Overview

Water vapor, as all molecules, has rotational transitions, in which the rotational angular momentum changes following allowed selection rules, and vibrational transitions in which the nuclei of the molecule change their distance following the fundamental vibrational modes of the molecule. In addition, H₂O has also electronic transitions related to the movement of the electrons.

Pure rotational transitions of water vapor fall in the millimeter, submillimeter, and far-infrared domains, while vibrational transitions fall in the infrared domain of the electromagnetic spectrum. As H₂O is a light species, most of its rotational transitions are in the far-IR domain.

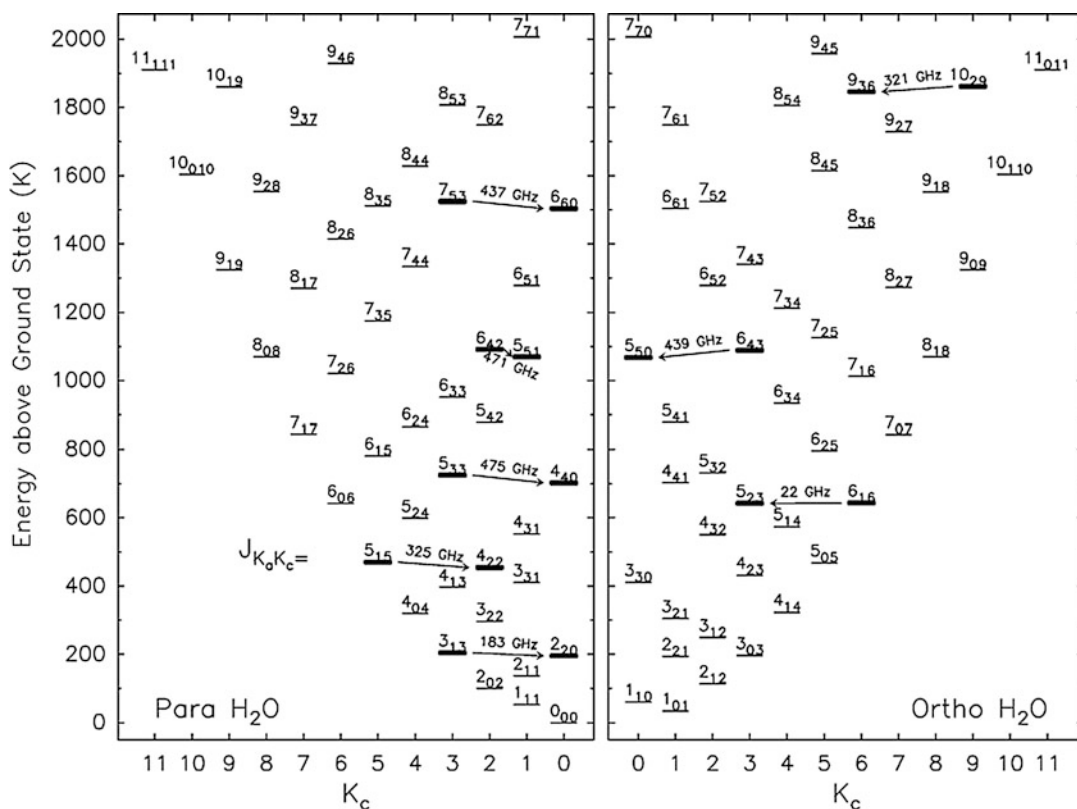
The observation of water vapor from ground-based observatories is practically impossible due to the strong telluric absorption produced in our

own atmosphere (see Cernicharo et al. 1990, for details on atmospheric transmission at mm and submm wavelengths for water vapor lines). Only after the launch of the ► [Infrared Space Observatory](#) it was possible to study the full rotational spectrum of water vapor in the far infrared (Cernicharo and Crovisier 2005).

The fundamental vibrational modes of water vapor ν_1 (symmetric stretching), ν_2 (bending mode), and ν_3 (antisymmetric stretching) occur at 3,657, 1,595, and 3,756 cm^{-1} , respectively (2.73, 6.27, and 2.66 mm). The rotation of the molecule is coupled to its vibration producing ro-vibrational bands with well-defined absorption features that can be even resolved at medium spectral resolution. The observation of these

bands toward astronomical objects was also possible with the Infrared Space Observatory (van Dishoeck et al. 1998; González-Alfonso et al. 1998; González-Alfonso et al. 2002). The role of infrared pumping in the intensity of the rotational lines of H_2O was discussed in detail by González-Alfonso and Cernicharo (1999) (Fig. 1).

The Herschel satellite has provided high spectral resolution of H_2O rotational lines permitting the study of the water abundance with unprecedented sensitivity in a large variety of molecular clouds, evolved stars, solar system bodies, protoplanetary disks, and galaxies (see, e.g., van Dishoeck et al. 2014, 2021; Alcolea et al. 2013; Bockelée-Morvan et al. 2012; Podio et al. 2013; González-Alfonso et al. 2012; Yang et al. 2013).



Water, Vibrational and Rotational Transitions, Fig. 1 Rotational levels of ortho and para water up to energies of 2,000 K. The rotational transitions indicated by arrows correspond to some of the maser lines observed from ground-based observatories. The two species of water vapor, ortho and para, result from the different projection of the spin of the two identical hydrogen atoms in the molecule with statistical weights 3:1 (ortho corresponds

to parallel spins, para to antiparallel spins). Under the physical conditions of the interstellar medium, the only way to transform ortho into para species is through reactions with protons. Hence, both species have to be considered as independent molecules having a different energy level structure and different frequencies for their rotational transitions

H₂O Observations from Ground-Based Observatories

Only a few transitions of H₂O having maser character have been observed from the ground, allowing in particular for the detection of H₂O for the first time in 1969 at 22 GHz through its $6_{16}-5_{23}$ rotational transition at 22.235 GHz (Cheung et al. 1969). The size of the emitting regions at this frequency is typically of the order of a few milliarcseconds (a few 10^{13} cm at the distance of Orion). Hence, no information has been obtained from ground-based observations on the role of water vapor at large spatial scales from this line. Other H₂O lines have been detected from ground- or airborne-based telescopes like the $3_{13}-2_{20}$ transition at 183 GHz (Waters et al. 1980; Cernicharo et al. 1990, 1994), the $4_{14}-3_{21}$ transition at 380 GHz (Phillips et al. 1980), the $10_{29}-9_{36}$ transition at 321 GHz (Menten and Melnick 1991), and the $5_{15}-4_{22}$ transition at 325 GHz (Menten et al. 1990; Cernicharo et al. 1999). All these lines have been detected toward interstellar and circumstellar molecular clouds. Other lines of H₂O between 400 and 500 GHz have been observed toward evolved stars with the APEX telescope (Menten et al. 2008).

Among these lines, only the $3_{13}-2_{20}$ transition at 183 GHz, for which the terrestrial atmosphere can be partially transparent under excellent weather conditions, has been used to map the emission of water at very large spatial scales (Cernicharo et al. 1994). As an example, the extent of water vapor from the map of the Orion molecular cloud shown in Cernicharo et al. (1994) is six orders of magnitude larger than the size of the spots detected at 22.235 GHz.

Cross-References

- H₂O
- Interstellar Chemical Processes
- Interstellar Cloud
- Interstellar Ices
- Interstellar Medium
- Interstellar Molecule
- Maser
- Molecular Cloud
- Molecular Line Map

- Molecules in Space
- Water in the Universe
- Water, Formation and Photodissociation
- Water, Related Interstellar Radicals and Ions

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Watson-Crick Pairing

Henderson James Cleaves II
 Earth-Life Science Institute (ELSI), Tokyo
 Institute of Technology, Tokyo, Japan
 Blue Marble Space Institute of Science,
 Washington, DC, USA
 Center for Chemical Evolution, Georgia Institute
 of Technology, Atlanta, GA, USA

Definition

In molecular biology, two nucleotides on complementary DNA or RNA strands that are connected via hydrogen bonds are called a base pair. In canonical Watson-Crick base pairing in DNA, adenine (A) forms a base pair with thymine (T) using two hydrogen bonds, and guanine (G) forms a base pair with cytosine (C) using three hydrogen bonds. In canonical Watson-Crick base pairing in RNA, thymine is replaced by uracil (U). The name of this

type of base-pairing derives from the names of two of the co-discoverers of the molecular structure of DNA, James Watson and Francis Crick. DNA with high GC content is more stable to denaturation or melting than DNA with low GC content. Watson-Crick base pairing is also the mechanism by which mRNA codons are recognized by anticodons on tRNA molecules during protein translation.

The purine nucleobases, adenine and guanine, are double-ringed molecules. The pyrimidine nucleobases, cytosine, uracil and thymine, are single-ringed molecules. In Watson-Crick base pairing, purines are only complementary with pyrimidines, partly due to the distance between the hydrogen-bonding surfaces and the nucleic acid backbone. GT and AC mispairings are unfavorable because the pattern of hydrogen donors and acceptors does not correspond structurally. Alternative hydrogen-bonding schemes, such as wobble base pairing and Hoogsteen base pairing, also occur, particularly in RNA, giving rise to complex and functional tertiary structures.

Cross-References

- ▶ [Hoogsteen Pair](#)
- ▶ [Nucleic Acid Base](#)
- ▶ [Nucleic Acids](#)
- ▶ [Purine Bases](#)
- ▶ [Pyrimidine Base](#)
- ▶ [Wobble Pair](#)

Wave Number

José Cernicharo Quintanilla
 Laboratory of Molecular Astrophysics,
 IFF-CSIC, Madrid, Spain

Definition

In certain molecular spectroscopies, the frequency of electromagnetic radiation is measured in units

of cm^{-1} , known as wave numbers. It corresponds to the inverse of the wavelength of the electromagnetic wave. The conversion factor between frequencies in MHz and frequencies in wave numbers is $1 \text{ cm}^{-1} = 29,979.2458 \text{ MHz}$. The wave number is also used as an energy unit. A photon of frequency ω wave numbers carries an energy of $\approx 2 \cdot 10^{-17} \omega \text{ erg} \approx 1.22 \cdot 10^{-5} \omega \text{ eV} \approx 1.43 \omega \text{ K}$.

Cross-References

► [Wavelength](#)

Wavelength

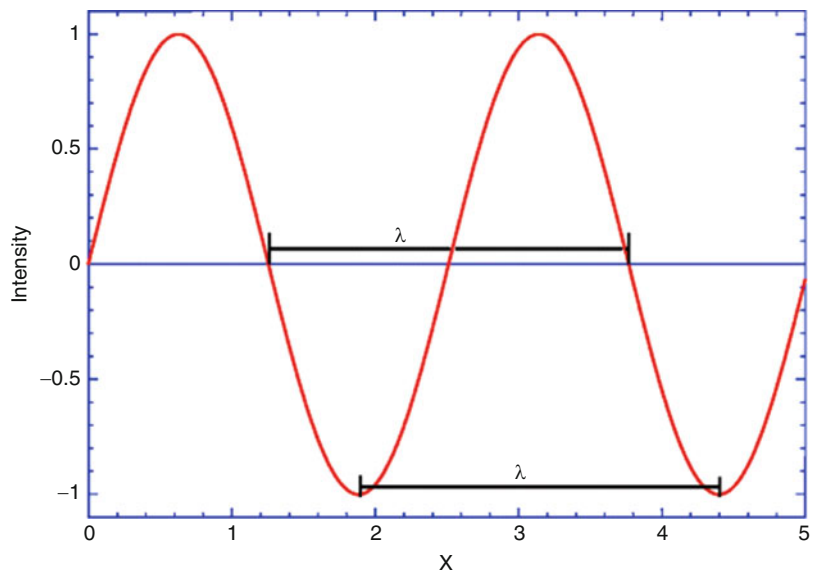
José Cernicharo Quintanilla
Laboratory of Molecular Astrophysics,
IFF-CSIC, Madrid, Spain

Definition

The wavelength of a signal is defined as the distance between two consecutive intensity

maxima (or minima) and corresponds to its spatial period (see Fig. 1). It is denoted by the Greek symbol lambda (λ). For an electromagnetic wave propagating in the vacuum, the wavelength is related to the frequency through the relation $\lambda = c/v$, where c is the speed of light ($299792.458 \text{ km s}^{-1}$) and v the frequency of the signal. The electromagnetic spectrum is divided in different ranges depending on the frequency of the photons (energy = $h\nu$, where h is the Planck constant; see Table 1; see also astrobiological data). Most media broadcasts use radiation in the radio domain. The rotation of molecules emits in the millimeter and sub-millimeter domains. Molecular vibrations produce emission in the far-, mid-, and near-infrared domains. Emission due to orbital changes of electrons in atoms and molecules occurs in the optical and ultraviolet domains. Nuclear changes produce emission in the extreme ultraviolet and X-ray domains. Each of these wavelength ranges corresponds to a specific branch of astrophysics for which specific instruments and technologies are developed.

Wavelength,
Fig. 1 Representation of a
sinusoidal wave with a
description of the
wavelength



Wavelength, Table 1 Electromagnetic spectrum range

Wavelength domain	λ (Å)	λ (cm)	λ (μm)	Frequency (MHz)	Color temperature range (K)	Energy (eV)
Radio	$>10^9$	>10	$>10^5$	$<3 \times 10^3$	<0.03	$<10^{-5}$
Microwave	10^9 – 10^8	10–1	10^5 – 10^4	3×10^3 – 3×10^4	0.03–0.3	10^{-5} – 10^{-4}
Millimeter	10^8 – 10^7	1–0.1	10^4 –1000	3×10^4 – 3×10^5	0.3–3	10^{-4} – 10^{-3}
Submillimeter	10^7 – 3×10^6	0.1–0.03	1000–300	3×10^5 – 10^6	3–10	10^{-3} – 4×10^{-3}
Far-infrared	3×10^6 – 4×10^5	0.03 – 4×10^{-3}	300–40	10^6 – 7.5×10^6	10–72	4×10^{-3} –0.03
Mid-infrared	4×10^5 – 10^4	4×10^{-3} – 5×10^{-4}	40–5	7.5×10^6 – 6×10^7	72–580	0.03–0.24
Near-infrared	5×10^4 –7000	5×10^{-4} – 7×10^{-5}	5–0.7	6×10^7 – 4.3×10^8	580–5600	0.24–1.8
Visible	7000–4000	7×10^{-5} – 4×10^{-5}	0.7–0.4	4.3×10^8 – 7.5×10^8	5600 – 10^4	1.8–3
Ultraviolet	4000–10	4×10^{-5} – 10^{-7}	0.4–0.001	7.5×10^8 – 3×10^{11}	10^4 – 3×10^6	3–1200
X-rays	10–0.1	10^{-7} – 10^{-9}	10^{-3} – 10^{-5}	3×10^{11} – 3×10^{13}	3×10^6 – 3×10^8	1.2×10^3 – 1.2×10^5
Gamma rays	<0.1	$<10^{-9}$	$<10^{-5}$	$>3 \times 10^{13}$	$>3 \times 10^8$	$>1.2 \times 10^5$

Weak Bonds

Jun-ichi Takahashi
Faculty of Engineering, Yokohama National
University, Yokohama, Japan

Definition

Weak chemical bonds are those forces of attraction that, in biological situations, do not take a large amount of energy to break. For example, hydrogen bonds are broken by energies in the order of 4–5 kcal/mol and van der Waals interactions have energies around 1 kcal/mol. In biological terms, ionic bonds, hydrogen bonds, and van der Waals interactions are considered weak bonds. In biological systems, weak bonds are being continually broken and reformed without the aid of enzymes. Weak bonds may be easily broken, but they are very important because they help to determine and stabilize the shapes of biological molecules. For example, they are important in stabilizing the secondary structure (alpha helix

and beta-pleated sheet) of proteins. Hydrogen bonds keep complementary strands of DNA together. Hydrogen bonds participate in enzymic catalysis.

Cross-References

- [Hydrogen Bond](#)
- [Van Der Waals Forces](#)

Weathering

Nicholas Arndt
Emeritus Professor, ISTERre, University Grenoble
Alpes, Grenoble, France

Definition

Weathering refers to the processes by which the rocky surface of the Earth is subjected to physical disintegration and chemical decomposition when

exposed to atmospheric or water-related agents. During weathering, rocks change color, texture, chemical and mineralogical composition, firmness, and/or form, with little or no transport of the loosened or altered material. Mineral and rock debris will constitute the skeleton of clastic sediments (i.e., sands), and through diagenesis, clastic sedimentary rocks (breccia, sandstone, etc.). The action of water and oxidizing conditions destabilizes high-temperature minerals such as ► [olivine](#), pyroxene, or plagioclase, converting them to low-temperature secondary minerals, mainly clays and iron oxides. In this process, the rock is converted partially or completely from hard solid material, commonly with large interlocking crystals, to soft, unconsolidated, hydrous, fine-grained material that is then subject to mechanical erosion. Two types of weathering can be distinguished: Mechanical weathering involves breakdown of the mineral or rock structure by the physical action of heat, water, or ice or by asteroidal impact. Chemical weathering entails the chemical breakdown of thermodynamically unstable minerals, usually in the presence of water. A typical product of mechanical weathering is ► [planetary regolith](#) and ► [terrestrial regolith](#), while clay minerals are a typical product of chemical weathering of silicate minerals.

Cross-References

- [Sedimentary Rock](#)

Weathering Profile

Daniele L. Pinti
Geotop, Research Centre for the Dynamics of the Earth System, Université du Québec à Montréal, Montréal, QC, Canada

Synonyms

[Alteration profile](#)

Definition

A weathering profile is a vertical assemblage of weathering zones (subsurface zones of alteration differing physically, chemically, or mineralogically from adjacent zones) from the unaltered bedrock to the surface soil. The nature of the weathering profile is a complex response to climatic and geologic controls and to long-term changes in surface environmental conditions. In modern Earth, weathering profiles are best developed at the equator (lateritic soils), where depths of 30 up to 100 m are found. Astrobiologists study paleo-weathering profiles (or paleosols) because their mineralogical and geochemical characteristics give constraints on the redox state of the atmosphere of early Earth.

Cross-References

- [Great Oxidation Event](#)
- [Oxygenation of the Earth's Atmosphere](#)
- [Paleosols](#)
- [Red Beds](#)
- [Redox Zonation](#)
- [Weathering](#)

Weightlessness

- [Microgravity](#)

White Dwarf

Jordi Isern
Institute for Space Sciences (ICE, CSIC),
Barcelona, Spain
Institute for Space Studies of Catalonia (IEEC),
Ed. Nexus, Barcelona, Spain
Section of Mathematics and Astronomy, Fabra
Observatory, Royal Academy of Sciences and
Arts of Barcelona (RACAB), Barcelona, Spain

Keywords

White dwarfs

Synonyms

Degenerate stars

Acronyms

WD	White dwarf
Ga	Giga-annum (10^9 years)
SDSS	Sloan Digital Sky Survey
SCSS	SuperCOSMOS Sky Survey

Definition

White dwarfs are the final outcome of low and intermediate mass stars. Because of the electron degeneracy they cannot ignite their nuclear fuel and their destiny is to cool down forever if they are single. On the contrary, if they are members of a close binary system they can interact with the companion and give rise to a plethora of astronomical phenomena or objects like novae, supernovae, or cataclysmic variables.

History

The first white dwarf, 40 Eridanus B, was discovered by Friederich Wilhelm Herschel in 1785, and the second one, Sirius B, by Alvan G. Clark, in 1862, both as members of a stellar binary system. The third one, the Van Manneken's Star, was discovered in 1917 and was a single star. Since then, the number of known white dwarfs has been steadily increasing thanks to different cosmological surveys (Rowell and Hambly 2011; Kleinman et al. 2013; Kepler et al. 2016) and the Gaia mission (Gentile Fusillo et al. 2019). At present the total number of known white dwarfs is near $\sim 300,000$ and this figure is expected to increase by two orders of magnitude when the Vera C. Rubin Observatory will be operating. A detailed description of how the understanding of these stars has evolved with time can be found in H. M. Van Horn (2015).

Overview

White dwarfs are the final outcome of the evolution of low and intermediate mass stars, those with a mass smaller than 8–9 solar masses. Their mass lies in the range of 0.15–1.35 solar masses, although the majority have a mass between 0.5 and 0.7 solar masses, being the average of the order of 0.6 solar masses. The size of these stars is of the order of the size of the Earth, which implies an average density of 10^6 g cm^{-3} . Their structure consists of a degenerate core that contains about the 98% of the mass of the star and a thin non-degenerate envelope.

In the majority of cases, this core is made of a mixture of ^{12}C and ^{16}O , with a distribution that depends on the mass and chemical composition of the parent star, plus a small amount of inherited metals. Some of them are in the form of ^{22}Ne , which is synthesized during the hydrogen and helium burning stages from the initial content in carbon, nitrogen, and oxygen. White dwarfs with a mass smaller than ~ 0.4 solar masses are made of helium, and those with a mass larger than ~ 1.05 solar masses are made of oxygen and neon. Helium white dwarfs can only be the outcome of the evolution of a binary system, and at least a fraction of the massive ones are the outcome of the merging of two degenerate stars in a binary system.

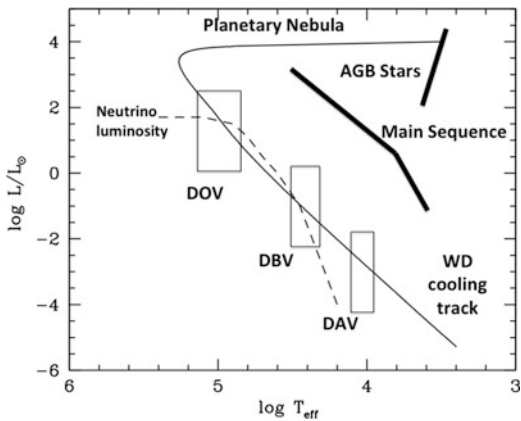
The structure and properties of white dwarfs are essentially determined by the equation of state of degenerate electrons (Chandrasekhar 1939) and, consequently, they cannot obtain energy from thermonuclear reactions. This means that in the case of single white dwarfs their evolution is just a cooling process in which the initially hot core provides the energy and the outer layers control the energy outflow. As it can be seen from Fig. 1, they span over a wide range of luminosities, from 10^3 to 10^{-4} times the solar luminosity, and temperatures, from nearly 200,000 K to less than 4,000 K. A simple calculation shows that this evolution is very long, since it takes more than 10 Ga to cool down from the planetary nebula stage to the present limit of detectability.

The transition from an AGB star to a white dwarf is not well known at present. Fortunately, white dwarfs are very hot at this epoch and neutrinos dominate the cooling (Fig. 1). As a consequence, all the initial thermal structures converge to a unique one when the luminosity reaches the value of $\sim 10^{-1.5}$ solar luminosities. This stage is very short, less than 10^8 years, and does not introduce severe distortions in the calculation of the age of the star. Within the luminosity interval of $10^{-1.5}$ – 10^{-3} solar luminosities, the equation of

state of the interior is that of a Coulomb liquid, the behavior of the star is relatively simple, and all the existing theoretical models are concordant.

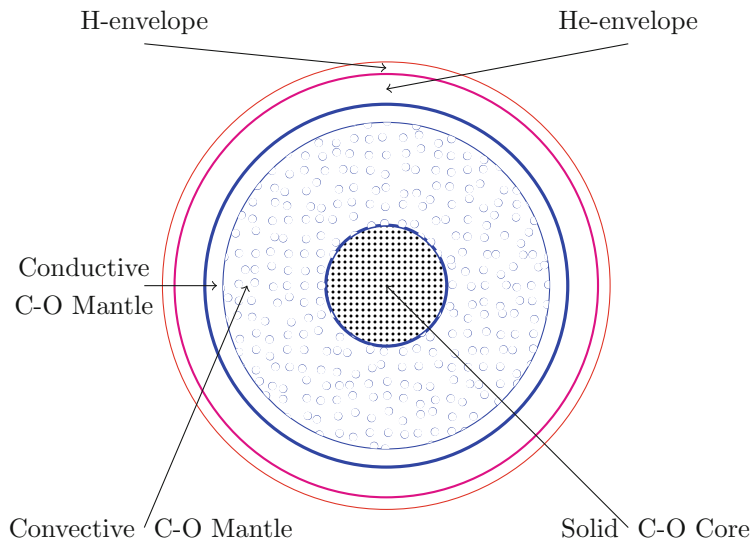
When luminosities are of the order of 10^{-3} solar luminosities, the exact value depends on the mass of the white dwarf, the plasma starts to crystallize and, because of the differences of solubility between the liquid and the solid phases, an oxygen-rich core surrounded by a carbon-rich mantle forms, a structure that is similar to the existing one in the Earth interior (see Fig. 2). This process implies a release of gravitational energy that can maintain the star warm for an additional period of time (Mochkovitch 1983). The presence of impurities like ^{22}Ne reinforces this effect and introduces additional time delays (Isern et al. 1991, 1998). When almost all the star has solidified, the specific heat follows the Debye’s law, the heat capacity is strongly reduced, and the star quickly fades.

In all cases, there is a thin helium layer of 10^{-2} – 10^{-4} solar masses surrounding the white dwarf core. This mantle, in turn, is itself surrounded by a layer made of pure hydrogen, which has a mass in the range of 10^{-4} – 10^{-12} solar masses, and can be absent in the $\sim 25\%$ of individuals. From the phenomenological point of



White Dwarf, Fig. 1 Evolution of a typical white dwarf in the Hertzsprung-Russell diagram

White Dwarf, Fig. 2 Structure of a white dwarf during the crystallization process



view, white dwarfs showing hydrogen in their spectra are named DA, while the remaining ones (the non-DA) are classified, in order of decreasing temperatures, as DO, DB, DQ, DZ, and DC depending on their spectral features. There are also some exotic objects, with anomalous compositions, that are suspected to be the outcome of the merging of two white dwarfs.

The evolution of the envelope is rather complicated (Fig. 3) and is a consequence of (i) a nonstandard initial chemical composition resulting from the evolution of AGB stars, (ii) a very efficient gravitational settling that induces the stratification of the envelope with the lightest element in the top (Schatzman 1958), and (iii) the action of different mechanisms that tend to restore the homogeneity like convective mixing, radiative levitation, thermal diffusion, accretion from the interstellar medium, and winds (Althaus et al. 2010; Fontaine et al. 2013).

The character DA, non-DA is linked to the origin of the white dwarf itself and can change along their evolution. DAs are born with a variety of H-layer masses. When they are hot, radiative levitation brings heavy elements to the surface, but as soon as the temperature drops, they settle down and disappear from the spectrum. When the temperature is low enough, convection appears in the envelope and the hydrogen layer mixes with the helium mantle. The DA white dwarf becomes

a non-DA, being those with thinner layers the first ones to do the transition.

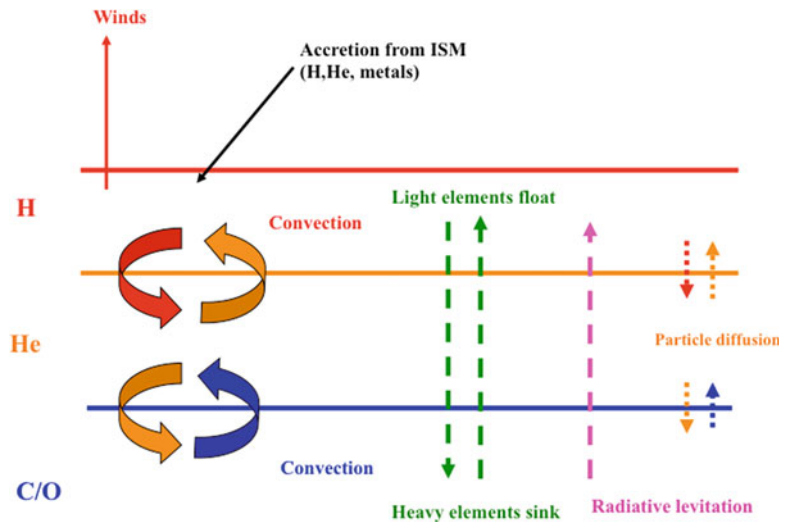
The evolution of non-DAs is more complicated. They are the descendants of He-rich planetary nebulae or the result of a merger episode. Their envelope is mainly made of helium with some traces of hydrogen that gradually floats to the surface and forms a thin hydrogen layer that grows with time. At the beginning of this cooling process, they look as DO stars but when the temperature becomes of the order of $\sim 50,000$ K the hydrogen layer becomes thick enough to hide the helium mantle and the white dwarf appears as a DA. When the temperature drops below 30,000 K, the helium layer becomes convective, it engulfs the hydrogen layer and the white dwarf becomes a non-DA once more, more precisely, a DB white dwarf. The lack of non-DA white dwarfs in the temperature range of 45,000–30,000 K is known as the DB-gap. Further cooling converts them into DZ and DC white dwarfs, the last ones being partially DAs in origin.

Basic Methodology

There are two important tools to confront theory with observations: the luminosity function and the seismological properties.

White Dwarf,

Fig. 3 Physical mechanisms operating in the envelope of white dwarfs



During their evolution, white dwarfs experience instabilities that cause periodic fluctuations in their luminosities and offer the possibility to analyze their interior (Cox 1980). These fluctuations are generated by global non-radial pulsations driven by buoyancy in the gravity field of the star (the so-called g-modes). These pulsations have typical amplitudes in the range of 0.1 mag to 0.4 mag and periods in the range of 100–7000 s. Although new divisions have recently appeared as a consequence of the spectacular improvement of the observational background, they are classified as: (i) DAVs or ZZ Ceti stars with temperatures and gravities in the range of 10,400–12,400 K and $\log g$ (cm^2s^{-1}) in the range of 7.5–9.1, respectively, and a hydrogen dominated atmosphere, (ii) DBVs or V777 Her stars with temperatures and gravities in the domain of 22,400–32,000 K and $\log g$ in the range of 7.5–8.3, respectively, and a helium-dominated atmosphere, (iii) DOV or GW Vir variables with temperatures and gravities in the range of 80,000 and 180,000 K and $\log g$ in the range of 5.5–7.5, respectively. See Córscico et al. 2019, Córscico 2020, and references there in for more information.

In contrast with the Sun and red giants, these pulsations are not induced by convection but by a mechanism related with the behavior of opacity in the partially ionized zones. The still existing uncertainties do not prevent to obtain information about the star. For instance, it has been possible to determine the mass and the internal stratification of several variables (Gianmichele et al. 2018; Bischoff-Kim et al. 2019; Córscico et al. 2019) or the cooling rate via the secular drift of the pulsation period ($dP/dt \sim 10^{-15} \text{ s}^{-1}$ in the case of the ZZ Ceti stars, as detected for the first time by Kepler et al. 1991).

The luminosity function is defined as the number density of white dwarfs of a given luminosity per unit of magnitude interval, i.e., the distribution in luminosity of white dwarfs along the cooling track (Weidemann 1968; Garcia-Berro and Oswalt 2016). Figure 4 displays the shape of this function obtained with the data provided by the SDSS and SCSS catalogues. The first noticeable property is the monotonic increase of the number of white dwarfs with the magnitude followed by a

shortfall of dim stars. This confirms that the evolution of these stars is just a simple gravothermal process of cooling since, on the one hand, low temperature stars accumulate because they cool down more slowly than the hot ones (Mestel 1952) and, on the other hand, they cannot reach an arbitrarily low temperature as a consequence of the finite age of the Galaxy (Winget et al. 1987).

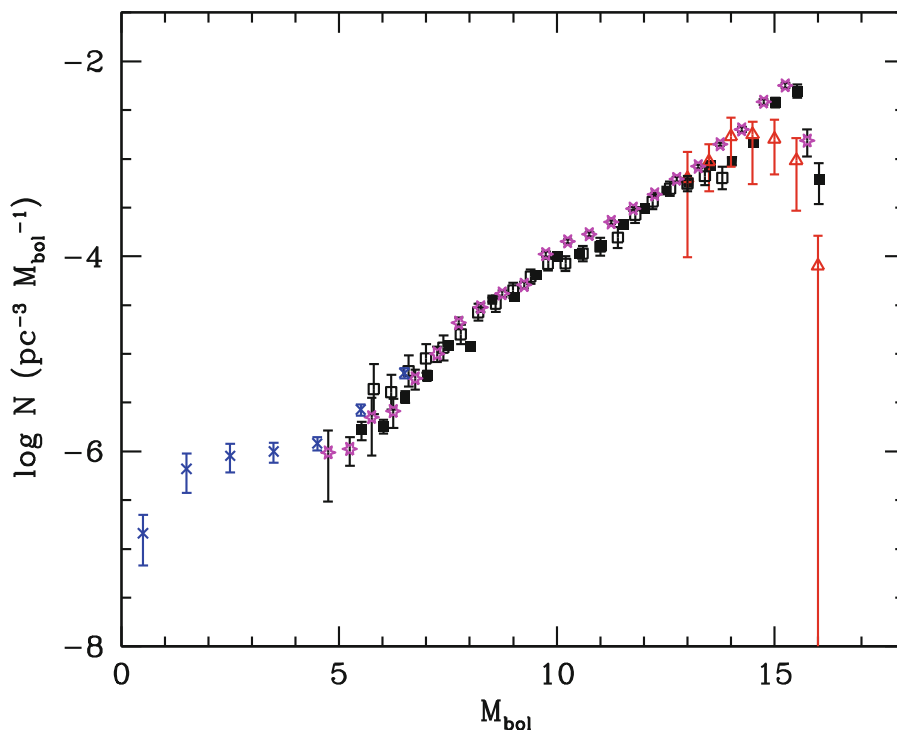
Key Research Findings

The most important results recently found are the confirmation of the stratified structure of the interiors as well as the role played by crystallization and the associated sedimentation of the internal layers. These improvements in the understanding of the evolution of white dwarfs have allowed to reconstruct, at least in part, the star formation history of the solar neighborhood.

Applications

A relevant application for Astrobiology is the determination of the bulk composition of rocky planets based on the observation of metal features in the spectra of cool white dwarfs (Jura and Young 2014). Since the time scale for sinking of elements heavier than helium is much smaller than the cooling age of white dwarfs it must be concluded that these metals have been accreted from the nearby circumstellar medium. At present it is widely accepted that this pollutant material comes from the remnants of the planetary system that was accompanying the parent star. Dynamical instabilities, planetesimal scattering, and tidal disruption led to the formation of an accretion disc from which matter is accreted to the white dwarf (Veras 2016). However, in order to extract the information provided by the spectra it is necessary to improve the models of atmosphere of white dwarfs as well as the diffusion mechanisms in such environments. The first results suggest that the geological properties of the Solar System are not uncommon in the Galaxy.

Another important application of white dwarfs is their ability for testing new ideas in Physics.



White Dwarf, Fig. 4 Luminosity functions obtained from the SDSS catalogue: Black solid squares (Harris et al. 2006). Blue crosses (Krziesinski et al. 2009). Magenta stars were obtained from the SCSS catalogue (Rowell and

Hambly 2011). Red triangles are from Legget et al. (1998). All of them contain DA and non-DA stars. Open black squares, only contain DAs (DeGennaro et al. 2008)

Very often nonstandard theories predict the existence of new particles or new phenomena that cannot be tested in terrestrial laboratories due to the energies involved. One way to alleviate the problem is to examine the perturbations they introduce in the normal evolution of stars (Raffelt 1996). Since the evolution of white dwarfs is a relatively simple process of cooling and the basic ingredients of their evolution are well identified they can be used for this purpose (Isern and Garcia-Berro 2008). In particular, just to cite few examples, white dwarfs have provided bounds to the mass of axions, to the secular drift of the Newton gravitational constant or to the density of magnetic monopoles.

Future Directions

Gaia and the cosmological surveys have provided an unprecedented and large set of accurate

photometric and astrometric data that are revolutionizing the existing ideas about white dwarfs and their role in the Galaxy. Unfortunately, an equivalent set of spectroscopic data is still lacking in order to determine their masses, their detailed chemical composition, the incidence of magnetism among them, or the nature of the mechanism that excites and quenches their pulsations, but projects like WEAVE or DESI and others will overcome this problem quite soon and will provide a deep insight on their nature.

Cross-References

- [Chandrasekhar's Limit](#)
- [Nova](#)
- [Planetary Nebula](#)
- [Stars](#)
- [Supernova](#)
- [Supernova Types](#)

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White Smoker

Nicholas Arndt

Emeritus Professor, ISTERre, University Grenoble Alpes, Grenoble, France

Definition

A white smoker is a hydrothermal vent emitting very alkaline hydrothermal fluids on the ocean floor. These fluids are cooler (260–300 °C) than those emitted by the ► [black smokers](#) (360 °C) and are sited away, or “off axis,” from the ► [mid-ocean ridge](#). Interaction of downward-seeping seawater with mafic or ► [ultramafic rocks](#) produces an alkaline fluid that precipitates silica and Ba- or Ca-sulfates when it mixes with seawater,

hence the white color. The interface between hot and alkaline hydrothermal fluids and seawater is believed to have provided the conditions required for the emergence of life. A notable example of white smoker' fields is Lost City Hydrothermal Field (or simply Lost City). This hydrothermal vent field located in central Atlantic Ocean, is a site of ultramafic-hosted ► [serpentinization](#), abiotically producing molecules such as methane which are fundamental to microbial life.

Cross-References

- [Black Smoker](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Mid-Ocean Ridge](#)
- [Serpentinization](#)

Whole Community Transcripts

- [Metatranscriptome](#)

Wobble Hypothesis (Genetics)

Juli Peretó
Institut Cavanilles de Biodiversitat i Biologia
Evolutiva, Universitat de València, València,
Spain

Definition

The Wobble hypothesis proposes that normal base pairing can occur between nitrogen bases in positions 1 and 2 of the codon and the corresponding bases (3 and 2) in the anticodon. Actually, the base 1 in anticodon can form non-Watson-Crick base pairing with the third position of the codon. The hypothesis is applicable to most (not all) tRNAs.

History

Hypothesis proposed by Francis Crick in 1966 to explain the observed degeneracy in the third position of a codon.

Cross-References

- [DNA](#)
- [Genetic Code](#)

Wobble Pair

Henderson James Cleaves
Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA
Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

A wobble pair, or wobble-base pair, is a hydrogen-bonded pairing between two ► [nucleotides](#) generally occurring between two RNA molecules. These base pairs are geometrically distinct from the canonical Watson–Crick-type base-pairing. The main wobble base pairs are hypoxanthine-uracil (I-U, where I represents inosine, the nucleoside formed from hypoxanthine), guanine-uracil (G-U), hypoxanthine-adenine (I-A), and hypoxanthine-cytosine (I-C). Wobble base pairs are of comparable thermodynamic stability to Watson–Crick base pairs. Wobble base pairs occur frequently in RNA secondary structure and are important for proper translation of the genetic code.

In 1966, Francis Crick proposed the Wobble hypothesis to account for the fact that most organisms do not seem to have as many tRNA molecules as would be required for complete translation of the genetic code. There are 64 possible codons in the

genetic code. During translation, each of these codons requires a tRNA molecule with a complementary anticodon to bring the appropriately charged amino acid into position on the ribosomal-mRNA complex. If each tRNA molecule paired only with its exactly complementary mRNA codon via Watson–Crick base-pairing, then 61 types of tRNA would be required (64 codons minus the 3 used as stop codons). Since most organisms have less than 45 distinct tRNA types, some tRNAs pair with more than 1 codon. The means by which this pairing promiscuity is achieved is via the use of wobble pairs formed between tRNA/mRNA complexes.

Cross-References

- [mRNA Display](#)
- [Translation](#)
- [Watson-Crick Pairing](#)

Woese, Carl

Stéphane Tirard

Centre François Viète d'Histoire des Sciences et des Techniques EA 1161, Faculté des Sciences et des Techniques de Nantes, Nantes, France

Carl Woese was an American microbiologist, born in New York in 1928. In 1977, he discovered the third lineage among the living beings, the Archaeas, which are microscopical entities, beside eukaryotes and prokaryotes. This discovery was based on the comparison of RNA sequences, showing that Archaea are no more close to prokaryotes than to eukaryotes.

This discovery constituted a fundamental transformation of the conception of the microscopical world and of the classification of living beings.

X

X-Rays (Organic Synthesis)

Jun-ichi Takahashi
Faculty of Engineering, Yokohama National
University, Yokohama, Japan

Definition

An X-ray is a form of electromagnetic radiation having a wavelength in the range of 0.01–10 nm, corresponding to energies in the range 120 eV–120 keV. These ranges are intermediate between vacuum ultraviolet light and gamma rays. Neutron stars, white dwarf stars, supernova remnants, cluster of galaxies, and black holes in active galaxy nuclei are sources of intense X-rays. X-rays and cosmic rays may be implicated in the prebiotic formation of organic compounds in the primitive Earth atmosphere.

Overview

From the standpoint of astrobiology, it has been proposed that electromagnetic radiation or cosmic rays are the effective energy sources for synthesizing the precursors of terrestrial organic compounds in the primitive Earth environment. Experiments designed to verify this hypothesis

have been conducted using photon beams from synchrotron-radiation light sources and proton, ion, or electron beams from high-energy particle accelerators, simulating electromagnetic radiation and cosmic rays from extraterrestrial circumstances. Small inorganic molecules in the primitive Earth atmosphere, especially nitrogen and carbon monoxide, are not readily decomposed by ultraviolet irradiation. Bond energies of nitrogen and carbon monoxide are 9.76 and 11.09 eV, respectively, corresponding to the photon energy of vacuum ultraviolet light. Higher-energy photons from the vacuum ultraviolet to X-ray region are therefore required for direct photolysis and to trigger the subsequent chemical processes that synthesize organic compounds.

Takahashi et al. (1999) simulated the process using 1–2 keV X-ray irradiation from a synchrotron source on a mixture of carbon monoxide, nitrogen, and water that represents the primitive Earth atmosphere. In the hydrolyzed product, several kinds of amino acids were detected by high-performance liquid ► [chromatography](#). The amount of glycine and alanine increased with the total energy absorbed by the gas molecules. The G-value (number of produced molecules per 100 eV absorbed energy) of the glycine production was 0.004, which was smaller than that of the proton beam irradiation by one order of magnitude. The antipodal optical isomers of alanine

were generated in almost equal quantities. The results show that the precursors for amino acids can be produced through X-ray-induced photolysis of inorganic molecules followed by synthesis into organic compounds. The X-ray irradiation effects can be attributed to two reaction schemes: (1) photochemical reactions preceded by core-level electronic excitation of the molecules and (2) radiation chemical reactions preceded by secondary electron generation.

Cross-References

- [Photochemistry](#)
- [Photochemistry, Atmospheric](#)
- [Radiochemistry](#)

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X-Rays (Stellar)

Thierry Montmerle
Institut d'Astrophysique de Paris, CNRS/
Université Paris, Paris, France

Keywords

Convection · Magnetic activity · Magnetic fields · Radiative force · Stellar winds

Synonyms

[Radiation](#)

Definition

In astronomy, the term “X-rays” corresponds to high-energy radiation seen in the 0.1–10 keV range. Among celestial bodies, all types of stars emit X-rays, with the exception of A-type stars (mass $\sim 2 M_{\odot}$, where $M_{\odot}$ is for one solar mass, effective temperature $\sim 10,000$ K on the main sequence). In terms of internal structure, A stars are at the boundary between “late-type,” cooler, lower-mass stars (equivalently “solar-type” stars), which have an outer convective zone and an inner radiative zone, and “early type,” hotter, higher-mass stars, which have a convective core and an outer radiative zone. Cool stars emit X-rays as a result of reconnection of magnetic fields generated by the dynamo effect in their outer convective zone, while hot stars emit X-rays as a result of shocks in the winds accelerated by radiation.

Overview

Stellar X-ray emission is ubiquitous: nearly all stars show some form of activity which translates into X-ray emission at some level. The X-ray emission mechanism is “thermal,” i.e., ► [bremsstrahlung radiation](#) is produced by gas heated to $\sim 10^6$ – 10^7 K mainly in two ways, depending on the nature of the stellar outer layers. In cool stars, the path to X-ray emission follows several steps, lasting several hours from beginning to end: convection → dynamo effect → surface magnetic fields → reconnection of magnetic field lines of opposite polarity → gas heating to million degrees → X-ray emission (flares) → cooling.

In hot (massive) stars, in general, magnetic fields are not involved, because the outer layers of hot stars are radiative, i.e., they are in stable gravitational equilibrium. However, radiation exerts a force on the atoms, and the uppermost layers, which have a lower density, are pushed away from the star and give rise to a *radiative stellar* wind. The resulting mass loss can be considerable for massive stars (in particular O stars and Wolf-Rayet stars). This is because their effective temperature can be very high (up to 10^5 K), producing a mass loss of $1 M_{\odot}$ in 1 Myr, at velocities reaching several 1000 km/s. But it can be shown that these

stellar winds are “radiatively unstable,” some parts of the wind being temporarily pushed more efficiently than others. This creates shocks within the wind, strong enough to heat parts of the wind to X-ray temperatures. In this case, the mechanism for X-ray emission is quite different from cool stars, as it does not involve magnetic fields. The steps are stellar UV radiation → radiative force → acceleration of heavy atoms → stellar wind (mass loss) → instabilities in the wind → supersonic shocks → sustained X-ray emission.

However, for some stars a “hybrid” mechanism (radiation + magnetic fields) has been found. Indeed, large-scale, stable magnetic fields (“magnetospheres”) have been detected and measured in a few percent of massive, hot stars. The reason is probably that these stars have somehow retained their “primordial” magnetic fields, i.e., the magnetic field built in the clump of interstellar matter that collapsed to form them. These stars have “magnetically confined” winds, with two properties: (1) the fact that the wind is forced to flow along magnetic field lines weakens the radiative instability and (2) in the closed regions of the magnetosphere, the flows from opposite latitudes are forced to converge at large distances from the star and eventually collide against each other, again heating the gas to X-ray temperatures.

This context explains in particular why A stars, which are fully radiative and have no magnetic fields, show no activity and do not emit X-rays.

Cross-References

- ▶ [Activity, Magnetic](#)
- ▶ [Bremsstrahlung Radiation](#)
- ▶ [Hertzprung-Russell Diagram](#)
- ▶ [Magnetic Field](#)

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XANES

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan
Blue Marble Space Institute of Science,
Washington, DC, USA

Georgia Institute of Technology, Center for
Chemical Evolution, Atlanta, GA, USA

Synonyms

[X-ray absorption near-edge structure](#)

Definition

XANES is a form of atomic adsorption spectroscopy used in chemical analysis. XANES can be used to determine a great deal of chemical information, for example, the formal valence of an atom and its coordination environment. XANES spectra can be used as a probe of the unoccupied band structure of a material. The near-edge structure is characteristic of environment and valence state. In a sample containing a mixture of sites or compounds, the measured spectra can be fit with linear combinations of XANES spectra of known species, and the proportion of each in the sample can be determined. Since X-ray absorption edges of light elements such as C, N, and O are located in soft X-ray region, analysis often must be conducted under high vacuum conditions. This technique has been applied to the characterization of meteoritic organics together with STXM (scanning transmission X-ray microscopy).

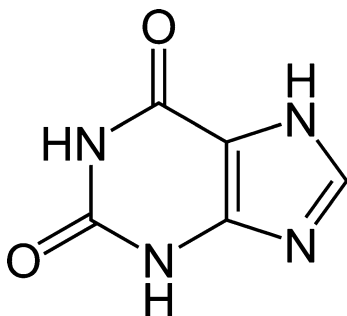
Xanthine

Kensei Kobayashi

Department of Chemistry, Yokohama National
University, Yokohama, Japan

Synonyms

[3,7-Dihydropurine-2,6-dione](#); [1H-purine-2,6-dione](#)



Xanthine, Fig. 1 Molecular structure of xanthine

Chemical Formula



Definition

Xanthine is one of the purine bases, which is widely distributed in the terrestrial biological system, though it is not included among the canonical five nucleic acid bases. Figure 1 shows a molecular structure of xanthine. Its molecular weight is 152.11. Its nucleoside is xanthosine. It is formed by hydrolysis of guanine or is enzymatically converted from guanine by guanine deaminase. It has been reported that some purine bases and pyrimidine bases including canonical nucleic acid bases existed in extracts from carbonaceous chondrites, but the detected bases have not been the same. Among various purines and pyrimidines, only xanthine was reported to be detected as a major base in Murchison meteorite both by GC/C/MS (Martins et al. 2008) and LC/MS (Callahan et al. 2011).

Cross-References

- Adenine
- Cytosine
- Guanine
- Meteorite, Murchison
- Nucleic Acids

- Thymine (T)
- Uracil (Ura)

References and Further Reading

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XDR

William M. Irvine
University of Massachusetts, Amherst, MA, USA

Synonyms

X-ray dissociation region; X-ray dominated region

Definition

XDRs are regions of the ► [interstellar medium](#) where the chemistry of the gas and dust is dominated by hard X-ray radiation (i.e., photon energies greater than about $1 \text{ keV} = 1.6 (10)^{-16} \text{ J}$, corresponding to wavelengths of about 1 nm or less). They are most prominent in the gas and dust neighboring the supermassive black holes in the nuclei of galaxies. The nomenclature is derived from the photon-dominated regions (PDRs) created by the far-ultraviolet flux near, for example, very hot stars (OB stars).

Cross-References

- Black Holes
- OB Association

Xerophile

Ricardo Amils
Departamento de Biología Molecular,
Universidad Autónoma de Madrid, Madrid, Spain

Definition

A xerophile is an ► [extremophile](#) organism that can develop with a low availability of ► [water](#), also known as ► [water activity](#). Xerophiles can survive in environments with water activity below 0.8. ► [Endolithic](#) and halophilic microorganisms are often xerotolerant.

Cross-References

- [Endolithic](#)
- [Halophile](#)

- [Water](#)
- [Water Activity](#)

X-ray Absorption Near-Edge Structure

- [XANES](#)

X-ray Dissociation Region

- [XDR](#)

X-ray Dominated Region

- [XDR](#)

Yeast

Aldo González

Centro de Biología Molecular, CBMSO Consejo Superior de Investigaciones Científicas
Universidad Autónoma de Madrid, Madrid, Spain

Keywords

Asci · Budding · *Cryptococcus* · Fungi · *Saccharomyces*

Definition

Yeasts are unicellular ► [fungi](#) that in some cases present dimorphism depending on culture media conditions.

Overview

According to recent revisions, yeasts are classified in the kingdom *Mycota*, phylum *Eu-Mycota*. They were included in the class *Endomycota* due to their capacity to form sexual spores in “asci.” In this group, monokaryon spores are released after one meiosis division, and afterward their nuclei could be joined to form dikaryon cells. This process was detected for the first time in this group of microorganisms. In general, their system of reproduction is based on a life cycle that combines firstly reproduction by budding and secondly by

division (binary fission) which is cellular division by simple mitosis and recombination after meiotic reduction. As with filamentous fungi, yeasts are grouped as (1) *Ascomycete*-type yeasts that produce ascospores, (2) *Basidiomycete*-type yeasts that produce basidiospores, and (3) *Deuteromycete*-type yeasts that do not produce sexual spores but have biochemical and/or morphological characteristics, which approximate them to some of the two large groups with complete sexual cycles. *Deuteromycete*-type yeasts follow the same pattern as filamentous fungi, that is, they stay in this group unless they find another sexually compatible cell in nature (mating type). When this event happens, mating occurs, and the zygote is formed. Afterward is the turn of the dikaryon; meiosis takes place which will regenerate the new sexual cycle. To date, more *Ascomycete*-type yeasts than *Basidiomycete*-type yeasts have been identified, mainly because of their importance to the field of nutrition where the genus *Saccharomyces* stands out. In recent years, the pathologies caused by species of *Cryptococcus* in patients with immunodeficiency have given rise to significant advances in the study of those genera that have a complete sexual cycle. Their dependence on a sexual cycle facilitates advances in the genetic and biochemical studies of these microorganisms. Their enormous capacity to reproduce in liquid culture allows experimentation, and the production of the sexual cycle under laboratory conditions allows the genetic manipulation of their

DNA molecules. The systematic classification of the yeasts that do not have well-defined sexual reproduction has led to their systematic classification using only characteristics of asexual reproduction as the basic criterion. Nevertheless, in the special case of yeasts, this asexual reproduction does not present clear morphological differences as is the case for filamentous fungi. For this reason, the taxonomy of this group is based on other aspects such as the structure of cell walls and biochemical criteria. Among the main biochemical tests are their ability to ferment and assimilate hydrocarbons and other compounds. These biochemical criteria contribute to differentiating them into groups. For instance, nitrate assimilation or growth on DBB enables *Asco*- or *Basidiomycete*-type yeasts to be differentiated. Therefore, this classification does not respond to phylogenetic criteria, and the grouping in class, subclass, order, family, genus, and species is merely instrumental. Nowadays, the analysis of DNA sequences (e.g., 18 S rDNA) has provided researchers with an extensive database with which to compare and reorganize their taxonomy at the phylogenetic level and reorder the different groups at the level of genus. To date, approximately 600 species of yeasts have been characterized.

Cross-References

- [Carbon Cycle, Biological](#)
- [Eukarya](#)
- [Fungi](#)
- [Heterotroph](#)
- [Phylogeny](#)

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Yellowstone

- [Yellowstone National Park, Natural Analogue Site](#)

Yellowstone Caldera

- [Yellowstone National Park, Natural Analogue Site](#)

Yellowstone National Park, Natural Analogue Site

Daniele L. Pinti
Geotop, Research centre for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

Keywords

Yellowstone · Supervolcano · Hydrothermal environments · Hot springs · Mars analogue site · Remote sensing · Thermophiles

Synonyms

Yellowstone; Yellowstone caldera

Acronyms

YNP

Definition

Yellowstone National Park is the first US national park, established in 1872. It is located largely in the northwest corner of Wyoming and extending into Montana and Idaho with a total surface area of 8983 km² and includes the Yellowstone Caldera (a caldera is a large crater formed by the collapse of the volcanic edifice after a powerful eruption). The Yellowstone Caldera is considered the largest supervolcano in North America. The Yellowstone National Park has been extensively studied in astrobiology for its many geothermal features, hydrothermal-related mineralization, and the microbial communities that flourish near or within the hot springs.

History

Established by the US Congress and signed into law by President Ulysses S. Grant on March 1, 1872, Yellowstone National Park (YNP) is the first national park in the USA and in the world. Commissioned to the US Army between 1886 and 1916, the administration of the park was passed to the US National Park service in 1917. In 1978, the site of the YNP was named a UNESCO World Heritage Site.

Overview

The Yellowstone National Park (YNP) is the centerpiece of the Greater Yellowstone Ecosystem, the largest remaining nearly intact ecosystem in the Earth's northern temperate zone. Together with its abundant surface hydrothermal

manifestations, nearly 10,000 including 300 geysers, the YNP is one of the best places to study astrobiology and particularly extremophiles microbial communities that flourish near hot springs.

The interest in astrobiology for studying the YNP is dual. First YNP is the site of the largest supervolcano in the North Hemisphere and thus it can be considered a “life killer,” for the consequences that a large super eruption could have had or could have in the future for the life on our planet or in moons and exoplanets where such large eruptions could occur. The second, as above indicated, for studying the numerous geothermal features, which house numerous microbial communities. This volcanic environment could be the natural analogue of early ecosystem on Earth and possibly other planets such as Mars.

YNP is a supervolcano: following the USGS definition, a supervolcano is “a volcanic centre 67 that at one point in time it erupted more than 68 1000 cubic kilometres of material”. For sake of comparison, the Plinian eruption of the Vesuvius of 79 AC that lasted 2 days and destroyed the towns of Pompei and Herculaneum, erupted less than 1 km³ of material. The Yellowstone volcanism is caused by the overriding of the North American plate on a mantle plume, causing the formation of a hotspot, as Hawaii did.

The Yellowstone supervolcano is centered on the Yellowstone caldera, the largest volcanic system in North America. The caldera – a large cauldron-like hollow that forms shortly after the emptying of a magma chamber during cataclysmic volcanic eruptions – was formed by exceptionally large explosive eruptions. Two of the YPN super eruptions are the larger even recorded in geological record and only rivaled by the eruption of the Toba supervolcano in Sumatra, 78,000 years ago. There are two magma chambers under the Yellowstone caldera. The first one is an upper-crustal single magma chamber about 60 km long, 29 km wide, and 5 to 12 km deep. Recently, Huang et al. (2015) have imaged the presence of an even larger and deeper magma chamber (4x in size than the shallower one described above), which connects directly with the mantle plume head.

The current Yellowstone caldera was created by a cataclysmic eruption that occurred 640,000 years ago (the Lava Creek Tuff eruption; Christiansen, 2001), which released more than 1000 km³ of ash, rocks and pyroclastic materials, and created a 1 km deep and 45 to 72 km large caldera depression. Yet, the most violent known eruption occurred 2.1 million years ago, ejecting 2450 km³ of volcanic material and depositing the Huckleberry Ridge Tuff (Christiansen, 2001). A smaller eruption occurred 1.3 million years ago, ejecting 280 km³ of material. Time recurrency of super eruptions in Yellowstone is roughly 600–800 kyrs, alarming authorities on the possibility of a future devastating eruption in North America. Indeed, each of the three climactic eruptions released vast amounts of ash that blanketed much of central North America, falling many thousands of kilometers away. The amount of ash and gases released into the atmosphere probably caused significant impacts to world weather patterns and led to the extinction of some species, primarily in North America.

Major volcanic activity ended 70,000 years ago. Within the YPN area, around 10,000 geothermal features and about two-thirds of the world's geysers are concentrated, likely the largest hydrothermal area in the world. Hydrothermal surface deposits and associated microbial mats and microbial communities of meso- and ► [thermophiles](#) live in the hot and highly mineralized waters of the Great Prismatic Springs. These extremophile communities have been the focus of numerous studies. Walter et al. (1972) recognized the bacterial origin of ► [stromatolites](#) composed of nearly amorphous silica. He also considered that hot springs were a good depositional analogue for ► [banded iron formations](#). Geobiological studies at Yellowstone have resulted in the discovery and identification of extremely acidic (pH = 1) ► [endolithic](#) microbial communities inhabiting the pore space of rocks in geothermal deposits. Subjected to silica mineralization, such endolithic communities constitute ► [biomarkers](#) that might potentially be preserved in the geological record and could provide

important clues about ancient life associated with ► [hydrothermal environments](#) on the Earth or elsewhere in the Solar System (Walker et al. 2005). Mineral deposits associated with the hot springs have also been used for testing remote sensing instrumentation (infrared and visible spectroscopy) for future exploration of extinct mineralized hydrothermal deposits on ► [Mars](#) (Helmann and Ramsey 2004).

The discovery of a heat-resistant bacteria at Yellowstone led to the discovery of the polymerase chain reaction (PCR, or DNA amplification) by Kary B. Mullis in 1983 (e.g., Saiki et al., 1988), a finding that earned him the 1993 Nobel Prize in Chemistry.

Cross-References

- [Banded Iron Formation](#)
- [Endolithic](#)
- [Geyser](#)
- [Hydrothermal Alteration](#)
- [Hydrothermal Environments](#)
- [Hydrothermal Vent Origin of Life Models](#)
- [Mars Analogue Sites](#)
- [Mars Analogues](#)
- [Mesophile](#)
- [Mud Volcanism](#)
- [Stromatolites](#)
- [Terrestrial Analog](#)
- [Thermophile](#)

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Yinghuo-1

Michel Viso
Innovaxiom, Paris, CX, France

Definition

Yinghuo-1, a Chinese satellite to explore ► [Mars](#), was part of the ► [Phobos-Grunt](#) mission which was lost few days after the launch (November 9, 2011). The probe, almost a cube ($71 \times 75 \times 60$ cm) weighing 110 kg, was dedicated to study the Martian atmosphere. The five-instrument payload included a plasma package, a magnetometer, a radio-occultation sounder, and an optical imaging camera with 200 m resolution at the lowest altitude.

YY Orionis Star

Steven W. Stahler
Department of Astronomy, University of
California, Berkeley, CA, USA

Keywords

Young star · Stellar wind

Definition

One of the characteristics of ► [T Tauri stars](#) is the generation of powerful winds. These winds are found spectroscopically, through the presence of a blue-shifted absorption dip in an optically thick emission line. Such lines are said to have P Cygni profiles. In YY Orionis stars, some lines have inverse P Cygni profiles. That is, the dip occurs in the red part of the spectrum, a signature that relatively cool gas is falling toward the star. From the types of lines in which the two different profiles appear, it seems that material close to the star is falling onto it while gas farther out is moving in a wind. A large fraction of classical T Tauri stars exhibit this complex behavior.

Cross-References

- [Pre-Main-Sequence Star](#)
- [T Tauri Star](#)

Z

Z (Astrophysics)

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

In astrophysics, Z is used to denote the mass fraction of all elements except hydrogen and helium in a star or other astronomical object. Those elements, considered as “heavy elements” and often called “metals” by astronomers, differ with respect to hydrogen and helium because their production implies processing by a star, either through nuclear reactions during the Main Sequence or giant phase or as a consequence of a ► [supernova](#) explosive event at the end of the star’s life. The abundance of these heavy elements is thus a very important indicator of the processing by stars in a galaxy.

In contrast, lower case z is used by astronomers to denote the ► [redshift](#) of a (typically) distant object moving away from the observer.

Cross-References

- [Main Sequence, Star](#)
- [Metallicity](#)
- [Stellar Evolution](#)
- [Supernova](#)

Z-Value

Catharine A. Conley
NASA Headquarters, Washington, DC, USA

Definition

The Z -value of a particular bioburden reduction process is the change in temperature that is required to change the ► [D-value](#) (inactivation of 90% of a population of the test microorganism under stated conditions) by one order of magnitude.

Cross-References

- [D-Value](#)
- [Planetary Protection](#)

Zenith

Daniel Rouan
LESIA, Observatoire Paris-Site de Meudon,
Meudon, France

Definition

Zenith is a term coming from the Arabian astronomers that designates the local upward

vertical for an observer at a given location on Earth. That is the direction where celestial objects suffer from the lowest atmospheric absorption.

Cross-References

- [Coordinate Systems](#)
- [Nadir](#)

Zeolites

Daniela Tirsch
German Aerospace Center DLR, Institute of
Planetary Research, Berlin, Germany

Synonyms

[Molecular sieves](#)

Definition

Microporous ► [minerals](#) consisting of AlO_4 SiO_4 tetrahedra, belonging to the group of tectosilicates. They are common hydrous alteration products of volcanic glasses and feldspars. These minerals characteristically emit steam when heated, which originates from adsorbed ► [water](#). Thus, the identification of zeolites on planets indicates the presence of water at the time of mineral formation. On ► [Earth](#), zeolites are common cements in pores of volcaniclastic sandstones and appear to be candidates for cementing ► [volcaniclastic sediments](#) on ► [Mars](#). Spectral analyses indicate the presence of zeolites (e.g., analcime ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$), chabazite ($((\text{Ca}, \text{Na}_2, \text{K}_2, \text{Mg})\text{Al}_2\text{Si}_4\text{O}_{12} \cdot 6\text{H}_2\text{O})$ in Martian dust, rocks, and regolith.

Cross-References

- [Cryovolcanism](#)
- [Earth](#)
- [Mars](#)
- [Mineral](#)
- [Planet](#)
- [Volcaniclastic Sediment](#)
- [Water](#)

Zero Age Main Sequence

Nikos Prantzos
Institut d'Astrophysique de Paris, Paris, France

Definition

The zero age main sequence (ZAMS) is defined by the positions occupied in the Hertzsprung-Russell diagram (luminosity versus effective temperature) by stars that are igniting for the first time their hydrogen fuel. Since the stellar luminosity increases with time during hydrogen fusion, the ZAMS locus for a star of given mass is its lowest position on the main sequence (for a given metallicity and rotational velocity). On the ZAMS, i.e., 4.5 Gyr ago, the Sun was 30% less luminous than today.

Cross-References

- [Hertzsprung-Russell Diagram](#)
- [Main Sequence, Star](#)
- [Stellar Evolution](#)

Zero-G

- [Microgravity](#)

Zinc Isotopes

Terry T. Isson^{1,2}, Mingyu Zhao¹ and Noah J. Planavsky¹

¹Department of Geology and Geophysics, Yale University, New Haven, CT, USA

²University of Waikato, Tauranga, New Zealand

Definition

Zinc has five naturally occurring stable isotopes (⁶⁴Zn, ⁶⁶Zn, ⁶⁷Zn, ⁶⁸Zn, and ⁷⁰Zn) with natural abundances of 48.6%, 27.9%, 4.1%, 18.8%, 0.6%, respectively. Because ⁶⁴Zn and ⁶⁶Zn are the most abundant, variations to the ratio of ⁶⁶Zn/⁶⁴Zn are typically reported, expressed in the conventional delta notation ($\delta^{66}\text{Zn}$) relative to the JMC-Lyon (close to exhaustion) and AA-ETH (latest) Zn standards.

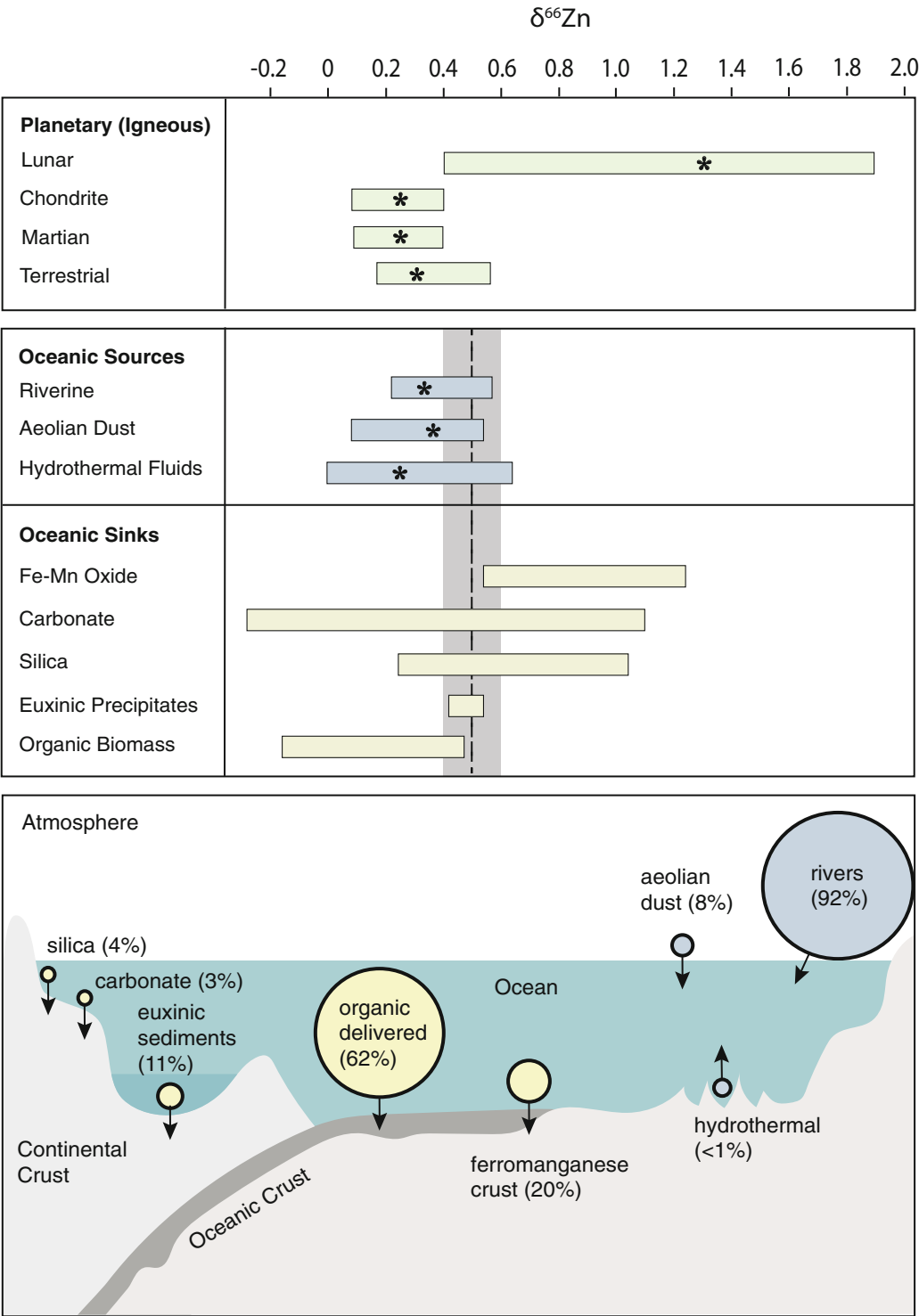
Zinc isotopes are routinely measured by multi-collector inductively coupled plasma source mass spectrometry (MC-ICP-MS). Measurements by the thermal ionization mass spectrometry (TIMS) are also possible but difficult due to the element's high first ionization potential, leading to a low Saha constant. Common column protocols for Zn purification can easily achieve sufficient recovery rate, but the degree of purification should be high for Zn as many elements can generate an interference on Zn isotopic measurements. Mass bias during Zn isotopic measurement can be corrected using techniques such as direct standard sample bracketing, Cu doping, and double spike. The measurement of Zn isotopes on natural samples, though relatively new, has already demonstrated utility in a wide variety of fields including ecology, environmental studies, geology, oceanography, planetary science, and medicine. This entry summarizes some notable applications of Zn isotopic work to astrobiology and the study of Earth's evolution. While mass independent fractionations of Zn isotopes have been predicted to occur with redox reactions between Zn^0 and Zn^{2+} , these have yet to be clearly

demonstrated in natural samples. Therefore, only mass-dependent applications are explored here.

The global cycling of Zn and its isotopic expressions at Earth's surface (e.g., within soils and in seawater) have been found to be dominated to a large degree by biological processes (Fig. 1). This is perhaps unsurprising given that Zn is a key nutrient for all life on Earth. Zn is the second most abundant micronutrient in phytoplankton biomass (Twining and Baines 2013) and is required as a cofactor in the functioning (activity) of over 300 enzymes in all six classes of enzymes, including key enzymes such as carbonic anhydrase and alkali phosphatase. It is well established that Zn plays a fundamental role in the replication and transcription of DNA, gene expression, and intra- and intercellular signaling (Maret 2013). Zinc is, therefore, essential for the growth and development of all known types of life. Culture experiment has demonstrated that Zn can be either toxic or limiting depending on Zn concentration, speciation, and the species of algae or bacteria. Nutrient limitation is never simple, not only because of co-limitation (e.g., Shaked et al. 2006) but also because other trace metals such as Cd and Co can substitute at least some of the functions of Zn (e.g., Price and Morel 1990; Sunda and Huntsman 1995).

Eukaryotes, in particular, have a strong affinity for Zn, relative to unicellular prokaryotes. In fact, based on predicted Zn-binding proteins derived from whole genome sequences, all major eukaryotic clades have been observed to bear high Zn requirements (Dupont et al. 2010; Isson et al. 2018). This is consistent with the most natural measurements of modern eukaryotic phytoplankton which appear to have elevated Zn demands and elevated Zn/C ratios relative to cyanobacteria (Twining et al. 2011). This contrast in Zn usage has been linked to the abundance of proteins (e.g., Zn fingers and RING domains) localized within the nucleus in eukaryotes, which are responsible for DNA–RNA transcription and protein–protein interactions (Dupont et al. 2010).

The distribution of Zn in seawater exhibits a simple nutrient-type profile, indicating that



Zinc Isotopes, Fig. 1 Range of $\delta^{66}\text{Zn}$ values of naturally occurring samples (Top). Planetary samples (green). $\delta^{66}\text{Zn}$ values of sources into and sinks out of the modern oceanic

reservoir (blue and yellow, respectively), fluxes (in %) are represented in the cartoon cross section of Earth's surface environment (bottom)

biological processes play a role in regulating the marine Zn cycle. Recent works that have attempted to reconcile Zn and Zn isotope vertical profiles reveal that in addition to biological uptake, reversible scavenging plays a role in driving Zn export from the surface oceans (Weber et al. 2018). While culture work indicates that the biological assimilation of Zn can be associated with variable δ isotopic fractionation values from the dissolved pool (John et al. 2007), the bulk of organic matter being exported from the marine environment is isotopically lighter than the global seawater average (Isson et al. 2018). This is responsible for sustaining a total dissolved marine isotopic signature that is heavier than that of riverine inputs (Fig. 1). On this basis, Zn isotopes have emerged as a potential tracer for organic matter sequestration and have recently been adopted to reconstruct changes in primary productivity and marine eukaryotic productivity over the course of Earth's history (Isson et al. 2018). In particular, Zn isotopes provide evidence for a late (post 800 Ma) rise of a productive, eukaryote-rich ecosystems (Isson et al. 2018) that are consistent with the emerging view from biomarker work (Brocks 2018).

There have been several other notable applications of Zn isotopes. Zn is a highly volatile element under solar nebular conditions and exhibits strong isotopic fractionation during volatilization. While the Zn isotopic composition of terrestrial and Martian rocks is indistinguishable (Fig. 1), lunar mare basalts span a much larger range. This has been suggested to be indicative of the style of the formation of the moon (Paniello et al. 2012). In medicine, Zn isotopes are currently being developed as a potential biomarker of breast cancer, on the basis that there is a difference in the Zn concentration of breast tissue between its healthy and malignant states and that this process is associated with the preferential enrichment of the tissue in the lighter isotope (Larner et al. 2015). Over the next decade, the use of Zn isotopes can be expected to increase substantially.

Cross-References

- Coenzyme
- Cofactor

- Eukaryote
- Micronutrients

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Zircon

Ian S. Williams
Research School of Earth Sciences, ANU College of Science, The Australian National University, Canberra, ACT, Australia

Keywords

Jack Hills · Hadean · Geochronology · U-Th-Pb isotopes · Oxygen isotopes · Moon · Meteorites

Synonyms

Zirconium silicate

Definition

Zircon is a silicate mineral (zirconium silicate) with the chemical formula ZrSiO_4 (tetragonal crystal system). It is a dense (4.7 g/cm^3), hard (7.5), pale pink to reddish brown, usually fine-grained ($<1 \text{ mm}$) trace mineral common in sedimentary and in silica-saturated (felsic) igneous rocks.

Overview

Zircon occurs in trace amounts in a wide variety of quartz-bearing ► [igneous rocks](#). It is physically and chemically robust under a wide range of geological pressures and temperatures, so it is also common in ► [metamorphic rocks](#) and as a detrital mineral in sediments and sedimentary rocks. Zircon occurs in lunar rocks and regolith and in some classes of meteorites (e.g., chondrites, eucrites, mesosiderites, lunaites).

Crystallizing zircon incorporates a variety of trace elements, including Hf, the Rare Earth Elements (REE), U, and Th. Because it incorporates little Pb and has a high closure temperature for trace element diffusion, zircon is widely used for ► [geochronology](#) using the radioactive decay of U and Th to Pb. U-rich zircon is prone to accumulate radiation damage, becoming metamict

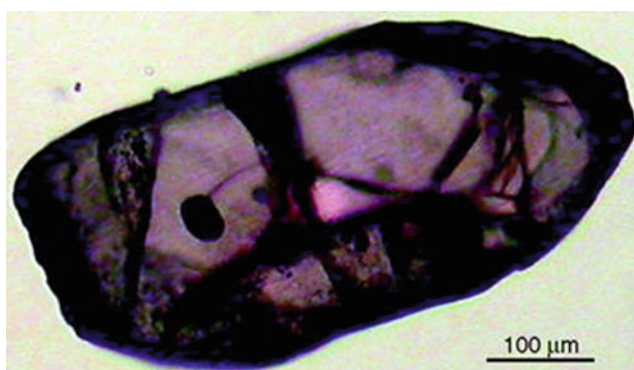
(*metamict* – having a disrupted crystal structure due to accumulated radiation damage), but above about 300°C , the crystal structure anneals.

Zircon grains are commonly zoned, preserving a record of the changing conditions under which they crystallized as chemical and isotopic differences on the scale of a few microns. Zircon can survive the partial melting of its host rock. It is not unusual for zircon grains from igneous or metamorphic rocks with a complex history to consist of a core of protolith zircon surrounded by successive overgrowths of zircon crystallized or recrystallized during later thermal events. The age and nature of those events can be determined by chemical and isotopic microanalyses of U-Th-Pb, O, Hf, and the REE.

The oldest dated terrestrial material is Hadean detrital zircon (Fig. 1) from the Jack Hills, Western Australia (4.4–4.2 Ga). Quartz inclusions in, and the oxygen isotopic compositions of, these zircon grains have been interpreted as evidence for continental crust and oceans on Earth within about 150 Myr of planetary formation (Wilde et al. 2001).

Zircon from lunar rocks and soils provides a direct means of dating the early lunar crust, showing that the lunar magma ocean cooled sufficiently for differentiated rocks to crystallize within 200 Myr of the formation of the Moon and that they continued to be produced for at least 400 Myr thereafter (Meyer et al. 1996). Some eucrites contain zircon of the same age as the Solar System, from which the initial Hf isotopic composition of the Solar System has been determined (Iizuka et al. 2015).

Zircon, Fig. 1 Detrital zircon crystals from the Jack Hills, Western Australia, are the oldest known remnants of crustal rocks from the early Earth. (Photograph: Jane Thorne)



Cross-References

- [Archean Environmental Conditions](#)
- [Cool Early Earth](#)
- [Earth, Formation, and Early Evolution](#)
- [Geochronology](#)
- [Hadean](#)
- [Jack Hills \(Yilgarn Craton, Western Australia\)](#)
- [Oxygen Isotopes](#)

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Zirconium Silicate

- [Zircon](#)

Zodiacal Light

Anny-Chantal Levasseur-Regourd
Sorbonne Univ./LATMOS, Paris, France

Keywords

Asteroidal dust · Cometary dust · Circumstellar disks · Exo-zodiacal clouds · Gegenschein · IDPs · Meteors · Zodiacal cloud

Definition

The zodiacal light is a faint veil of light visible in the Earth's night sky. Brighter towards the Sun and the ► [ecliptic](#), it originates in solar light scattered by a huge cloud of dust particles, mostly of cometary and asteroidal origin. The brightness increases toward the Sun and the near-ecliptic region; it corresponds to an increase in the space density of the cloud, which has a lenticular shape around the Sun. A minor brightness enhancement toward the antisolar region corresponds to a backscattering effect. Thermal emission from zodiacal particles forms, away from the galactic plane, the most prominent component in the near-infrared sky.

History

Although some hints are suspected in ancient texts, Childrey (1661) possibly gave the first description of the zodiacal light. Cassini (1683) provided a detailed interpretation, with the zodiacal light originating in a flattened cloud that scatters better the light when the line of sight gets closer to the Sun and its equator. Dortous de Mairan (1733) suggested that the cloud expands further than the terrestrial orbit. During the nineteenth century, Brorsen (1854) described a slight brightness enhancement around the antisolar direction, later called *gegenschein* by Humboldt, and Wright (1874) provided evidence for the linear polarization of the zodiacal light.

Precise measurements of the brightness and polarization of the zodiacal light have begun in the twentieth century. The question of the stability of the zodiacal cloud on a scale of more than a few centuries or millennia is thus still open, together with that of the characteristics of exozodiacal clouds.

Overview

The zodiacal light, seldom visible through the naked eye as a faint cone of light (Fig. 1), extends over the whole celestial sphere; it represents a

Zodiacal Light,

Fig. 1 Zodiacal light over La Silla. The image was taken in September 2009 at ESO's Observatory in Chile (2400 m, 29° S), facing west after sunset. (From Y. Beletsky)



foreground veil for the observation of faint, possibly extended, astronomical sources. The characteristics of the zodiacal light and of the zodiacal thermal emission allow the retrieval of some of the intrinsic properties of the zodiacal dust, which has recently been found to be, within the inner solar system, mainly built of cometary dust, and thus rich in organic compounds.

Basic Methodology

Introduction

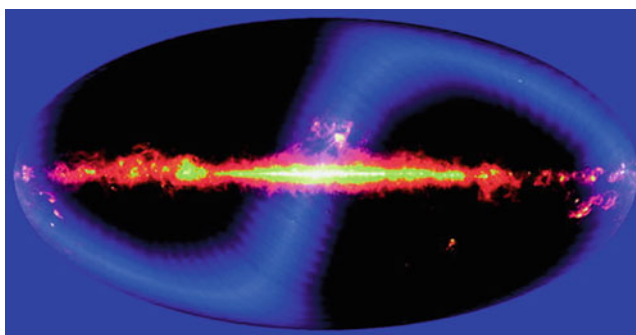
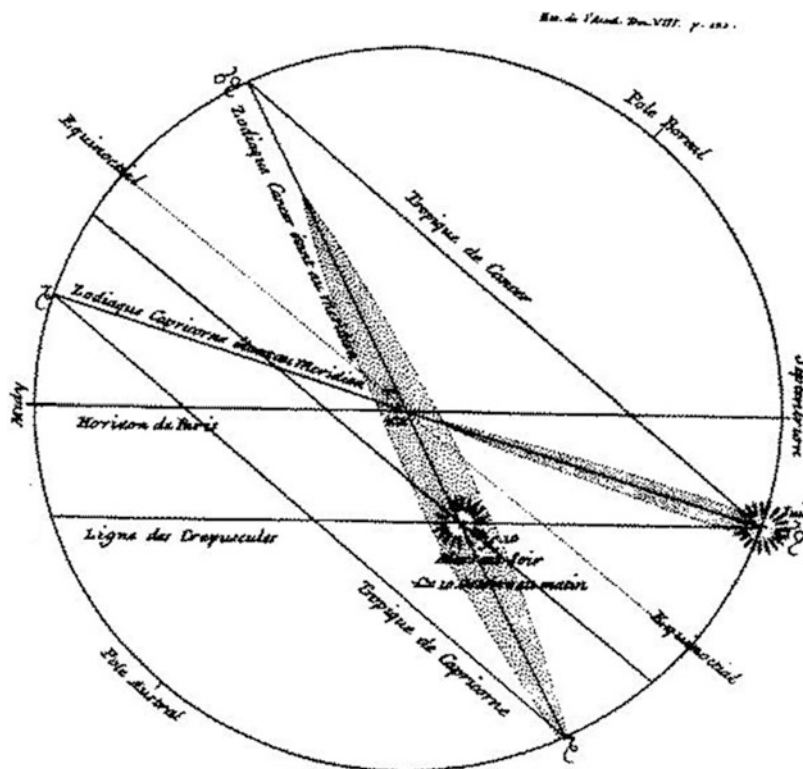
In the absence of contamination by terrestrial lights and moonlight, the zodiacal light appears to the naked eye as a faint whitish cone of light, about 1 h after sunset or before sunrise. It is visible when the zodiac (that is, the ring of constellations along the ecliptic) is high above the horizon. It is thus relatively easy to detect in tropical latitudes, while, in midlatitudes, it is mainly detectable in spring toward the west after the evening twilight and in autumn toward the east before the morning twilight (Fig. 2). Spectrographic observations have established that the zodiacal light spectrum is similar to that of the Sun. Together with measurements of the partial linear polarization, expected from solar light scattered by an optically thin medium, such results have confirmed that the zodiacal light originates in the scattering of light by the zodiacal cloud. This interplanetary cloud is formed by tiny dust particles (in the tens of micron-sized range)

and mostly extends from the Sun to the asteroidal belt. Forward scattering makes it rather bright when observing at small solar angles, while back-scattering builds up the gegenschein.

Although the zodiacal light is entangled with other components of the light of the night sky, precise ground-based measurements, together with circum-terrestrial and interplanetary space observations (from, e.g., OSO 2 and 5, D₂A, Skylab, Helios 1 and 2, Pioneer 10 and 11, SMEI or New Horizons spacecraft), have pointed out spatial and annual variations, respectively, attributed to the crossing of near-Earth meteoritic streams (Levasseur and Blamont 1973) and to the localization of the plane of symmetry of the cloud; at 1 au from the Sun, it is close to the invariable plane of the solar system, with an ascending node about 96° and an inclination about 1.5° (Dumont and Levasseur-Regourd 1978). After corrections are made, tables and maps providing information on the average zodiacal light brightness and linear polarization, as a function of the ecliptic latitude and the helio-ecliptic longitude of the observations, are derived (Leinert et al. 1998; Buffington et al. 2016; Lasue et al. 2020). Toward the ecliptic poles (where the zodiacal light is minimal), the zodiacal brightness is about $76 \times 10^{-8} \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ for a wavelength of about 0.55 μm , and its partial linear polarization is about 20%. Studies in the infrared domain (from, e.g., IRAS, COBE, or Spitzer spacecraft, Fig. 3) have established that this thermal emission

Zodiacal Light,

Fig. 2 Drawing of the zodiacal light from midlatitudes during springtime, while the ecliptic is raising steeply above the horizon. (From J.D. Cassini)



Zodiacal Light, Fig. 3 Image of the infrared sky at 25, 60, and 100 μm (represented, respectively, in *blue*, *green*, and *red* colors) obtained from the NASA COBE spacecraft. The Milky Way lies horizontally across the

middle of the image; the zodiacal thermal emission is also a prominent feature by 25 μm (here in *blue*) in the vicinity of the ecliptic plane

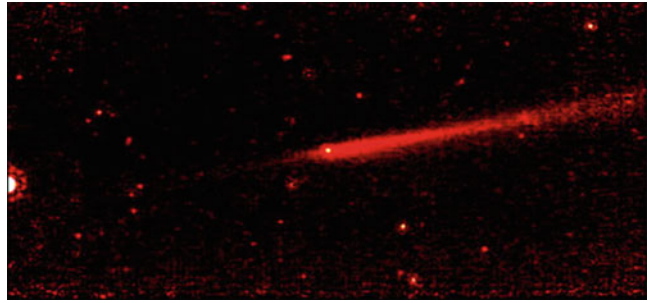
is a most prominent component in the 5–100 μm spectral domain. Infrared surveys accentuate the spatial variations that typically originate in low-ecliptic latitude dust bands attributed to collisions between [▶ asteroids](#), and in dust trails along the perihelion part of the orbits of several short-period [▶ comets](#) (Fig. 4).

Dust Properties, Orbits, and Sources

The brightness and thermal emission vary along the observational line-of-sight. Inversion techniques are thus needed to tentatively derive local values of brightness and polarization, as well as estimations (through numerical and experimental simulations) of the properties of the dust particles,

Zodiacal Light,

Fig. 4 Dust trail of comet 67P/Churyumov-Gerasimenko. The trail was detected from the NASA Spitzer Space Telescope at 24 μm . (From W. Reach et al.)



(e.g., shape, geometric albedo, spatial density, temperature). Such approaches have typically established that the tiny dust particles are not spherical and may consist of dark aggregates with various porosities. The size distribution of the dust particles (as deduced from near-Earth cumulative fluxes measurements) follows approximately a power law with an index of -3 for particles below 20 μm , with a value of about -4.4 for larger sizes. For solar distances of about 1 AU in the ecliptic, the dust particles consist of a roughly equally divided mixture of minerals, such as silicates, and more absorbing organic molecules, such as HCN polymers and various tholins (e.g., Lasue et al. 2007, 2020). The zodiacal cloud is heterogeneous: near the ecliptic plane at 90° phase angle; the local albedo increases with decreasing solar distance R as about $R^{-0.3}$, while the local polarization decreases with decreasing R and presents a steep decrease below 0.3 au (Dumont and Levasseur-Regourd 1988; Levasseur-Regourd et al. 1991).

Such results are in agreement with the dynamical properties of the particles that build up the zodiacal cloud (Dermott et al. 2001; Koschny et al. 2019). Their orbits are not stable, since they are not only subject to the solar gravity, but also to radiative forces, such as the ► [Poynting-Robertson drag](#) that causes their orbits to spiral towards the Sun and the solar radiation pressure that expels the smallest and fluffiest particles (for sizes below $\approx 1 \mu\text{m}$) out of the solar system. Meanwhile, dust particles may suffer weathering, collisions, radiative torques, or sublimation of their (semi-volatile) organics, and thus fragmentations, leading to the abovementioned drastic decrease in polarization close to the Sun.

Therefore, assuming that the zodiacal cloud is (or at least has been for a while) stable, continuous sources of new particles are required.

The question of the origin of dust particles that replenish the zodiacal cloud has been extensively discussed. After the detection of asteroidal bands and cometary trails by IRAS in 1983, it had been suggested that the main source could be dust released by asteroidal collisions (Sykes and Greenberg 1986), while evidence was found for dust particles trapped in a circumsolar ring in resonant lock with the Earth (Reach 2010). Other minor sources of dust have been detected, such as dust from Mars, from the Jupiter and Saturn systems or interstellar dust (e.g., Rowan-Robinson and May 2013; Jorgensen et al. 2020). However, the main source, at least in the inner solar system, presently seems to come from periodic comets (Nesvorný et al. 2010; Plane 2012). Such dust particles are estimated to contribute for at least 80% in mass to the flux of micrometeorites reaching the Earth upper atmosphere and to plunge into it at relative velocities below 15 km/s (Carillo-Sanchez et al. 2016; Nesvorný et al. 2020). The properties of interplanetary dust particles collected in the atmosphere (CP-IDPs) or in Antarctica snows (UCAMMs) indeed fairly agree with those of cometary dust particles derived from missions to periodic comets, such as ► [Vega](#), ► [Giotto](#), ► [Stardust](#), and all the more ► [Rosetta](#). While such particles have low densities (few tens to hundreds of kg/m^3), are aggregates of grains (down to sizes $\approx 100 \text{ nm}$) with hierarchical structures, and are rich in carbonaceous compounds, it is indeed estimated that irregularly shaped particles and fluffy aggregates bring up to $\sim \pi^3$ times more organics to the Earth's

surface in volume than compact spherical particles (e.g., Mannel et al. 2016; Bardyn et al. 2017; Levasseur-Regourd et al. 2018).

Astrobiological Implications, Back in Time and Away in Space

There is evidence for a major contribution of cometary dust to the zodiacal cloud and to the flux of cosmic dust particles reaching the surface of the Earth (Flynn et al. 2004). During the ► [Late Heavy Bombardment](#), which possibly took place about 4 million years ago, large amounts of cometary dust could be released by cometary nuclei injected in the inner solar system. The spatial density of the zodiacal cloud was orders of magnitude greater and the zodiacal light was at least 10^4 times brighter than nowadays (Nesvorný et al. 2010). The fluffy structure and moderate velocity of dust particles of cometary origin would have favored the survival of their organic compounds during their atmospheric entry (Levasseur-Regourd et al. 2006, 2018). Such dust particles, mostly coming periodic comets, are also a major source of cosmic dust in the atmospheres of terrestrial planets, and even possibly of giant planets (Plane et al. 2018; Carillo-Sanchez et al. 2020). They could possibly have significantly contributed to the enrichment of early Earth and telluric planets in carbonaceous compounds.

Far away from our solar system, circumstellar disks (such as protoplanetary and debris disks) and exozodiacal dust clouds have been discussed as a potential source of noise in the detection of exoplanets, and specifically of exo-Earths inside the star's habitable zone. While modeling of dust in such disks seems to favor the presence of irregular porous particles, instead of compact spherical particles (Levasseur-Regourd et al. 2020), a good understanding of the properties of our zodiacal cloud is mandatory to define relevant models of exo-zodiacal clouds. While a significant part of their dust may, as well as in our solar system, originate in small bodies, many questions about the contribution of dust streams from ► [hot Jupiters](#) and the geometries of planetary systems with highly eccentric planets would need to be carefully considered.

Key Research Findings

Source of the Zodiacal Light

The zodiacal light originates in the scattering of solar light by a wide cloud of dust particles, which somehow extends from the Sun to the asteroidal belt along the ecliptic plane. Numerous observations, together with numerical and experimental simulations, have established that these dust particles are irregular, porous, and rich in organic matter.

Origin of Zodiacal Dust Particles

The main source of zodiacal dust particles seems to be, in the inner solar system, dust released by periodic comets. Theoretical and observational approaches have established that dust particles from periodic comets contribute for at least 80% in mass to the flux of micrometeorites reaching the Earth upper atmosphere.

Astrobiological Significance

There is evidence for a major contribution of cometary dust to the zodiacal cloud and to the flux of cosmic dust particles reaching the surface of the Earth. During a ► [Late Heavy Bombardment](#), fluffy zodiacal dust particles entering the atmosphere of terrestrial planets at rather low speeds could have released huge amounts of organic matter on their surfaces.

Future Directions

Studies of zodiacal light and interplanetary dust had flourished at the beginning of the space age with concerns about the risks of impacts on spacecraft, fortunately found to be limited by the low spatial density of the zodiacal dust. Key questions are presently related to differences between periodic and dynamically new comets, and to the delivery of organics to planets and exoplanets, nowadays and in the early solar system, not to mention interstellar comets and exo-zodiacal dust.

Future space missions are expected to provide answers to the abovementioned questions. Comet Interceptor mission (an ESA-JAXA project) could reveal crucial differences between the properties

of dust within periodic comets and dynamically new comets. An interstellar probe, as presently studied in the USA, could perform in situ studies of zodiacal dust and of interstellar dust in the local galactic environment. Meanwhile, new measurements of zodiacal and exozodiacal light, together with more elaborate numerical and experimental simulations (on Earth and under long duration microgravity environment) are being developed.

Cross-References

- Asteroid
- Comet (Nucleus)
- Debris Disk
- Dust Grain
- Ecliptic
- Exozodiacal Light
- Giotto Spacecraft
- Hot Jupiters
- Interplanetary Dust Particle
- Late Heavy Bombardment
- Poynting-Robertson Drag
- Rosetta Spacecraft
- Stardust Mission
- Vega 1 and 2 Spacecraft

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Zwitterion

Henderson James Cleaves

Earth-Life Science Institute (ELSI), Tokyo
Institute of Technology, Tokyo, Japan

Blue Marble Space Institute of Science,
Washington, DC, USA

Center for Chemical Evolution, Georgia Institute
of Technology, Atlanta, GA, USA

Definition

In chemistry, a zwitterion (from the German “hybrid ion”), or inner salt, is a compound containing both a formal positive and a formal negative charge on different atoms. As the molecule contains two opposite charges, it is electrically neutral. Some common examples of zwitterions are ► [amino acids](#) such as ► [glycine](#) (at physiological pH, as the state of the ionizable groups is pH dependent), although many amino acids contain a third ionizable group. Most zwitterions are fairly soluble in water and thus poorly soluble in many organic solvents.

Cross-References

- [Amino Acid](#)
- [Glycine](#)

Astrobiological Data and Chronological History of Life on Earth

General Data

Muriel Gargaud¹ and William M. Irvine²

¹Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

²Department of Astronomy, University of Massachusetts, Amherst, MA, USA

International System Units

Basic units	Name	Symbol	
Length	Meter	m	
Mass	Kilogram	kg	
Time	Second	s	
Electric current	Ampere	A	
Thermodynamic temperature	Kelvin	K	
Amount of substance	Mole	mol	
Luminous intensity	Candela	cd	
Additional units	Name	Symbol	
Plane angle	Radian	rad	
Solid angle	Steradian	sr	
Derived units	Name	Symbol	
Energy	Joule	J	$\text{m}^2 \text{kg s}^{-2} \equiv \text{N m}$
Force	Newton	N	$\text{m kg s}^{-2} \equiv \text{J m}^{-1}$
Pressure	Pascal	Pa	$\text{m}^{-1} \text{kg s}^{-2} \equiv \text{N m}^{-2}$
Electric charge	Coulomb	C	s A
Magnetic flux	Weber	Wb	$\text{m}^2 \text{kg s}^{-2} \text{A}^{-1}$
Magnetic flux density	Tesla	T	$\text{kg s}^{-2} \text{A}^{-1} \equiv \text{V s m}^{-2}$
Magnetic field strength			A m^{-1}
Inductance	Henry	H	$\text{m}^2 \text{kg s}^{-2} \text{A}^{-2}$
Power	Watt	W	$\text{m}^2 \text{kg s}^{-2} \equiv \text{J s}^{-1}$
Electric potential difference	Volt	V	$\text{m}^2 \text{kg s}^{-3} \text{A} \equiv \text{J C}^{-1}$
Frequency	Hertz	Hz	s^{-1}

Other Units

	Name	Symbol	
Length	Fermi	fm	10^{-15} m
	Angstrom	Å	10^{-10} m
	Micron	μm	10^{-6} m
Time	Minute	min, mn	60 s
	Hour	h	3,600 s
	Day	d	86,400 s
	Year	a, y	$3.156 \times 10^7 \text{ s}$

(continued)

	Name	Symbol	
Volume	Liter	L	$10^{-3} \text{ m}^3 \equiv 1 \text{ dm}^3$
Mass	Ton	t	10^3 kg
Temperature	Degree Celsius	$^{\circ}\text{C}$	Temperature comparison $0^{\circ}\text{C} = 273.15 \text{ K} = 32^{\circ}\text{F}$ $100^{\circ}\text{C} = 373.15 \text{ K} = 212^{\circ}\text{F}$ Temperature scale $\text{K} = ^{\circ}\text{C} + 273.15$
Force	Dyne (cgs system)	dyn	10^{-5} N
Energy	Erg (cgs system)	erg	10^{-7} J
	Calorie	cal	4.184 J
	Electron-volt	eV	$1.6 \times 10^{-19} \text{ J}$
	Kilowatt-hour		$3,600 \times 10^3 \text{ J}$ $\text{J} = 8.6042 \times 10^5 \text{ cal}$
Pressure	Bar	bar	10^5 Pa
	Atmosphere	atm	$1.01325 \times 10^5 \text{ Pa}$
	mercury mm	torr	$1.3332 \times 10^2 \text{ Pa}$
Magnetic flux density	Gauss	gauss	10^{-4} T
Concentration	Molarity	M	$\text{mol} \cdot \text{l}^{-1}$
Molar mass			g/mol
Reaction rate			$\text{cm}^3 \cdot \text{s}^{-1}$
Angle	Degree	$^{\circ}$	$1^{\circ} = \pi/180 = 1.74 \times 10^{-2} \text{ rad}$
	Minute	'	$1' = \pi/10,800 = 2.91 \times 10^{-4} \text{ rad}$
	Second	"	$1'' = \pi/648,000 = 4.85 \times 10^{-6} \text{ rad}$
			$1 \text{ rad} = 57.296^{\circ} = 3.44 \times 10^3'$ $= 2.06 \times 10^5''$

International System Prefixes

10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y
10^1	deca	Da
10^2	hecto	H
10^3	kilo	K
10^6	mega	M
10^9	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zetta	Z
10^{24}	yotta	Y

Fundamental Physical Constants

Newtonian constant of gravitation	G	$6.672\,59(85) \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
Acceleration of free fall on Earth	g	$9.806\,65 \times \text{ms}^{-1}$
Speed of light in vacuum	c	$2.997\,924\,58 \times 10^8 \text{ ms}^{-1}$
Planck constant	h	$6.626\,075\,5(40) \times 10^{-34} \text{ Js}$
Planck mass	$(hc/2\,\pi G)^{1/2}$	$2.176\,71(14) \times 10^{-8} \text{ kg}$
Planck length	$(hG/2\,\pi c^3)^{1/2}$	$1.616\,05(10) \times 10^{-35} \text{ m}$
Planck time	$(hG/2\,\pi c^5)^{1/2}$	$5.390\,56(34) \times 10^{-44} \text{ s}$
Boltzmann constant	k	$1.380\,658(12) \times 10^{-23} \text{ J K}^{-1}$
Black body constant	a	$7.564 \cdot 10^{-16} \text{ J m}^{-3} \text{ K}^{-4}$
Stefan Boltzmann constant	σ	$5.670\,51(19) \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Perfect gas constant	R	$8.314\,510(70) \text{ J K}^{-1} \text{ mol}^{-1}$
Elementary charge	e	$1.602\,176\,462(63) \times 10^{-19} \text{ C}$
Electron rest mass	m_e	$9.109\,389\,7(54) \times 10^{-31} \text{ kg}$
Proton rest mass	m_p	$1.672\,623\,1(10) \times 10^{-27} \text{ kg}$
Neutron rest mass	m_n	$1.674\,928\,6(10) \times 10^{-27} \text{ kg}$
Proton/electron mass ratio		$1\,836.152\,701(37)$
Hydrogen atomic mass		$1.673\,534\,4 \times 10^{-27} \text{ kg}$
Electron rest mass energy equivalent (eV)	$m_e c^2$	$0.511 \times 10^6 \text{ eV}$
Atomic mass unit	u	$1.660\,540\,2(10) \times 10^{-27} \text{ kg} \equiv 1/12 \text{ of } ^{12}\text{C mass}$
Avogadro constant	N	$6.022\,136\,7(36) \times 10^{23} \text{ mol}^{-1}$
Vacuum permittivity constant	$1/(\mu_0 c^2)$	$8.854\,187\,817 \times 10^{-12} \text{ m}^{-3} \cdot \text{kg}^{-1} \text{ s}^4 \text{ A}^2$
Vacuum permeability constant	μ_0	$4\pi \times 10^{-7} \text{ m kg s}^{-2} \text{ A}^{-2}$
Ice melting temperature ($P = 1 \text{ atm}$)	$0\,^\circ\text{C}$	273.150 K
Water triple point (H_2O)		$T = 273.160 \text{ K}, P = 611.73 \text{ Pa (6.11 mbar)}$
Bohr radius	a_0	$0.529\,177\,249(24) \times 10^{-10} \text{ m}$
Electron volt-energy relationship	E_0	$1.602\,177\,33(49) \times 10^{-19} \text{ J}$
Electron volt-wavelength relationship	λ_0	$12\,398.428 \times 10^{-10} \text{ m}$
Electron volt-frequency relationship	ν_0	$2.417\,988\,36(72) \times 10^{14} \text{ s}^{-1}$
Electron volt-temperature relationship	(E_0/k)	$11\,604.45 \text{ K}$

Mendeleev Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 1.00794 H	Helium 2 4.00260 He											Boron 5 10.811 B	Carbon 6 12.011 C	Nitrogen 7 14.006 N	Oxygen 8 15.999 O	Fluorine 9 18.998 F	Neon 10 20.180 Ne
Lithium 3 6.941 Li	Beryllium 4 9.012 Be											Aluminum 13 26.982 Al	Silicon 14 28.086 Si	Phosphorus 15 30.974 P	Sulfur 16 32.06 S	Chlorine 17 35.45 Cl	Argon 18 39.948 Ar
Sodium 11 22.990 Na	Magnesium 12 24.305 Mg											Gallium 31 69.723 Ga	Germanium 32 72.630 Ge	Arsenic 33 74.922 As	Selenium 34 78.96 Se	Bromine 35 79.904 Br	Krypton 36 83.80 Kr
Potassium 19 39.098 K	Calcium 20 40.078 Ca	Scandium 21 44.956 Sc	Titanium 22 47.88 Ti	Vanadium 23 50.942 V	Chromium 24 51.996 Cr	Manganese 25 54.938 Mn	Iron 26 55.845 Fe	Cobalt 27 58.933 Co	Nickel 28 58.69 Ni	Copper 29 63.546 Cu	Zinc 30 65.38 Zn	Indium 49 114.818 In	Tin 50 118.710 Sn	Antimony 51 121.757 Sb	Tellurium 52 127.6 Te	Iodine 53 126.905 I	Xenon 54 131.29 Xe
Rubidium 37 85.468 Rb	Sr 87.62 Sr	Yttrium 39 88.906 Y	Zirconium 40 91.224 Zr	Niobium 41 92.906 Nb	Molybdenum 42 95.94 Mo	Technetium 43 [98] Tc	Ruthenium 44 101.07 Ru	Rhodium 45 102.91 Rh	Palladium 46 106.90 Pd	Silver 47 107.87 Ag	Cadmium 48 112.41 Cd	Thallium 81 204.38 Tl	Lead 82 207.2 Pb	Bismuth 83 208.98 Bi	Po [209] Po	Astatine 85 [210] At	Rn [222] Rn
Cesium 55 132.91 Cs	Barium 56 137.33 Ba		Hafnium 72 178.49 Hf	Tantalum 73 180.95 Ta	Tungsten 74 183.84 W	Rhenium 75 186.21 Re	Osmium 76 190.23 Os	Iridium 77 192.22 Ir	Pt 195.08 Pt	Au 196.97 Au	Hg 200.59 Hg						
Francium 87 [223] Fr	Ra [226] Ra		Rutherfordium 104 [261] Rf	Dubnium 105 [262] Db	Seaborgium 106 [266] Sg	Berkelium 107 [267] Bk	Californium 108 [271] Cf	Einsteinium 109 [272] Es									
			Lanthanum 57 138.91 La	Cerium 58 140.12 Ce	Praseodymium 59 140.91 Pr	Neodymium 60 144.24 Nd	Promethium 61 [145] Pm	Samarium 62 150.36 Sm	Europium 63 151.96 Eu	Gadolinium 64 157.25 Gd	Terbium 65 158.93 Tb	Dysprosium 66 162.50 Dy	Holmium 67 164.93 Ho	Erbium 68 167.26 Er	Thulium 69 168.93 Tm	Ytterbium 70 173.05 Yb	Lutetium 71 174.97 Lu
			Actinium 89 [227] Ac	Thorium 90 232.04 Th	Protactinium 91 [231] Pa	Uranium 92 238.03 U	Neptunium 93 [237] Np	Plutonium 94 [244] Pu	Americium 95 [243] Am	Curium 96 [247] Cm	Berkelium 97 [247] Bk	Californium 98 [251] Cf	Einsteinium 99 [252] Es	Fermium 100 [257] Fm	Mendelevium 101 [258] Md	Nobelium 102 [259] No	Livermorium 103 [260] Lv

METALS

Alkali Metals
 Transition Metals
 Lanthanides
 Alkali Earths
 Other Metals
 Actinides

NON-METALS

Hydrogen
 Halogens
 Other Non-Metals
 Noble Gases

STANDARD CONDITIONS
(P = 100 kPa; T = 298 K)

Gas **Liquid**
Solid **Synthetic**

Astronomical Data

Muriel Gargaud¹, William M. Irvine²,
Daniel Rouan³ and José Cernicharo Quintanilla⁴

¹Laboratoire d'Astrophysique de Bordeaux, Floirac, France

²Department of Astronomy, University of Massachusetts, Amherst, MA, USA

³LESIA, Observatoire Paris-Site de Meudon, Meudon, France

⁴Laboratory of Molecular Astrophysics, IFF-CSIC, Madrid, Spain

Units and General Data

Distance units	
Astronomical unit (AU)	1.495,978,707,00 × 10 ¹¹ m
	206,264.8 AU
1 parsec (pc)	3.085,677,6 × 10 ¹⁶ m
	3.261,563,8 light-years
1 light-year	9.460730 × 10 ¹⁵ m
	6.324 × 10 ⁴ AU
Time units	
1 sidereal day	23 h 56 mn 04.098 s (average time)
1 tropical year	365.2422 average solar days
1 sidereal year	365.2564 average solar days
Accessible universe	
Number of galaxies	~10 ¹¹
Hubble parameter	There is an unsolved tension between the value determined by the Planck satellite consortium: 67.4 km/s/Mpc = 2.1 × 10 ⁻¹⁸ s ⁻¹ and the value derived from Cepheid measurements: 74.0 km/s/Mpc = 2.3 × 10 ⁻¹⁸ s ⁻¹
Age	13.7 Gyr
Dark energy content	69.2%
Dark matter content	25.9%
Baryonic matter content	4.9%
Our Milky Way galaxy	
Number of stars	~10 ¹¹
Diameter	~10 ²¹ m
Baryonic mass (stars + gas)	~5 10 ¹⁰ M _{Sun} ~ (10 ⁴¹ kg)
Dark matter mass (up to virial radius)	~10 ¹² M _{Sun} ~ (2 10 ⁴² kg)
Distance of the Sun to the galactic center	2.4 10 ²⁰ m (=8 kpc)
Sun	
Radius	6.955,08 × 10 ⁸ m
Mass	1.9891 × 10 ³⁰ kg
Solar luminosity	3.845(8) × 10 ²⁶ W
Core temperature	1.557 × 10 ⁷ K
Core pressure	2.334 × 10 ¹⁶ Pa

(continued)

Distance units	
Photosphere temperature	5780 K
Corona temperature	$2\text{--}3 \times 10^6$ K
Average mass density	1.41×10^3 kg m ⁻³
Rotation period	24.5 days at equator, increases with latitude
Earth/Moon	
Earth's mass	$5.974,2 \times 10^{24}$ kg
Moon's mass	7.34×10^{22} kg
Earth's average radius	6371.23×10^3 m
Earth's equatorial radius	6378.136×10^3 m
Earth-Moon distance (semimajor axis)	3.844×10^8 m
Earth-Sun distance (semimajor axis)	1.496×10^{11} m

Comparative Planetology

Object	Semi major axis of the orbit ^a		Revolution period (d day, y year, terrestrial)	Eccentricity (e)
	AU	Million km		
Mercury	0.3871	57.9092	87.969 d	0.2056
Venus	0.7233	108.2089	224.701 d	0.0068
Earth	1.0000	149.65979	365.2564 d	0.0167
Moon	2.570×10^{-3}	0.3844	27.3217 d	0.0549
Mars	1.5234	227.9364	686.98 d	0.0934
Jupiter	5.2034	778.4120	11.862 y	0.0484
Europa	4.4851×10^{-3}	0.671	3.551181 d	0.009
Saturn	9.5371	1426.7254	29.457 y	0.0542
Titan	8.167×10^{-3}	1.2218	15.945 d	0.0291
Uranus	19.1913	2870.9722	84.019 y	0.0472
Neptune	30.0690	4498.2529	164.767 y	0.0086

^aOr to main planet for satellites

Object	Equatorial radius km	Mass $\oplus = 1$	Average density g cm ⁻³	Surface gravity ^a m s ⁻²	Surface escape velocity ^a km s ⁻¹
Sun	695,508	332,946.0	1.41	274.0	617.5
Mercury	2439.7	0.0553	5.43	3.72	4.25
Venus	6051.8	0.8150	5.24	8.87	10.36
Earth	6378.136	1.000	5.515	9.81	11.18
Moon	1737.4	0.012300	3.34	1.62	2.38
Mars	3397	0.1074	3.94	3.71	5.02
Jupiter	71,492	317.82	1.33	23.12	59.54
Europa	1565	0.008026	3.04	1.8	2.0
Saturn	60,268	95.161	0.70	8.96	35.49
Titan	2575	0.02226	1.90	0.14	2.7
Uranus	25,559	14.371	1.30	8.69	21.29
Neptune	24,764	17.147	1.76	11.0	23.71

^aOr at $P = 1$ bar for gaseous planets

Object	Mean obliquity (degree)	Visual geometric albedo	Sidereal rotation period (d day, h hour)
Sun		–	25.7 d
Mercury	0.0	0.11	58.6462 d
Venus	177.3	0.65	243.0185 d ^a
Earth	23.45	0.37	23.9345 h
Moon	6.683	0.12	27.3217 d
Mars	25.19	0.15	24.6230 h
Jupiter	3.12	0.52	9.9249 h
Europa	–	0.67	2.5512 d
Saturn	26.73	0.47	10.6562 h
Titan	–	0.22	15.9454 h
Uranus	97.86	0.51	17.2400 h ^a
Neptune	29.58	0.51	16.1100 h

^aRetrograde rotation

Other Symbols and Abbreviations

c	Light speed
E _a	Activation energy
K	Chemical equilibrium constant
k	Reaction coefficient
	Boltzmann’s constant
R	“Rectus” configuration (chirality)
S	“Sinister” configuration (chirality)
L, D	Old nomenclature still used to define the absolute configuration of monosaccharides and amino acids
	D – dextrorotatory
	L – levorotatory
δ	Chemical shift (NMR)
λ	Wavelength
μ	Dipole moment
μm	Micron
ν	Frequency
[]	Concentration (mol · l ^{−1})
→	Chemical equilibrium
←	
↔	Mesomery
UV	Ultraviolet
IR	Infrared
NMR	Nuclear magnetic resonance
a	Ellipse semimajor axis
e	Ellipse eccentricity
i	Inclination
PSR	Pulsar
QSO	Quasar
ISM	Interstellar medium
AGB	Asymptotic giant branch

(continued)

PMS	Pre-main sequence
γ	Photon
ν	Neutrino
	Sun
	Mercury
	Venus
	Earth
	Mars
	Jupiter
	Saturn
	Uranus
	Neptune

Electromagnetic Spectrum

Wavelength domain	λ (angstroms)	λ (centimeters)	λ (microns)	Frequency (MHz)	Color temperature range (K)	Energy (eV)
Radio	$>10^9$	>10	$>10^5$	$<3 \times 10^3$	<0.03	$<10^{-5}$
Microwave	$10^9 - 10^8$	$10 - 1$	$10^5 - 10^4$	$3 \times 10^3 - 3 \times 10^4$	$0.03 - 0.3$	$10^{-5} - 10^{-4}$
Millimeter	$10^8 - 10^7$	$1 - 0.1$	$10^4 - 1000$	$3 \times 10^4 - 3 \times 10^5$	$0.3 - 3$	$10^{-4} - 10^{-3}$
Submillimeter	$10^7 - 3 \times 10^6$	$0.1 - 0.03$	$1000 - 300$	$3 \times 10^5 - 10^6$	$3 - 10$	$10^{-3} - 4 \times 10^{-3}$
Far infrared	$3 \times 10^6 - 4 \times 10^5$	$0.03 - 4 \times 10^3$	$300 - 40$	$10^6 - 7.5 \times 10^6$	$10 - 72$	$4 \times 10^{-3} - 0.03$
Mid infrared	$4 \times 10^5 - 5 \times 10^4$	$4 \times 10^{-3} - 5 \times 10^{-4}$	$40 - 5$	$7.5 \times 10^6 - 6 \times 10^7$	$72 - 580$	$0.03 - 0.24$
Near infrared	$5 \times 10^4 - 7000$	$5 \times 10^{-4} - 7 \times 10^{-5}$	$5 - 0.7$	$6 \times 10^7 - 4.3 \times 10^8$	$580 - 5600$	$0.24 - 1.8$
Visible	$7000 - 4000$	$7 \times 10^{-5} - 4 \times 10^{-5}$	$0.7 - 0.4$	$4.3 \times 10^8 - 7.5 \times 10^8$	$5600 - 10^4$	$1.8 - 3$
Ultraviolet	$4000 - 10$	$4 \times 10^{-5} - 10^{-7}$	$0.4 - 0.001$	$7.5 \times 10^8 - 3 \times 10^{11}$	$10^4 - 3 \times 10^6$	$3 - 1200$
X-rays	$10 - 0.1$	$10^{-7} - 10^{-9}$	$10^{-3} - 10^{-5}$	$3 \times 10^{11} - 3 \times 10^{13}$	$3 \times 10^6 - 3 \times 10^8$	$1.2 \times 10^3 - 1.2 \times 10^5$
Gamma rays	<0.1	$<10^{-9}$	$<10^{-5}$	$>3 \times 10^{13}$	$>3 \times 10^8$	$>1.2 \times 10^5$

Molecules Detected in the Interstellar or Circumstellar Medium

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H ₂	C ₃ *	c-C ₃ H	C ₅ *	C ₅ H	C ₆ H	CH ₃ C ₃ N	CH ₃ C ₄ H	CH ₃ C ₅ N	HC ₉ N	c-C ₆ H ₆ *	HC ₁₁ N
AlF	C ₂ H	<i>l</i> -C ₃ H	C ₄ H	<i>l</i> -H ₂ C ₄	CH ₂ CHCN	HCOOCH ₃	CH ₃ CH ₂ CN	(CH ₃) ₂ CO	CH ₃ C ₆ H	C ₂ H ₅ OCH ₃ ?	C ₆₀ *
AlCl	C ₂ O	C ₃ N	C ₄ Si	C ₂ H ₄ *	CH ₃ C ₂ H	CH ₃ COOH	(CH ₃) ₂ O	(CH ₂ OH) ₂	C ₂ H ₅ OCHO	<i>m</i> -C ₃ H ₇ CN	C ₇₀ *
C ₂ **	C ₂ S	C ₃ O	<i>l</i> -C ₃ H ₂	CH ₃ CN	HC ₅ N	C ₇ H	CH ₃ CH ₂ OH	CH ₃ CH ₂ CHO	CH ₃ OC(O)CH ₃	<i>i</i> -C ₃ H ₇ CN	c-C ₆ H ₅ CN
CH	CH ₂	C ₃ S	c-C ₃ H ₂	CH ₃ NC	CH ₃ CHO	H ₂ C ₆	HC ₇ N	CH ₃ CHCH ₂ O	CH ₃ C(O)CH ₂ OH	1-c-C ₅ H ₅ CN	C ₆₀ ⁺ *
CH ⁺	HCN	C ₂ H ₂ *	CH ₂ CN	CH ₃ OH	CH ₃ NH ₂	CH ₂ OHCHO	C ₈ H	CH ₃ OCH ₂ OH	c-C ₅ H ₆	2-c-C ₅ H ₅ CN	1-C ₁₀ H ₇ CN
CN	HCO	NH ₃	CH ₄ *	CH ₃ SH	c-C ₂ H ₄ O	<i>l</i> -HC ₆ H*	CH ₃ C(O)NH ₂	c-C ₆ H ₄	HOCH ₂ CH ₂ NH ₂	CH ₃ C ₇ N?	2-C ₁₀ H ₇ CN
CO	HCO ⁺	HCCN	HC ₃ N	HC ₃ NH ⁺	H ₂ CCHOH	CH ₂ CHCHO (?)	C ₈ H ⁻	H ₂ CCCCHC ₃ N			c-C ₉ H ₈
CO ⁺	HCS ⁺	HCNH ⁺	HC ₂ NC	HC ₂ CHO	C ₆ H ⁻	CH ₂ CCHCN	C ₃ H ₆	C ₂ H ₅ NCO			1-c-C ₅ H ₅ CCH
CP	HOC ⁺	HNCO	HCOOH	NH ₂ CHO	CH ₃ NCO	H ₂ NCH ₂ CN	CH ₃ CH ₂ SH	C ₂ H ₅ NH ₂ ?			2-c-C ₅ H ₅ CCH
SiC	H ₂ O	HNCS	H ₂ CNH	C ₅ N	HC ₅ O	CH ₃ CHNH	CH ₃ NHCHO	HC ₇ NH ⁺			
HCl	H ₂ S	HOCO ⁺	H ₂ C ₂ O	<i>l</i> -HC ₄ H*	HOCH ₂ CN	CH ₃ SiH ₃	HC ₇ O				
KCl	HNC	H ₂ CO	H ₂ CN	<i>l</i> -HC ₄ N	HCCCHNH	H ₂ NC(O)NH ₂	HCCCHCHCN				
NH	HNO	H ₂ CN	HNC ₃	c-H ₂ C ₃ O	HC ₄ NC	HCCCH ₂ CN	H ₂ CCHC ₃ N				
NO	MgCN	H ₂ CS	SiH ₄ *	H ₂ CCNH (?)	c-C ₃ HCCCH	HC ₃ NH ⁺	H ₂ CCCHCCCH				
NS	MgNC	H ₃ O ⁺	H ₂ COH ⁺	C ₅ N ⁻	<i>l</i> -H ₂ C ₅	CH ₂ CHCCCH					
NaCl	N ₂ H ⁺	c-SiC ₃	C ₄ H ⁻	HNCHCN	MgC ₅ N	MgC ₆ H					
OH	N ₂ O	CH ₃ *	HC(O)CN	SiH ₃ CN	CH ₂ C ₃ N	C ₂ H ₃ NH ₂					
PN	NaCN	C ₃ N ⁻	HNCNH	C ₅ S							
SO	OCs	PH ₃	CH ₃ O	MgC ₄ H							
SO ⁺	SO ₂	HCNO	NH ₄ ⁺	CH ₃ CO ⁺							
SiN	c-SiC ₂	HOCN	H ₂ NCO ⁺	C ₃ H ₃							
SiO	CO ₂ *	HSCN	NCCNH ⁺	H ₂ C ₃ S							
SiS	NH ₂	H ₂ O ₂	CH ₃ Cl	HCCCHS							
CS	H ₃ ⁺ *	<i>l</i> -C ₃ H ⁺	MgC ₃ N	C ₅ O							
HF	H ₂ D ⁺ , HD ₂ ⁺	HMgNC	NH ₂ OH	C ₅ H ⁺							
HD	SiCN	HCCO	HC ₃ O ⁺	HCCNCH ⁺							
FeO?	AlNC	CNCN	HC ₃ S ⁺								
O ₂	SiNC	HONO	H ₂ C ₂ S								
CF ⁺	HCP	MgC ₂ H	C ₄ S								
SiH?	CCP	HCCS	HC(O)SH								
PO	AlOH	HNCN	HC(S)CN								
AlO	H ₂ O ⁺	H ₂ NC	HCCCCO								
OH ⁺	H ₂ Cl ⁺	HCCS ⁺									
CN ⁻	KCN										
SH ⁺	FeCN										
SH	HO ₂										
HCl ⁺	TiO ₂										
TiO	C ₂ N										
ArH ⁺	Si ₂ C										
N ₂	HS ₂										
NO ⁺	HCS										
NS ⁺	HSC										
HeH ⁺	NCO										
	CaNC										
	NCS										

All species were detected by radio astronomy except molecules marked with one or two *asterisks* that were only detected in the infrared domain by means of their rovibrational or rovibronic spectra, respectively. Entries with a *question mark* are tentative – some are presented as detections in the literature. Entries with a *question mark* in parentheses are likely detections, viewed as somewhat tentative because of the small number of (unambiguous) lines – some are presented as detections in the literature. In some instances, detections are viewed as secure in spite of a small number of lines; available documentation gives further details. The *l* indicates a linear molecule or a molecule that contains a linear backbone; the *c* indicates a cyclic molecule or a molecule with a cyclic subunit. The questionable detections of aminoacetic acid, H₂NCH₂COOH, aka glycine, and 1,3-dihydroxypropanone, aka dihydroxyacetone, do not appear in the table.

Molecules Detected in Extragalactic Sources

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	>8 atoms
OH	H ₂ O	H ₂ CO	<i>c</i> -C ₃ H ₂	CH ₃ OH	CH ₃ C ₂ H	<i>l</i> -HC ₆ H*	<i>c</i> -C ₆ H ₆ *
CO	HCN	NH ₃	HC ₃ N	CH ₃ CN	CH ₃ NH ₂		C ₆₀ * (?)
H ₂ *	HCO ⁺	HNCO	CH ₂ NH	<i>l</i> -HC ₄ H*	CH ₃ CHO		
CH	C ₂ H	H ₂ CS?	NH ₂ CN	HC(O)NH ₂			
CS	HNC	HOCO ⁺	<i>l</i> -C ₃ H ₂				
CH ⁺	N ₂ H ⁺	<i>c</i> -C ₃ H	H ₂ CCN				
CN	OCS	H ₃ O ⁺	H ₂ CCO				
SO	HCO	<i>l</i> -C ₃ H	C ₄ H				
SiO	H ₂ S						
CO ⁺	SO ₂						
NO	HOC ⁺						
NS	C ₂ S						
NS	H ₂ O ⁺						
NH	HCS ⁺						
HF							
SO ⁺							

All species were detected by radio astronomy except molecules marked with one or two *asterisks* that were only detected in the infrared domain by means of their rovibrational or rovibronic spectra, respectively. Entries with a *question mark* are tentative – some are presented as detections in the literature. Entries with a *question mark* in parentheses are likely detections, viewed as somewhat tentative because of the small number of (unambiguous) lines – some are presented as detections in the literature. In some instances, detections are viewed as secure in spite of a small number of lines; available documentation gives further details. The *l* indicates a linear molecule or a molecule that contains a linear backbone; the *c* indicates a cyclic molecule or a molecule with a cyclic subunit. The questionable detections of aminoacetic acid, H₂NCH₂COOH, aka glycine, and 1,3-dihydroxypropanone, aka dihydroxyacetone, do not appear in the table.

Another useful resource is the web page A Hyper-Bibliography of Known Astromolecules (http://www.astrochymist.org/astrochymist_mole.html) of The Astrochymist (<http://www.astrochymist.org/>) with tables of interstellar and circumstellar molecules, cometary molecules, molecules on planetoids, planetary molecules, and molecules in brown dwarfs and stellar atmospheres. The Cologne Database for Molecular Spectroscopy (CDMS; <https://cdms.astro.uni-koeln.de/classic/molecules>) also provides lists of detected molecules in various Galactic and extragalactic environments.

See also the entry: ► [Molecules in Space](#)

Exoplanets

For an update on exoplanets, see:

<http://exoplanets.org>

<http://exoplanet.eu>

References and Further Reading

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Geological Data

Hervé Martin¹, Daniele L. Pinti² and Muriel Gargaud³

¹Laboratoire Magmas et Volcans, Université Clermont Auvergne, OPGC, CNRS, IRD, Campus des Cézeaux, Aubière Cedex, France

²GEOTOP Research Center for the dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

³Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

General Information

Whole Earth	
Age of the Earth	4.550 Ga
Age of the oldest known terrestrial material (zircon from Jack Hills, Australia)	4.404 Ga
Age of the oldest known terrestrial rock (Acasta gneiss, Canada)	4.030 Ga
Equatorial radius	6378.136 km
Polar radius	6356.753 km
Ellipticity	0.00335281
Total surface area	$510 \times 10^6 \text{ km}^2$
Ocean surface area	$361 \times 10^6 \text{ km}^2$
Continental surface area	$149 \times 10^6 \text{ km}^2$
Mass	$5.974 2 \times 10^{24} \text{ kg}$
Mean density	5.515 g cm^{-3}
Deepest oceanic trench (Marianas)	11,034 m
Highest mountain (Everest)	8848.86 m
Present-day oceanic ridge length	~80,000 km
Solid inner core	
Depth from surface	5155 km
Radius	~1223 km
Average density	12 g cm^{-3}
Volume	$8.45 \times 10^{10} \text{ km}^3$
Mass	$1.18 \times 10^{23} \text{ kg}$
Liquid outer core	
Depth	2891 km
Thickness	~2264 km
Average density	10 g cm^{-3}
Volume	$1.65 \times 10^{11} \text{ km}^3$
Mass	$1.65 \times 10^{24} \text{ kg}$
Lower mantle (mesosphere)	
Depth	670 km
Thickness	~2231 km
Average density	5 g cm^{-3}

(continued)

Volume	$5.87 \times 10^{11} \text{ km}^3$
Mass	$2.93 \times 10^{24} \text{ kg}$
Upper mantle	
Depth	~30 km
Thickness	~640 km
Average density	3.2 g cm^{-3}
Volume	$3.08 \times 10^{11} \text{ km}^3$
Mass	$0.986 \times 10^{24} \text{ kg}$
Oceanic crust	
Average thickness	7 km
Average density	2.9 g cm^{-3}
Age of the oldest known oceanic crust	0.165 Ga
Volume	$2.0 \times 10^9 \text{ km}^3$
Mass	$6.2 \times 10^{21} \text{ kg}$
Continental crust	
Average thickness	30 km
Average density	2.75 g cm^{-3}
Age of the oldest known continental crust	4.03 Ga
Volume	$7 \times 10^9 \text{ km}^3$
Mass	$1.9 \times 10^{22} \text{ kg}$
Average surface magnetic flux density	$5 \times 10^{-5} \text{ T}$
Heat flux	$42 \times 10^{12} \text{ W}$
Range of lithospheric plate motion rate	$1\text{--}10 \text{ cm year}^{-1}$

Decay Constants (λ)

Parent nuclide	Daughter nuclide	Decay constant
^{228}Th	^{224}Ra	$3.63 \times 10^{-1} \text{ year}^{-1}$
^{210}Pb	^{210}Bi	$3.11 \times 10^{-2} \text{ year}^{-1}$
^{32}Si	^{32}P	$2.1 \times 10^{-3} \text{ year}^{-1}$
^{226}Ra	^{222}Rn	$4.33 \times 10^{-4} \text{ year}^{-1}$
^{14}C	^{14}N	$1.245 \times 10^{-4} \text{ year}^{-1}$
^{231}Pa	^{227}Ac	$2.11 \times 10^{-5} \text{ year}^{-1}$
^{230}Th	^{226}Ra	$9.21 \times 10^{-6} \text{ year}^{-1}$
^{59}Ni	^{59}Co	$9.12 \times 10^{-6} \text{ year}^{-1}$
^{41}Ca	^{41}K	$6.93 \times 10^{-6} \text{ year}^{-1}$
^{81}Kr	^{81}Br	$3.03 \times 10^{-6} \text{ year}^{-1}$
^{234}U	^{230}Th	$2.83 \times 10^{-6} \text{ year}^{-1}$
^{36}Cl	^{36}Ar	$2.30 \times 10^{-6} \text{ year}^{-1}$
^{26}Al	^{26}Mg	$9.80 \times 10^{-7} \text{ year}^{-1}$
^{107}Pd	^{107}Ag	$6.5 \times 10^{-7} \text{ year}^{-1}$
^{60}Fe	^{60}Ni	$4.62 \times 10^{-7} \text{ year}^{-1}$
^{10}Be	^{10}B	$4.59 \times 10^{-7} \text{ year}^{-1}$
^{182}Hf	^{182}W	$7.7 \times 10^{-8} \text{ year}^{-1}$
^{129}I	^{129}Xe	$4.3 \times 10^{-8} \text{ year}^{-1}$
^{92}Nb	^{92}Zr	$1.93 \times 10^{-8} \text{ year}^{-1}$

(continued)

Parent nuclide	Daughter nuclide	Decay constant
^{53}Mn	^{53}Cr	$1.87 \times 10^{-8} \text{ year}^{-1}$
^{244}Pu	$^{131-136}\text{Xe}$	$8.66 \times 10^{-9} \text{ year}^{-1}$
^{235}U	^{207}Pb	$9.849 \times 10^{-10} \text{ year}^{-1}$
^{146}Sm	^{142}Nd	$6.73 \times 10^{-10} \text{ year}^{-1}$
^{40}K	^{40}Ar	$5.50 \times 10^{-10} \text{ year}^{-1}$
^{40}K	^{40}Ca	$4.96 \times 10^{-10} \text{ year}^{-1}$
^{238}U	^{206}Pb	$1.551 \times 10^{-10} \text{ year}^{-1}$
^{130}Te	^{130}Xe	$8.66 \times 10^{-22} \text{ year}^{-1}$
^{87}Rb	^{87}Sr	$1.42 \times 10^{-11} \text{ year}^{-1}$
^{187}Re	^{187}Os	$1.64 \times 10^{-11} \text{ year}^{-1}$
^{176}Lu	^{176}Hf	$1.93 \times 10^{-11} \text{ year}^{-1}$
^{232}Th	^{208}Pb	$4.95 \times 10^{-11} \text{ year}^{-1}$
^{40}K	^{40}Ar	$5.81 \times 10^{-11} \text{ year}^{-1}$
^{147}Sm	^{143}Nd	$6.54 \times 10^{-12} \text{ year}^{-1}$
^{138}La	^{138}Ce	$2.24 \times 10^{-12} \text{ year}^{-1}$
^{130}Te	^{130}Xe	$8.66 \times 10^{-22} \text{ year}^{-1}$

Temperature Range of Magma Emplacement

Granitic magma	700–800 °C
Basaltic magma	1250–1350 °C
Komatiitic magma	1650 °C

The International Stratigraphic Chart

Available on the International Commission on Stratigraphy Internet site <https://stratigraphy.org/ICSchart/ChronostratChart2021-10.pdf> (latest version accessed 2022/01/06).

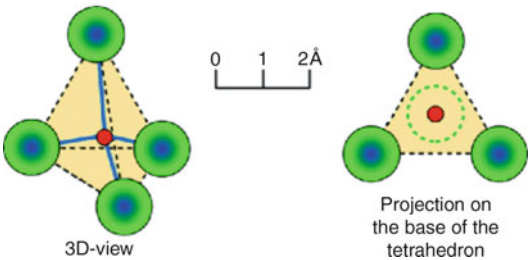
Geological Time Scale and Evolution of Life

Aeon	Era		System	Epoch	Ma	Life evolution (Ma)
PHANEROZOIC	Cenozoic	Quaternary	Quaternary	Holocene	Present	
				Pleistocene	0.01	Homo sapiens, modern human beings (0.12)
		Tertiary	Neogene	Pliocene	2.59	Australopithecus (3–1.4)
				Miocene	5.3	1 st biped human ancestor (6–5)
			Paleogene	Oligocene	23.03	
				Eocene	33.9	Mammal's expansion (55)
				Paleocene	55.8	1 st primates (58)
					66.5	
						Dinosaur's extinction (65)
	Mesozoic	Secondary	Cretaceous		145.5	
			Jurassic			
			Triassic		199.6	1 st mammals (225) 1 st dinosaurs (230)
	Paleozoic	Primary	Permian		251.0	
			Carboniferous		299.0	1 st reptiles (320)
			Devonian		359.2	1 st terapods "amphibians" (400)
			Silurian		416	1 st macrofossil of plants (424)
			Ordovician		443.7	1 st microscopic remains of plants (470–450)
			Cambrian		488.3	1 st chordates (520) 1 st shelled invertebrates (525)
					542	1 st mineralized animal skeleton (545)
PRECAMBRIAN	PROTEROZOIC					1 st multicellular eukaryotes (1200–1000)
						1 st eukaryotes (1900)
					2500	1 st cyanobacteria (2500)
						1 st bacteria (3500)
					4000	
					4568	

Mineralogical Short Summary

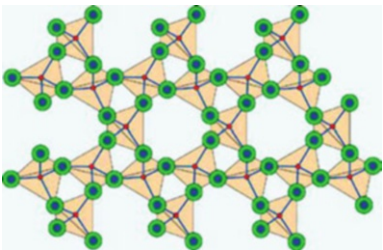
Silicates

More than 95% of the Earth’s crust and mantle rock minerals are silicates. Silicates dominate also the other telluric planets of our Solar system and most likely the Earth-like rocky exoplanets. Silicate structure is based on the tetrahedron $[\text{SiO}_4]^{4-}$; however, sometimes one of the silicon (Si^{4+}) atoms is replaced by an atom of aluminum (Al^{3+}) which has an ionic radius close to that of silicon, but a different valency number. The different families of silicate minerals consist of different spatial arrangements of silica tetrahedra. The tetrahedron $[\text{SiO}_4]^{4-}$ is not electrically neutral; thus, it must be linked with different cations to reach electric neutrality.



Basic framework of silicates: oxygen atoms (green) are located at the extremities of a tetrahedron. The silicon atom (red) occupies the center of the silica tetrahedron. On the right projection, the oxygen atom located above the tetrahedron is represented by dots, and the atom sizes are reduced half their real size to make the structure visible.

Tectosilicates: these anhydrous minerals consist in a 3D framework of silicate tetrahedra. This is the largest mineral group on Earth, comprising nearly 75% of the crust. The series of plagioclases are common minerals in the Moon’s highlands (anorthosite rocks).		
Family of silica		
Quartz	SiO_2	
Coesite	SiO_2	At pressure >2 GPa
Feldspar		
Potassic feldspar	Orthoclase	$K [\text{AlSi}_3\text{O}_8]$
Plagioclase: <i>plagioclase is a solid-solution series having a composition intermediate between albite and anorthite end-members. Alkaline feldspars range from albite to orthose.</i>		
Sodic feldspar	Albite	$\text{Na} [\text{AlSi}_3\text{O}_8]$
Calcic feldspar	Anorthite	$\text{Ca} [\text{Al}_2\text{Si}_2\text{O}_8]$
Feldspathoid		
Leucite	$K [\text{AlSi}_2\text{O}_6]$	
Nepheline	$\text{Na} [\text{AlSiO}_4]$	



3D structure of tectosilicates sharing four oxygen atoms

(continued)

Phyllosilicates: Hydrated minerals where tetrahedra share three oxygen atoms resulting in a planar framework. Clay minerals belong to this family.

Talc	$Mg_3 [Si_4O_{10}] (OH)_2$
------	----------------------------

Micas

Muscovite (white mica)	$KAl_2 [AlSi_3O_{10}] (OH)_2$
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Biotite (brown mica)	$K(Fe, mg)_3 [AlSi_3O_{10}] (OH)_2$
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Chlorites

Clinocllore	$Mg_5 Al (OH)_6 [AlSi_3O_{10}] (OH)_2$
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Serpentines

Antigorite	$Mg_6 (OH)_6 [Si_4O_{10}] (OH)_2$
------------	-----------------------------------

Clay

Kaolinite	$Al_4 (OH)_6 [Si_4O_{10}] (OH)_2$
-----------	-----------------------------------

Illite	$KAl_2 [AlSi_3O_{10}] (OH)_2$
--------	-------------------------------

Inosilicates: Tetrahedra share only two oxygen atoms resulting in a linear framework. They are commonly called “chain silicates.” common minerals in mafic and intermediate magmatic rocks, some of them are found in meteorites (such as enstatite in the enstatite chondrite family).

Single-chain inosilicates: Pyroxenes (*anhydrous minerals*)

Orthopyroxenes

Enstatite	Mg_2	$[Si_2O_6]$
-----------	--------	-------------

Hypersthene	$(Fe, Mg)_2$	$[Si_2O_6]$
-------------	--------------	-------------

Clinopyroxenes

Diopside	$CaMg$	$[Si_2O_6]$
----------	--------	-------------

Augite	(Ca, Fe, Mg) (Fe, Mg)	$[Si_2O_6]$
--------	------------------------------	-------------

Jadeite	$NaAl$	$[Si_2O_6]$
---------	--------	-------------

Aegyrine	$NaFe^{+++}$	$[Si_2O_6]$
----------	--------------	-------------

Double-chain inosilicates: Amphiboles (*hydrated minerals*)

Ortho-amphiboles

Anthophyllite	Mg_7	$[Si_8O_{22}] (OH, F)_2$
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Clino-amphiboles

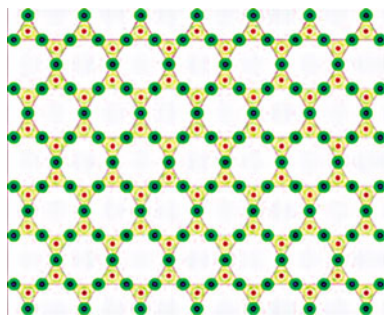
Cummingtonite	$(Mg, Fe)_7$	$[Si_8O_{22}] (OH, F)_2$
---------------	--------------	--------------------------

Actinolite	$Ca_2 (Fe, Mg)_5$	$[Si_8O_{22}] (OH, F)_2$
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Hornblende	$(Ca, Na, K)_2$ $(Fe, MgAl)_5$	$[Si_6 (Si, Al)_2 O_{22}]$ $(OH, F)_2$
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Glaucophane	$Na (Fe, Mg)_3 Al_2$	$[Si_8O_{22}] (OH, F)_2$
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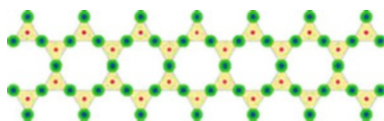
Riebeckite	$Na Fe_3^{++} Fe_2^{+++}$	$[Si_8O_{22}] (OH, F)_2$
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Planar structure of phyllosilicates formed by parallel sheets of silicate tetrahedra



Single chain of silica tetrahedra of pyroxenes



Double chain of silica tetrahedra

(continued)

Sorosilicates: Hydrated minerals sharing only one oxygen atom resulting in isolated double tetrahedra groups		
Lawsonite	$CaAl_2$	$[Si_2O_7](OH)_2, H_2O$

Epidotes		
Zoisite	Ca_2Al_3	$[(Si_2O_7)(SiO_4)O](OH)$
Allanite	$(Ca, La, Ce)_2(Al, Fe^{+++})_3$	$[(Si_2O_7)(SiO_4)O](OH)$

Nesosilicates: Anhydrous minerals resulting in single silica tetrahedra. Olivine is a common mineral in terrestrial mantle rocks (peridotite), while zircon is a common accessory mineral in felsic magmatic rocks. Garnets form a common mineral group in metamorphic rocks as well as in high-pressure peridotites.

Peridots		
Forsterite	Mg_2	$[SiO_4]$
Fayalite	Fe_2	$[SiO_4]$
Olivine*	$(Mg, Fe)_2$	$[SiO_4]$

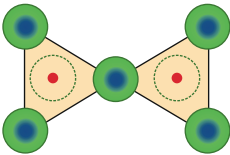
*The olivine group is a solid-solution series ranging from the iron end-member fayalite and the magnesium end-member forsterite.

Garnet		
Pyrope	Mg_3Al_2	$[SiO_4]_3$
Almandine	Fe_3Al_2	$[SiO_4]_3$
Grossular	Ca_3Al_2	$[SiO_4]_3$

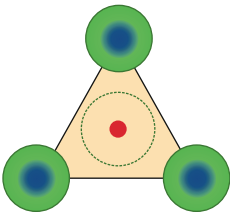
Zircons		
Zircon	Zr	$[SiO_4]$
Thorite	Th	$[SiO_4]$

Sub-nesosilicates: Like nesosilicates, sub-nesosilicates consist of single silica tetrahedron; however, in addition, they possess oxygen atoms that are not linked to Si or Al in tetrahedron

Andalusite	Al_2O	$[SiO_4]$	Low P and low T
Kyanite	Al_2O	$[SiO_4]$	Moderate P, low T
Sillimanite	Al_2O	$[SiO_4]$	High T
Staurolite	$Fe(OH)_2$	$([SiO_4])_2$	
Chloritoid	$(Fe, Mg)Al_2O$	$[SiO_4](OH)_2$	
Sphene (titanite)	$CaTiO$	$[SiO_4]$	



Sorosilicate framework with the sharing of a single oxygen atom



Nesosilicate framework with single tetrahedral

Nonsilicate Minerals

By this term are designated all mineral groups that do not contain silicon. They appear in all kinds of rocks, but some of them mainly occur on the surface of the Earth as sedimentary rocks (carbonates, halides, hydroxides, sulfates, etc.) or in ore deposits. Some of them are commonly found in meteorites (such as spinel, a common mineral in the Ca-Al-rich inclusions (CAIs)) or on other planetary surfaces (iron oxides, hydroxides, and halides in Mars)

Native	
Gold	Au
Silver	Ag
Graphite	C

(continued)

Diamond	<i>C</i> at pressure > 5 GPa
Iron	<i>Fe</i>
Oxides	
Hematite	<i>Fe₂O₃</i>
Magnetite	<i>Fe₃O₄</i>
Ilmenite	<i>FeTiO₃</i>
Rutile	<i>TiO₂</i>
Spinel	<i>(Fe, Mg) Al₂O₄</i>
Uraninite	<i>UO₂</i>
Hydroxides	
Goethite	<i>FeO (OH)</i>
Limonite	<i>FeO (OH), nH₂O</i>
Gibbsite	<i>Al (OH)₃</i>
Boehmite	<i>AlO (OH)</i>
Halides	
Halite	<i>NaCl</i>
Sylvite	<i>KCl</i>
Fluorine	<i>CaF₂</i>
Sulfides	
Pyrite	<i>FeS₂</i>
Galena	<i>PbS</i>
Sphalerite	<i>ZnS</i>
Chalcopyrite	<i>CuFeS₂</i>
Sulfates	
Barite	<i>BaSO₄</i>
Anhydrite	<i>CaSO₄</i>
Gypsum	<i>CaSO₄, 2H₂O</i>
Jarosite	<i>K Fe₃⁺⁺⁺ (OH)₆ (SO₄)₂</i>
Carbonates	
Calcite	<i>CaCO₃</i>
Aragonite	<i>CaCO₃</i>
Siderite	<i>FeCO₃</i>
Dolomite	<i>Ca, Mg(CO₃)₂</i>
Phosphates	
Apatite	<i>Ca₅ [PO₄]₃ (F, Cl, OH)</i>
Monazite	<i>(Ce, La, Th)[PO₄]</i>

Rock Classification for Astrobiologists

Three main rock types exist on Earth and on some telluric (or rocky) planet and moon:

1. Endogenous or magmatic (synonym: igneous) rocks resulting from crystallization of magma. Typically, magma is generated at depth in the crust (anatexis) or in the mantle.
2. Exogenous or sedimentary rocks resulting from alteration, erosion, transport, deposition, and ► [diagenesis](#) of rock debris (clastic or detrital rocks) or direct precipitation of dissolved salts from a fluid (evaporites). They are generated and emplaced at the surface of a planet.
3. Metamorphic rocks resulting from mineralogical and structural changes of preexisting sedimentary or magmatic rocks when subjected to heat and pressure changes in the interior of the planet.

Magmatic or Igneous Rocks

Igneous rocks result from magma crystallization such that their classification is mainly based on two parameters: (1) the place (and conditions) where magma crystallized and (2) the chemistry of the crystallizing magma.

Place of Magma Crystallization

Depending on their temperature, density, and viscosity, some magmas cool and solidify at depth, within the outer rocky layer of a planet, i.e., the crust. In other words, they do not reach the planetary surface. These accumulations of solidified magmas at depth are termed “plutons” or “batholiths” and the derived rocks “plutonic rocks.” If magmas can reach the surface of a planet, they are termed “effusive” and derived rocks “volcanic rocks.” Usually volcanic rocks, as the term indicates, are emitted at the surface through fractures or centers, progressively building constructional volcanic edifices or “volcanoes.” Textures of igneous rocks are basically controlled by the rate of magma cooling. If magmas cool very slowly, as in plutons, igneous rocks develop large conspicuous crystals, this coarse-grained texture being called “granular.” Occasionally some crystals (phenocrysts) are larger than the groundmass, in which case the texture is known as porphyritic. If the magmas cool rapidly, as in volcanic effusive rocks, the crystals are smaller and elongated (microlites), such that the texture is referred to as “microplitic.” In the case of brutal cooling, crystals do not have enough time to form, resulting in a glass (not crystallized matter commonly called “groundmass”), and then the texture is called “hyaline” or “glassy.”

Chemistry of the Crystallizing Magma

The chemical composition of magmas controls the type of minerals that will be crystallized. Schematically, magmas and derived igneous rocks are classified based on the SiO_2 and MgO content. The MgO -rich ($\sim 30\%$) and SiO_2 -poor ($\sim 42\%$) magmas are termed “ultramafic.” The MgO -poor ($\leq 1\%$) and SiO_2 -rich ($\geq 70\%$) magmas are termed “felsic.” Between these two endmembers, igneous rocks are referred to as mafic and intermediate. Crystallization processes and the chemical composition of magmas account for the diversity of existing igneous rocks (Table 1).

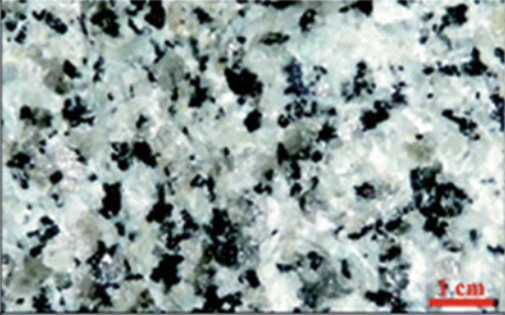
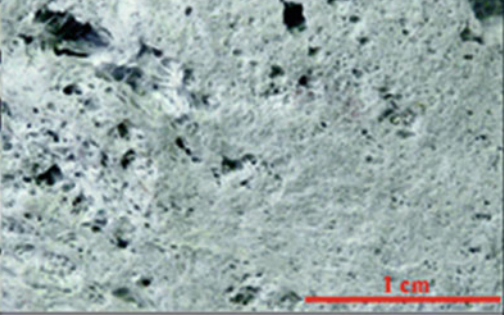
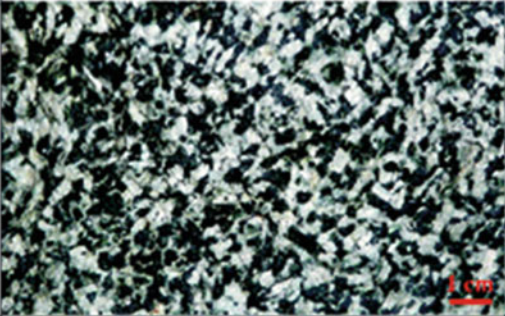
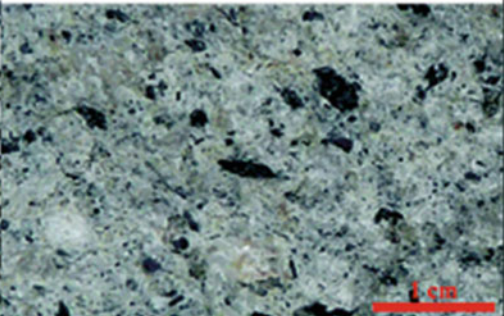
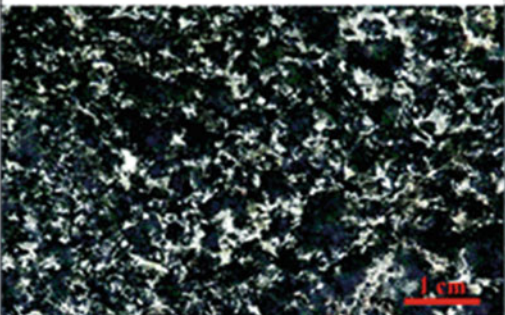
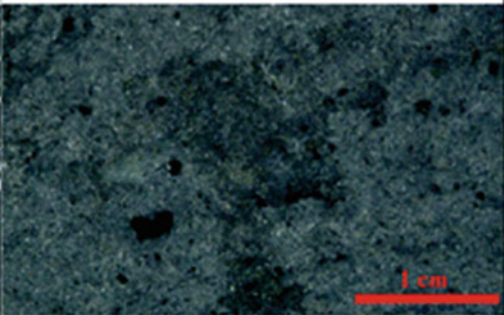
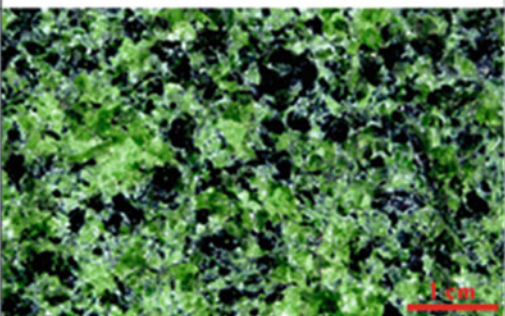
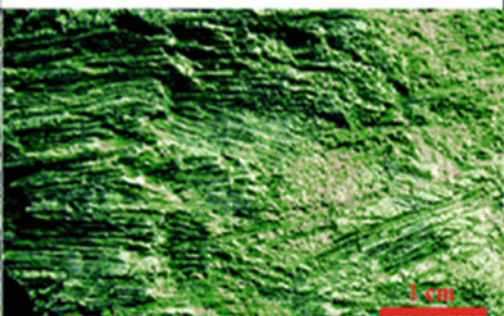
The abovementioned classification is very rough. Geologists propose more elaborated classification schemes based mainly on the nature of minerals contained in rocks (Fig. 1). For example, granite is a plutonic endogenous igneous rock rich in silica (quartz) and feldspars (plagioclase albite [$\text{NaAlSi}_3\text{O}_8$] or anorthite [$\text{CaAl}_2\text{Si}_2\text{O}_8$] and alkaline feldspar orthoclase [KAlSi_3O_8]). Depending on the type of feldspars contained in granite, we can distinguish the following parental rocks:

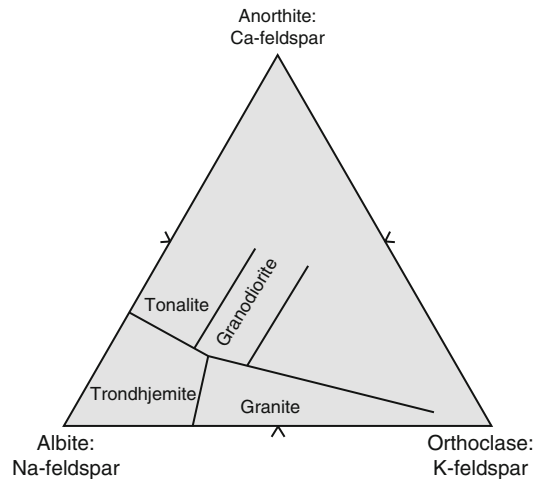
- *Tonalite*: dominated by calcic plagioclase
- *Trondhjemite*: dominated by sodic plagioclase
- *Granodiorite*: containing two feldspars but with plagioclase more abundant than the potassic feldspar
- *Granite*: containing two feldspars but with potassic feldspar equal or more abundant than plagioclase

Sedimentary Rocks

Sedimentary rocks are formed on the surface of a planet by chemical ► [weathering](#) and mechanical erosion of preexisting rocks of any nature, igneous, metamorphic, or sedimentary. The detritus is transported as solid particles in suspension by rivers, glaciers, or wind while ions are transported in solution in water. Transport is achieved in sedimentary basins such as lakes, epicontinental seas, or the ocean where they form deposits of sediments (such as sand). By progressive burial by other sediments and

Geological Data, Table 1 Simplified igneous rock classification based on the crystallization processes (controlling the size and form of the crystals) and the chemical composition of magmas which controls the relative abundance and nature of the minerals (Photos H. Martin)

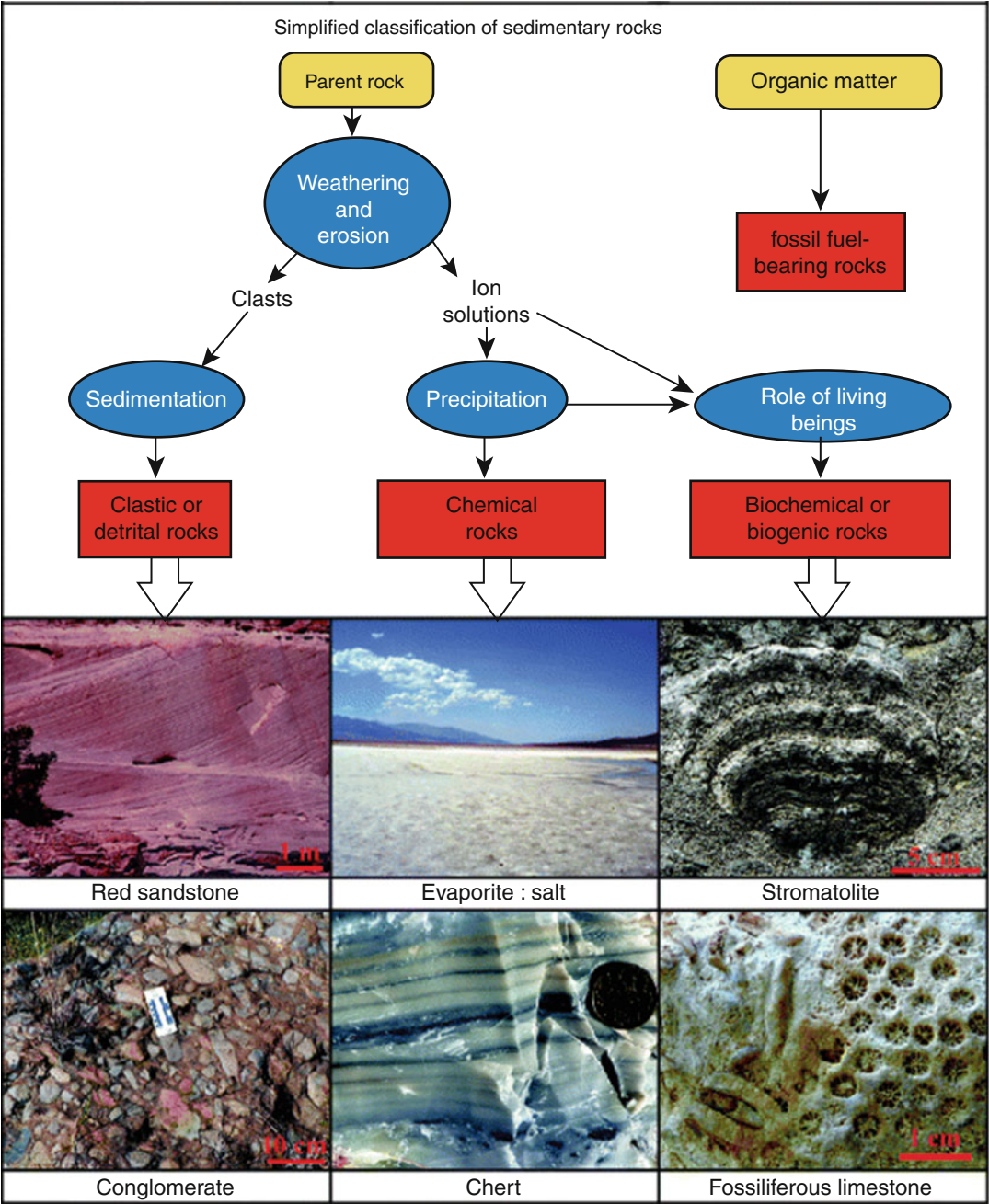
	Plutonic Rocks Magma crystallized at depth	Volcanic or Effusive Rocks Magma crystallized at surface
Acid Magma		
	<i>Granite</i>	<i>Rhyolite</i>
Intermediate Magma		
	<i>Diorite</i>	<i>Andesite</i>
Mafic Magma		
	<i>Gabbro</i>	<i>Basalt</i>
Ultramafic Magma		
	<i>Peridotite</i>	<i>Komatiite</i>



Geological Data, Fig. 1 Classification diagram for acid plutonic rocks containing more than 10% of quartz. This classification is based on the relative abundance of feldspars (Or orthoclase, Ab Albite, An Anorthite)

circulation of interstitial waters, sediments are subjected to a series of physical and chemical processes called ► [diagenesis](#) that transforms them into hard sedimentary rocks (sand → sandstone). The main classification schemes are based on the chemical nature of the sediment, its genesis, or its depositional environment. The most used is the one based on the genetic processes:

1. *Clastic (or detrital) rocks*: they are formed by the transport and accumulation of solid particles (detritus or clasts). There exist around 50 classification schemes for the clastic and particularly silico-clastic rocks; the most known is the one based on the size of the solid particles composing the rocks. For small particles ($<63\ \mu\text{m}$), clastic rocks are called “lutite” or “pelite” (older term). Shales or clays (composed of clay minerals or phyllosilicates) are typical lutites. For particles with intermediate size ($2\ \text{mm} < \text{particle} < 63\ \mu\text{m}$), the rock is called “arenite.” Sandstone is the typical rock of this class. For particle sizes bigger than 2 mm, the rock is called “rudite.” Conglomerates and breccias are the most widespread rudites.
2. *Chemical rocks*: they are generated by direct precipitation of ions dissolved in seawater or lacustrine water when they reach conditions of supersaturation. Rocks are generally deposited in the form of salts such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), halite (NaCl), or sylvite (KCl). The resulting rocks are called evaporites. Precipitation of ions can be produced also by physicochemical changes in the environment such as precipitation of inorganic chert (Precambrian cherts) from hydrothermal fluids.
3. *Biogenic or biochemical rocks*: they are also formed by the precipitation of ions in water, but contrary to chemical cherts and evaporites, this precipitation is controlled by organisms (biochemical). This is the case for most carbonate rocks which are precipitated as calcite or aragonite (CaCO_3) or more rarely silica (by radiolarians and sponges) to form the skeletons of marine and lacustrine organisms. After the death of these organisms, the accumulation of shells can result in sedimentary rock (bioclastic carbonates or modern cherts). The accumulation and progressive transformation (diagenesis) of organic matter into sedimentary rocks can generate fossil fuels such as coal, bitumen, and petroleum (Fig. 2).



Geological Data, Fig. 2 Diagram illustrating the principles of the sedimentary rock classification. Photos represent examples of clastic rocks (*left*), chemical rocks (*center*), and biogenic rocks (*right*). (Photos H. Martin)

Geological Data,

Fig. 3 Metamorphic rock (gneiss) showing a near-horizontal foliation. Black crystals (mica) have been all recrystallized perpendicular to the direction of the main pressure. The large feldspars (white crystals) are also deformed to follow the foliation plan. (Photo H. Martin)



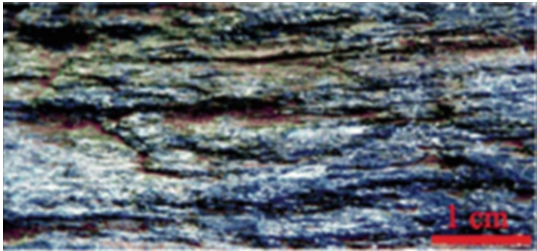
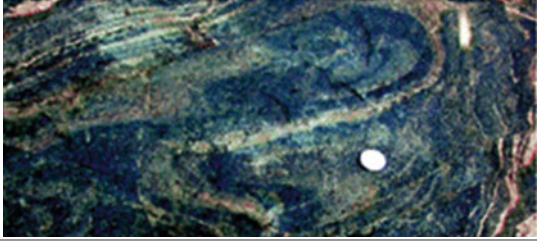
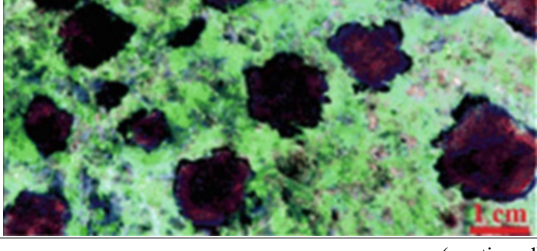
Metamorphic Rocks

Metamorphic rocks are igneous or sedimentary rocks that are transported, often driven by plate tectonics, in environments where temperature (T) and pressure (P) are different from the surface of Earth. A classic example is when basalts from the oceanic crust are transported deeper into the lithosphere in subduction zones. Minerals that were stable at the Earth's surface P, T conditions will become unstable and be replaced by new mineral species. All transformation reactions take place at the solid state. They are often accompanied by change in the texture of rocks, and thus, planar minerals such as mica or acicular minerals like amphiboles and pyroxenes will be reoriented perpendicular to the main pressure direction delineating a preferential orientation plan called "foliation" (Fig. 3). Three metamorphic regimes exist:

- *Shock metamorphism*: the less common when rocks are affected by a rapid change of pressure (ultrahigh pressure) caused by the impact of an asteroid or comet at the surface of Earth or of other rocky planets and moons.
- *Contact metamorphism*: refers to changes in a rock at contact – therefore heated – by a magma intrusion. Changes are controlled mainly by the increase in temperature. Marble – formed by contact metamorphism of limestone – is a classic example.
- *Regional metamorphism*: refers to changes in a rock affected by contemporary increase in temperature and pressure. Typical environments are orogenic belts and subduction zones. Gneiss is the typical rock.

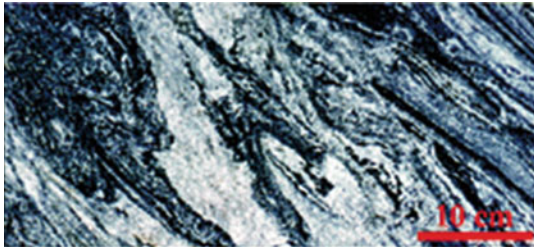
Pending the origin of the protolith (i.e., the original rocks), geologists generally add the term ortho- and para- for defining metamorphic rocks derived from igneous and sedimentary rocks, respectively. A gneiss derived from a granite will be called an orthogneiss, while a gneiss derived from argillaceous sediments will be termed as paragneiss (Table 2).

Geological Data, Table 2 Some common metamorphic rocks (Photos H. Martin)

Mica schist Consists in a mineralogical assemblage of mica and quartz, without or with very few feldspars. The abundance of mica crystals draws a planar structure called foliation.		
Gneiss Quartz- and feldspar-bearing metamorphic rock, which also often contains micas. Depending on its origin, it is called paragneiss (metamorphosed sediment) or orthogneiss (metamorphosed granitic rock).	Paragneiss	
	Orthogneiss	
Amphibolite Mainly made up of amphibole and plagioclase feldspar, it can occasionally contain quartz. It generally results from the metamorphism of basalts.		
Eclogite A rock consisting in an assemblage of garnet (red) and pyroxene (green). It is generated by high-pressure metamorphism of a basalt. For instance, during progressive subduction, oceanic basalts are transformed into amphibolites, then into garnet-bearing amphibolites, and finally into eclogites (sample F. Cariou).		

(continued)

Geological Data, Table 2 (continued)

Migmatite	
At high temperatures, during the process of anatexis, a gneiss begins to melt, giving rise to small veins of granitic magma. Such a partially molten rock is called migmatite. The picture shows white veins (granitic liquid) associated with black levels that are the unmelted residues of fusion.	

Average Compositions of the Earth’s Geochemical Reservoirs

	N = atomic number	M = atomic mass g/mol	E = electro-negativity	Unit	C1 chondrite	Bulk solid earth	Core	Primitive mantle	Upper mantle	Oceanic crust	Bulk continental crust	Ocean	Atmosphere
H	1	1.00794	2.1	%	2.02	0.0257	0.06	0.01	0.00025		0.14	10.8	0.000053
He	2	4.002602		ppm	56 (nL/g)							0.0000069	5.2
Li	3	6.941	0.98	ppm	1.49	1.08	0	1.6	1.57	10	16	0.18	
Be	4	9.012182	1.47	ppm	0.0249	0.046	0	0.068	0.0442	0.5	1.9	0.000225	
B	5	10.811	2.01	ppm	0.87	0.203	0	0.3	0.07	4	11	4.39	
C	6	12.011	2.5	%	3.5	0.73	0.2	0.0120	0.0018		0.02	0.0028	0.0337
N	7	14.00674	3.07	ppm	3180	55	170	2	0.05		56	8.5	780,900
O	8	15.9994	3.50	%	46.4	30.5	0	44	44		45	85.7	20.95
F	9	18.998403	4.1	ppm	58.2	17.1	0	25	9.8		553	1.3	
Ne	10	20.1797		ppm	203 (pL/g)						0.00007	0.04	18
Na	11	22.989768	1.01	%	0.51	0.18	0	0.267	0.214	2.08	2.36	1.05	
Mg	12	24.3050	1.23	%	9.65	15.39	0	22.8	22.8	4.64	3.20	0.135	
Al	13	26.981539	1.47	%	0.86	1.59	0	2.35	2.23	8.47	8.41	0.00000016	
Si	14	28.0855	1.74	%	10.65	16.5	6.4	21	21	23.1	26.77	0.0003	
P	15	30.973762	2.06	ppm	1080	1101	3200	90	54	873	2000	0.07	
S	16	32.066	2.44	%	5.4	0.634	1.9	0.025	0.024		0.0404	0.0885	0.0001
Cl	17	35.4527	2.83	ppm	680	74.5	200	17	2.55		244	19,000	0.001
Ar	18	39.948		ppm	751 (pL/g)						1.2	0.6	9300
K	19	39.0983	0.91	%	0.0550	0.0164	0	0.024	0.0024	0.125	0.99	0.038	
Ca	20	40.078	1.04	%	0.925	1.71	0	2.53	2.4	8.08	5.29	0.04	
Sc	21	44.95591	1.2	ppm	5.92	10.93	0	16.2	15.4	38	21.9	0.0000006	
Ti	22	47.88	1.32	%	0.044	0.0813	0	0.12	0.0928	0.9	0.54	0.0000001	
V	23	50.9415	1.45	ppm	56	94.4	120	82	82	250	138	0.0019	
Cr	24	51.9961	1.56	ppm	2650	3720	9000	2625	2625	270	135	0.0003	
Mn	25	54.93805	1.6	ppm	1920	1974	4000	1045	1045	1000	852	0.0002	
Fe	26	55.847	1.64	%	18.1	30.3	85	6.26	6.26	8.16	5.6	0.00000056	
Co	27	58.9332	1.7	ppm	500	838	2500	105	105	47	26.6	0.00039	
Ni	28	58.6934	1.75	ppm	10,500	17,690	52,000	1960	1960	135	59	0.0054	
Cu	29	63.546	1.75	ppm	120	60.9	125	30	29.1	86	27	0.0002	
Zn	30	65.39	1.66	ppm	310	37.1	0	55	55	85	72	0.0037	
Ga	31	69.723	1.82	ppm	9.2	2.74	0	4	3.8	17	16	0.00003	
Ge	32	72.61	2.02	ppm	31	7.24	20	1.1	1.1	1.5	1.3	0.000051	
As	33	74.92159	2.2	ppm	1.85	1.67	5	0.05	0.01	1	2.5	0.0026	
Se	34	78.96	2.48	ppb	21,000	2560	8000	75	71	160	130	0.00012	
Br	35	79.904	2.74	ppb	3570	300	700	50	5		880	65,000	
Kr	36	83.80		ppb	8.7 (pL/g)							0.29	1140
Rb	37	85.4678	0.89	ppm	2.3	0.405	0	0.6	0.041	2.2	49	0.124	
Sr	38	87.62	0.99	ppm	7.25	13.4	0	19.9	12.93	130	320	8.1	

(continued)

	N = atomic number	M = atomic mass g/mol	E = electro- nega- tivity	Unit	C1 chondrite	Bulk solid earth	Core	Primitive mantle	Upper mantle	Oceanic crust	Bulk continental crust	Ocean	Atmosphere
Y	39	88.90585	1.11	ppm	1.57	2.95	0	4.3	3.65	32	19	0.000013	
Zr	40	91.224	1.22	ppm	3.82	7.1	0	10.5	6.19	80	132	0.000026	
Nb	41	92.90638	1.23	ppm	0.240	0.45	0	0.658	0.11	2.2	8	0.000015	
Mo	42	95.94	1.3	ppm	0.9	1.66	5	0.05	0.03	1	0.8	0.01	
Tc	43	98.9063	1.36	ppm									
Ru	44	101.07	1.42	ppb	710	1310	4000	4.9	4.9	1	0.57	0.0007	
Rh	45	102.9055	1.45	ppb	130	242	740	0.91	0.91	0.2	0.06		
Pd	46	106.42	1.35	ppb	550	1010	3100	3.9	3.9	0.2	1.5		
Ag	47	107.8682	1.42	ppb	200	54.4	150	8	7.8	26	56	0.28	
Cd	48	112.411	1.46	ppb	710	76	150	40	39.2	130	80	0.00011	
In	49	114.82	1.49	ppb	80	7.5	0	11	8.5	72	52	0.000115	
Sn	50	118.71	1.72	ppb	1650	251	500	130	97.5	1400	1700	0.81	
Sb	51	121.757	1.82	ppb	140	46.2	130	5.5	1.1	17	200	0.33	
Te	52	127.60	2.01	ppb	2330	285.7	850	12	12	3	5		
I	53	126.90447	2.21	ppb	450	50	130	10	1		710	64	
Xe	54	131.29		ppb	8.6 (pL/g)							0.066	86
Cs	55	132.90543	0.86	ppb	190	35	65	21	504	30	2600	0.5	
Ba	56	137.327	0.97	ppm	2.41	4.46	0	6.6	0.45	25	456	0.021	
La	57	138.9055	1.08	ppm	0.237	0.437	0	0.648	0.08	3.7	20	0.0000029	
Ce	58	140.115	1.06	ppm	0.613	1.148	0	1.675	0.538	11.5	43	0.0000028	
Pr	59	140.90765	1.07	ppm	0.0928	0.171	0	0.254	0.114	1.8	4.9	0.00000064	
Nd	60	144.24	1.07	ppm	0.457	0.844	0	1.25	0.738	10	20	0.0000028	
Pm	61	146.9151	1.07	ppm								—	
Sm	62	150.36	1.07	ppm	0.148	0.274	0	0.406	0.305	3.3	3.9	0.00000045	
Eu	63	151.965	1.01	ppm	0.0563	0.104	0	0.154	0.119	1.3	1.1	0.0000013	
Gd	64	157.25	1.11	ppm	0.199	0.367	0	0.544	0.430	4.6	3.7	0.0000007	
Tb	65	158.92534	1.10	ppm	0.0361	0.068	0	0.099	0.080	0.87	0.6	0.00000014	
Dy	66	162.50	1.10	ppm	0.246	0.455	0	0.674	0.559	5.7	3.6	0.00000091	
Ho	67	164.93032	1.10	ppm	0.546	0.102	0	0.149	0.127	1.3	0.77	0.00000022	
Er	68	167.26	1.11	ppm	0.16	0.296	0	0.438	0.381	3.7	2.1	0.00000087	
Tm	69	168.93421	1.11	ppm	0.0247	0.046	0	0.068	0.060	0.54	0.28	0.00000017	
Yb	70	173.04	1.06	ppm	0.161	0.297	0	0.441	0.392	5.1	1.9	0.00000082	
Lu	71	174.967	1.14	ppm	0.0246	0.046	0	0.0675	0.061	0.56	0.30	0.00000015	
Hf	72	178.49	1.23	ppm	0.103	0.191	0	0.283	0.167	2.5	3.7	0.0000016	
Ta	73	180.9479	1.33	ppm	0.0136	0.025	0	0.037	0.006	0.3	0.7	0.0000025	
W	74	183.85	1.40	ppm	0.093	0.170	0.47	0.029	0.002	0.5	1	0.000001	
Re	75	186.207	1.46	ppb	40	75.3	230	0.28	0.27	0.9	0.188	0.0084	
Os	76	190.2	1.52	ppb	490	900	2750	3.43	3.43	0.004	0.041	0.0000017	
Ir	77	192.22	1.55	ppb	455	835	2550	3.18	3.18	0.02	0.037	0.00000115	
Pt	78	195.08	1.44	ppb	1010	1866	5700	7.07	7.07	2.3	1.5	0.000117	
Au	79	196.96654	1.42	ppb	140	164	500	0.98	0.96	0.23	1.3	0.011	
Hg	80	200.59	1.44	ppb	300	23.1	50	10	9.8	20	30	0.15	
Tl	81	204.3833	1.44	ppb	140	12.2	30	3.5	3.5	12	500	0.0123	
Pb	82	207.2	1.55	ppb	2470	232	4000	150	20	800	11,000	0.03	
Bi	83	208.98037	1.67	ppb	110	9.85	25	2.5	0.5	7	18	0.017	
Po	84	208.9824	1.76										
At	85	209.9871	1.96										
Rn	86	222.0176											
Fr	87	223.0197	0.86										
Ra	88	226.0254	0.97										
Ac	89	227.0278	1.00										
Th	90	232.0381	1.11	ppm	0.029	0.054	0	0.0795	0.06	0.22	5.6	0.0000004	
Pa	91	231.03588	1.40										
U	92	238.0289	1.44	ppm	0.0074	0.0139	0	0.0203	0.002	0.1	1.3	0.0033	

Table showing the composition of the different Earth shells. Data are from Anders and Grevesse (1989), Taylor and McLennan (1985), McDonough and Sun (1995), Rudnick and Fountain (1995), McDonough (1998), Rudnick and Gao (2003) and the Geochemical Earth Reference Model (GERM) Internet site <http://www.earthref.org/GERM>).

References and Further Reading

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Chemical and Biological Data

Muriel Gargaud¹, Ricardo Amils²,
Carlos Briones³, Henderson James Cleaves II⁴ and
Felipe Gomez³

¹Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

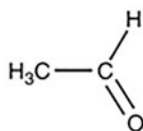
²Departamento de Biología Molecular, Universidad Autónoma de Madrid, Madrid, Spain

³Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

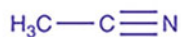
⁴Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

Main Prebiotic Precursors of Biomolecules

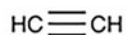
Acetaldehyde
(ethanal)



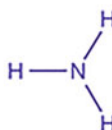
Acetonitrile



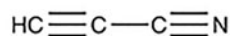
Acetylene



Ammonia



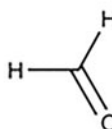
Cyanoacetylene



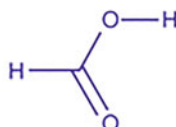
Ethylene (ethene)



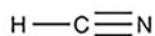
Formaldehyde
(methanal)



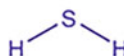
Formic Acid
(methanoic acid)



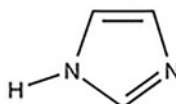
Hydrogen Cyanide



Hydrogen Sulfide



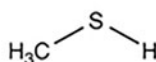
Imidazole
(1,3 diaza cyclopentadiene)



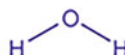
Methane



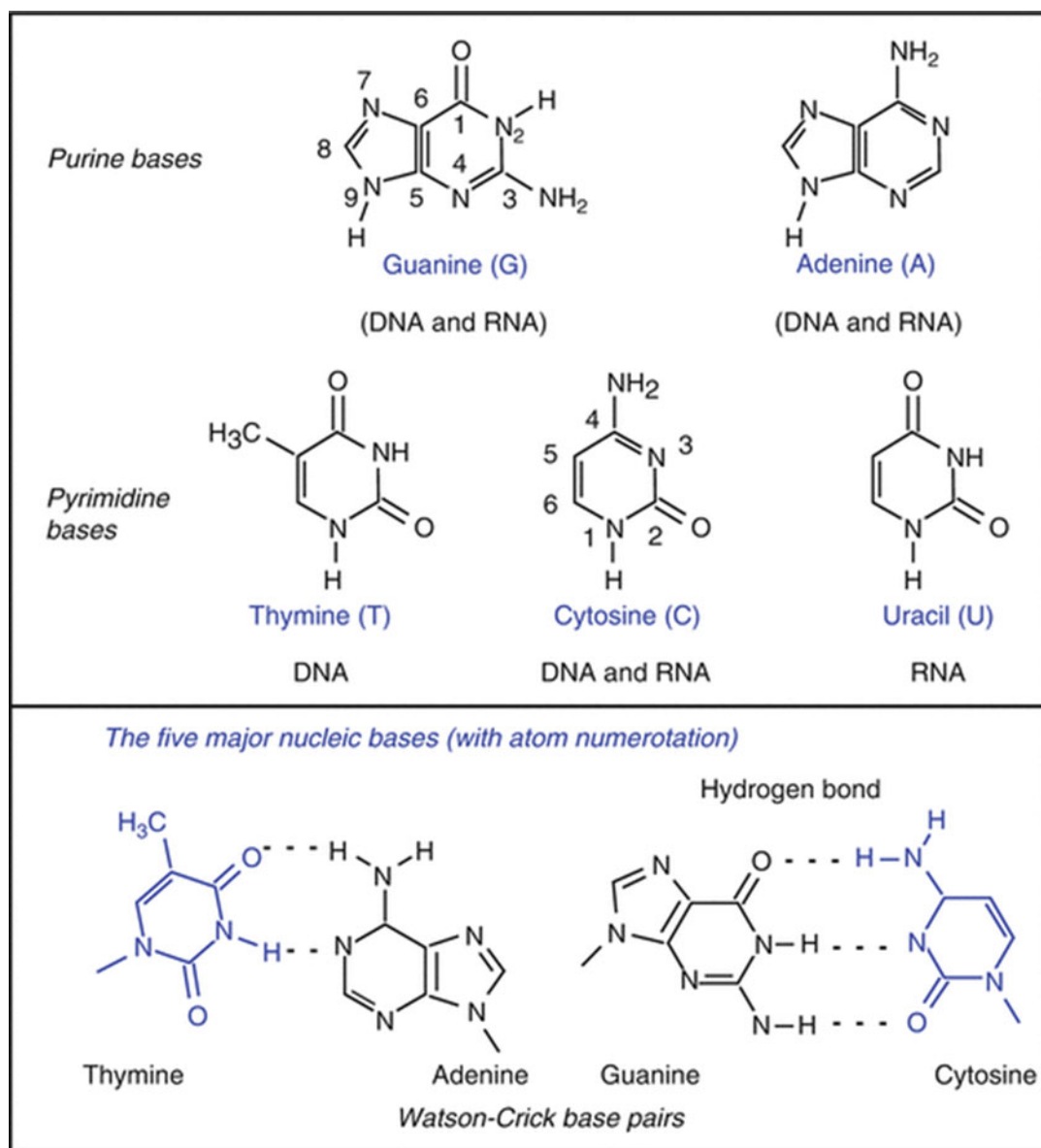
Methylmercaptan
(methanethiol)



Water
(hydrogen oxide)



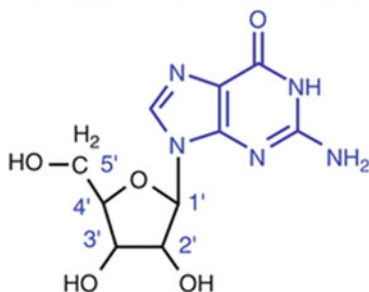
Nucleic Bases



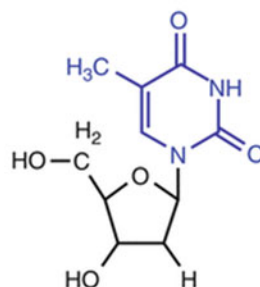
Nucleosides and Nucleotides

Nucleosides

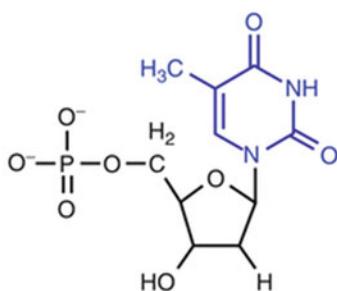
Adenosine, 2'-deoxyadenosine
Guanosine, 2'-deoxyguanosine
Thymidine, 2'-deoxythymidine
Uridine
2'-deoxythymidine



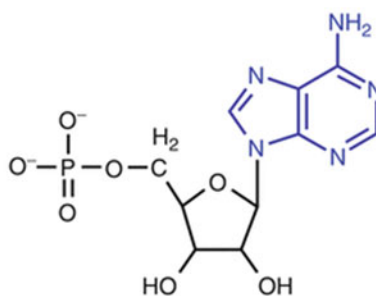
Guanosine
(RNA)



2'-deoxythymidine
(DNA)

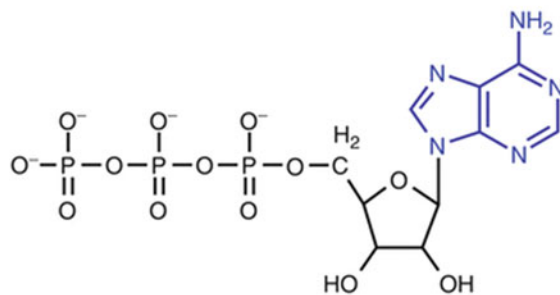


2'-deoxythymidine-5'-monophosphate
(DNA)



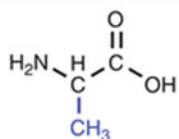
Adenosine-5'-monophosphate (AMP)
(RNA)

Some nucleotides

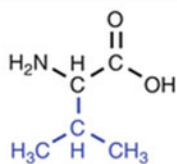


Adenosine-5'-triphosphate (ATP)

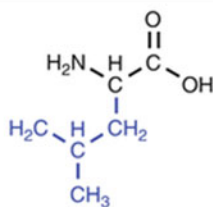
Genetically Encoded Amino Acids



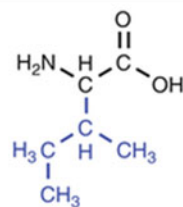
Alanine (Ala, A)



Valine (Val, V)

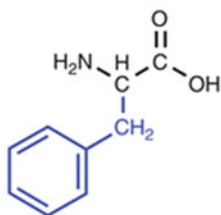


Leucine (Leu, L)

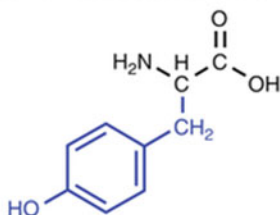


Isoleucine (Ile, I)

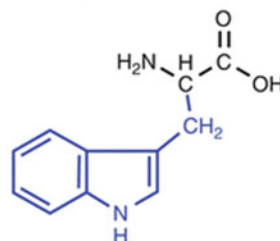
Hydrophobic aliphatic amino acids



Phenylalanine (Phe, F)

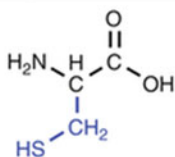


Tyrosine (Tyr, Y)

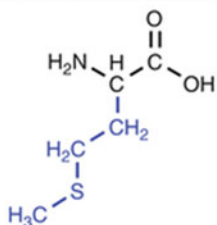


Tryptophan (Trp, W)

Aromatic amino acids

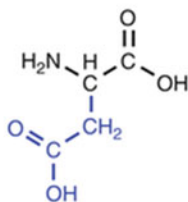


Cysteine (Cys, C)

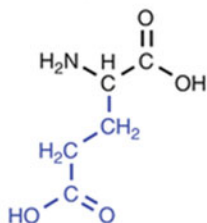


Methionine (Met, M)

Sulfur containing amino acids



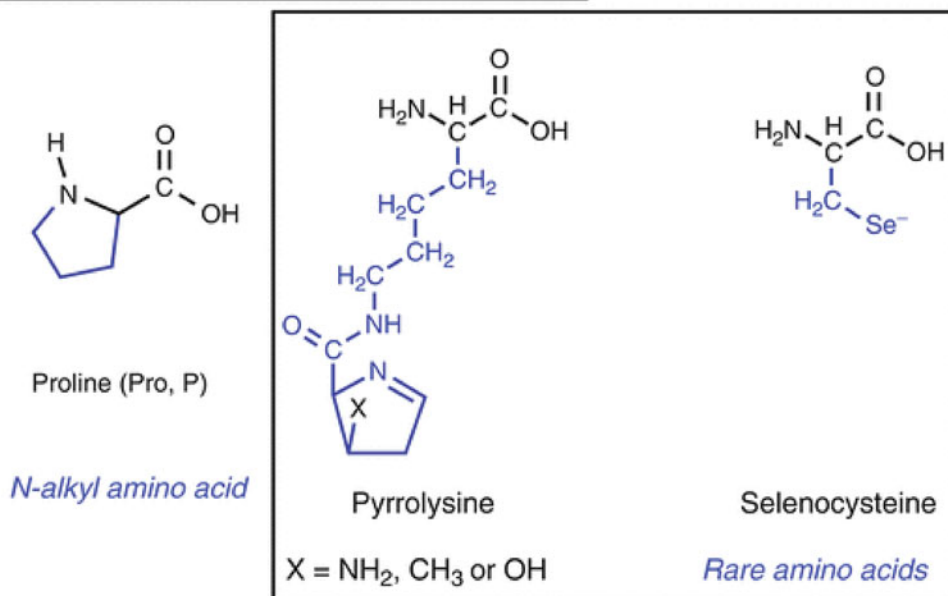
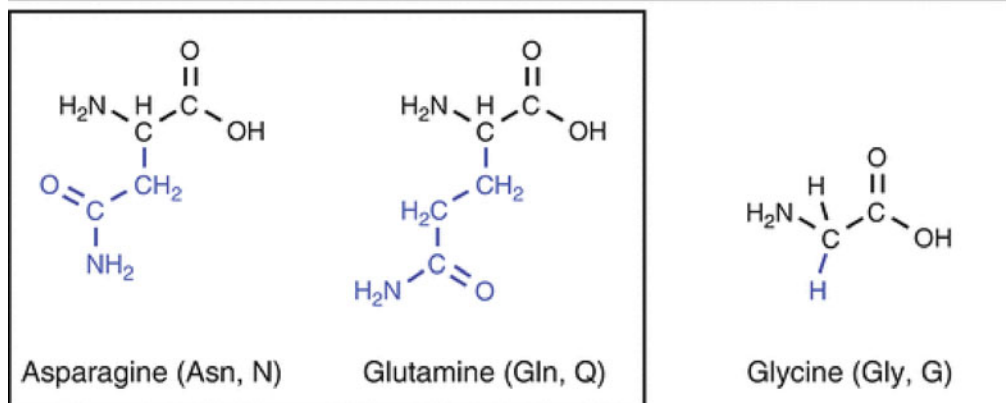
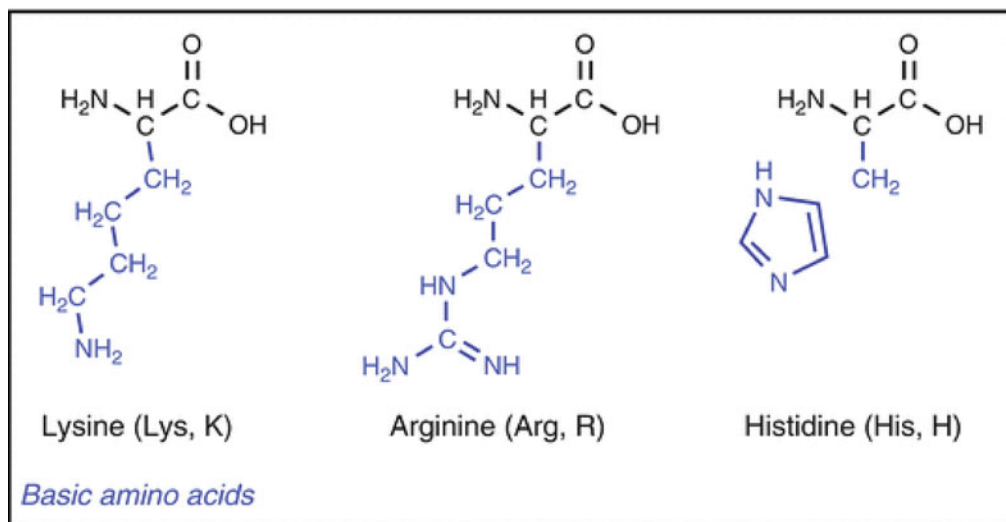
Aspartic acid (Asp, D)



Glutamic acid (Glu, E)

Acidic amino acids

Limits of Life



Parameter	Limit	Microorganism	Note
Lower temperature	−12 °C	<i>Psychromonas ingrahamii</i>	Breeze J, Cady N, Staley JT (2004) Subfreezing growth of the sea ice bacterium <i>Psychromonas ingrahamii</i> . Micro Ecol 47:300–304
Upper temperature	122 °C <i>Methanopyrus kandleri</i>	<i>Methanopyrus kandleri</i>	Takai K, Nakamura K, Toki T, Tsunogai U, Miyazaki M, Miyazaki J, Hirayama H, Nakagawa S, Nunoura T, Horikoshi K (2008) Cell proliferation at 122 °C and isotopically heavy CH ₄ production by a hyperthermophilic methanogen under high-pressure cultivation. Proc Natl Acad Sci U S A 105(31):10949–10,954
	121 °C strain 121 (130 °C upto 2 h for survivability in the case of strain 121)	Strain 121	Kashefi K, Lovley DR (2003) Extending the upper temperature limit for life. Science 301: 934
Lower pH	pH 0	<i>Picrophilus torridus</i> , thrives at 65 °C	Schleper C, Puehler G, Holz I, Gambacorta A, Janekovic D, Santarius U, Klenk HP, Zillig W (1995) <i>Picrophilus</i> gen. Nov., fam. Nov.: a novel aerobic, heterotrophic, thermoacidophilic genus and family comprising archaea capable of growth around pH 0. J Bacteriol 177(24):7050–7059
Upper pH	pH 11–12	<i>Bacillus firmus</i> OF4, <i>Nitrosomonas halophila</i> ANs 5	Sorokin D. Yu., Tourova TP, Schmid M, Wagner M, Koops H-P, Kuenen JG, Jetten M (2001) Isolation and properties of obligately chemolithoautotrophic and extremely alkali-tolerant ammonia-oxidizing bacteria from Mongolian soda lakes. Arch Microbiol 176:170–177 Sturr MG, Guffanti AA, Krulwich TA (1994) Growth and bioenergetics of alkaliphilic <i>Bacillus firmus</i> OF4 in continuous culture at high pH. J Bacteriol 176:3111–3116
Salinity	Saturated NaCl	Depends on the salt	Dead Sea and mono lake microbiology DasSarma S, Arora P (2006) Halophiles. In: Encyclopedia of life sciences. Wiley
Radiation	5000 Gy (no loss of viability) to 15,000 Gy (37% viability)	<i>Deinococcus radiodurans</i>	Moseley BEB, Mattingly A (1971) Repair of irradiated transforming deoxyribonucleic acid in wild type and a radiation-sensitive mutant of <i>Micrococcus radiodurans</i> . J Bacteriol 105: 976–983
Water activity	0.61	Filamentous fungi and yeasts	Grant WD (2004) Life at low water activity. Philos Trans R Soc Lond B Biol Sci 359(1448):1249–1267
	0.75	Bacteria	
Pressure	Mariana trench in the western Pacific Ocean: 11 km below sea level	Prokaryotes	Deepest point on earth Kato C (1999) Barophiles (Piezophiles). In: Horikoshi K, Tsujii K (eds) Extremophiles in deep-sea environments. Springer, Tokyo, pp. 91–111

Chronological History of Life on Earth

Muriel Gargaud¹, Francis Albarède²,
Nicholas Arndt³, Carlos Briones⁴,
Henderson James Cleaves II^{5,6,7},
Matthieu Gounelle⁸, Emmanuelle J. Javaux⁹, Daniele L. Pinti¹⁰
and Sean N. Raymond¹¹

¹Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, Pessac, France

²Ecole Normale Supérieure de Lyon, Lyon, France

³ISterre, Université Grenoble Alpes, Grenoble, France

⁴Centro de Astrobiología (CSIC/INTA), Consejo Superior de Investigaciones Científicas, Madrid, Spain

⁵Earth–Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan

⁶Blue Marble Space Institute of Science, Washington, DC, USA

⁷Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA, USA

⁸Laboratoire de Minéralogie et Cosmochimie du Muséum (LMCM) MNHN USM 0205 - CNRS UMR 7202, Muséum National d'Histoire Naturelle, Paris, France

⁹Early Life Traces & Evolution-Astrobiology, UR Astrobiology, Université de Liège, Liège, Belgium

¹⁰Geotop, Research Center for dynamics of the Earth system, Université du Québec à Montréal, Montréal, QC, Canada

¹¹Laboratoire d'Astrophysique de Bordeaux, CNRS, Université de Bordeaux, Floirac, France

The following 22 pages form a table and should be read even page numbers on the left and odd page numbers on the right.

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Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
PROTEROZOIC	Later evolution of Earth and Life (2.2 - 0.54 Ga)	542–520 Ma				Large morphological diversification of metazoans (pluricellular Eukaryotes)	
		542 Ma				First major biological crisis among Eukaryotes	Extinction of soft body fauna
		555 Ma				First mineralized animal	Several calcified macroscopic metazoans (Cloudina, Namacalathus,...)
		580–542 Ma				Ediacara fauna, first large and complex organisms, first calcified organisms around 550 Ma	Bloom of soft body fauna after last glaciation event
		580 Ma				Gaskiers glaciation	Glaciation is probably less intense?
		599–584 Ma				Doushantuo fossils	Phosphatized animal embryos, florideophytes red algae
		635–600 Ma				Marinoan glaciation	Snowball Earth probably triggered by an increase of bioproductivity and atmospheric O ₂ and the consequent decrease of atmospheric CH ₄ and CO ₂
		640 Ma				First traces of the Ediacara-type fossils: Twitya discs; possible biomarkers of sponges or sponge ancestors	
		725–710 Ma				Sturtian glaciation	Snowball Earth probably triggered by an increase of bioproductivity and atmospheric O ₂ and the consequent decrease of atmospheric CH ₄ and CO ₂
		750 Ma				1st testate amoebae	Population of various morphotypes of VSM (vase-shaped microfossils) preserved as pyritic or phosphatic molds
		780–620 Ma				Protist scales	Mineralized ornamented and perforated microscopic scales preserved in cherts
		1 Ga				Possible reptation traces made by large protists. First possible Vaucheriale (multicellular) algae	Exquisite preservation of diverse organic-walled microfossils (including protists and the multicellular vaucheriale algae) in the Lakhanda Fm, Siberia
		1.2–0.70 Ga				Supercontinent Rodinia formation then breakup	Evidence from paleomagnetic data, chemostratigraphy (carbon isotopes)
		1.2–0.75 Ga				1st multicellular eukaryotes: Bangiophyte red algae. Other multicellular algae, Cladophorale green algae and Vaucheriale algae, also occur in the 750 Ma shales in Spitsbergen and other localities	The 1st fossil eukaryote that can be related to an extant group

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
	Burgess Pass (Canada) and Chengjiang (china) fauna	Well-documented, many fossils	Numerous new species and animal body plans, including worms, arthropods, sponges	Burgess shale fauna; Chengjiang fauna; Eukarya; Evolution (biological); Biodiversity
	Disappearance of soft body organisms fossils			
	Nama Group, Namibia; and in other localities worldwide		Animal biomineralization	
	Traces and fossils of soft body organisms worldwide			Ediacara fauna; Ediacaran period
Stratigraphic ages estimated based on isotopic profiles ($^{13}\text{C}/^{12}\text{C}$ or $^{87}\text{Sr}/^{86}\text{Sr}$)	Accumulation of glacial sediments		Environmental stress, with possible evolutionary consequences (extinctions, radiations)?	Glaciation
Radiometric ages	Preservation by phosphatization or as carbonaceous compressions		Diversification of red algae, first animal traces	
	Accumulation of glacial sediments		Environmental stress, with possible evolutionary consequences (extinctions, radiations)?	Snowball Earth; Glaciation
			Possibly first animal record	Ediacara fauna; Ediacaran period
	Accumulation of glacial sediments		Environmental stress, with possible evolutionary consequences (extinctions, radiations)?	Glaciation
Radiometric datings	Chuar Group, Arizona; and other localities	Diverse localities; population of diverse morphology of protists with a test related to filose and lobose amoebae	Appearance of supergroup Amoebozoa; direct evidence for heterotroph eukaryotes, possible protist biomineralization	
	Tindir Group, northwest Canada		Protist biomineralization	
			Appearance of supergroup Heterokonts	
			Impact on ocean chemistry and circulation, may affect evolution of life	Rodinia
Age not well constrained but most probably 1–1.2 Ga based on chemostratigraphy and lithostratigraphic correlation	Implies earlier origin of unicellular red algae	Single locality but occurrence as population, characteristic radial cellular division, presence of holdfast	Evidence for eukaryotic multicellularity, eukaryotic photosynthesis, sex, appearance of supergroup Plantae	Eukaryotes, origin and early evolution of

(continued)

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
PROTEROZOIC	Later evolution of Earth and Life (2.2 - 0.54 Ga)	1.5 Ga				Eukaryotic microfossils	Population of smooth-walled, and ornamented acritarchs; first spiny acritarchs (acanthomorphs)
		1.80–1.65 Ga				Eukaryotic microfossils	Population of smooth-walled and ornamented acritarchs
		1.8 Ga				Deep ocean still anoxic	Deep ocean may have remained anoxic until 0.6 Ga
		1.9 Ga				Possible iron bacteria and other microorganisms	Complex microbial communities at interface between oxygenated and ferruginous waters, in stromatolitic and non-stromatolitic cherts
		2.1 Ga				Oldest non-stromatolitic microfossils	Pyritized complex form of probable multicellular colonies of macroscopic size in oxygenated marine waters
		2.15–2.1 Ga				Cyanobacteria (confirmed)	Indisputable microfossils (colonies, akinetes) of photosynthetic aerobic organism (cyanobacteria)
	Towards oxygenation of the atmosphere (2.5 to 2.2 Ga)	2.2 Ga				Increase of atmospheric O ₂	After 2.2 Ga, the O ₂ level remains above 1% PAL
		2.2 Ga				Major glaciation event recorded in the Transvaal Supergroup of South Africa, considered as the first Snowball Earth	Probably triggered by a rise of O ₂ and consequent decrease of atmospheric methane
		2.25–2.05 Ga				Increase of bioproductivity	Oxygenic photosynthesis becomes a major biochemical process
		2.32 Ga				First evidence for atmospheric oxygen	pO ₂ < 10 ⁻⁵ PAL before 2.32 Ga, and > 10 ⁻⁵ after
		2.45–2.22 Ga				2.5–2.2 Ga, three episodes of glaciations in the Huronian Supergroup of Canada	

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
Radiometric datings	Microfossils from the 1500 Ma Roper Group, northern Australia		Evolution of eukaryotic nucleus and cytoskeleton	Acritarchs
Radiometric datings	Large spheromorphs with medial split opening structures (cyst opening) and one ornamented spheromorph with concentric striations, in shales from China, Australia		Unicellular Eukaryotes	Eukaryotes, origin and early evolution of; Acritarchs
	Last Banded Iron Formation (BIF)			Banded Iron Formation
	Gunflint formation, Ontario, Canada; and other worldwide localities	Widespread record	Abundant filamentous and coccoidal microfossils, but also unusual morphologies	Gunflint microbiota; Gunflint Formation
Radiometric datings	Franceville group, Gabon		Biological affinities unknown	
Radiometric datings	Belcher group, Canada (2.15 Ga); Franceville group, Gabon (2.1 Ga)		Oxygenic Photosynthesis	Cyanobacteria
	Paleosols			
	Diamictite deposits			
	Worldwide excursion of $\delta_{13}\text{C}$			Photosynthesis
	Transition from mass-independent to normal mass dependent fractionation of S isotopes (implies an O_3 layer)	The corresponding O_2 level is inferred from a photochemical model of the atmosphere (Pavlov and Kasting 2002)		Oxygenation of the Earth's atmosphere
Radiometric age of the crosscutting Nipissing mafic dyke	Diamictite deposits		-Separates oceans. -When deglaciation occurs large amounts of nutrients appear -Might be one reason for the progress of photosynthesis (very hypothetical)?	Glaciation

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
ARCHEAN	Emergence of life and its context (3.8 - 2.5 Ga)	2.5 Ga				Biochemical indicator of Cyanobacteria and eukaryotes	
		2.7 Ga				"Golden Age" of methanotrophs	
		2.7 Ga				Unambiguous presence of life	
		2.7 Ga				Major episode of crustal growth. Formation of a super-continent	Huge volumes of juvenile continental crust were generated. This period (2.7–2.5 Ga) is also the moment when Earth dynamics changed from archaic to modern (similar to today's dynamics)
		2.7 Ga				Disputed evidence for cyanobacteria, eukaryotes and local availability of O ₂	
		2.8–2.7 Ga				Possible oxidizing event	No trace of atmospheric O ₂ , though
		2.9 Ga				First evidence of glaciation in the form of diamictite deposits in the Pongola Supergroup of South Africa	
		3.2 Ga				First cellular organic-walled microfossils	Biogenicity, endogenicity and syngenicity of microfossils are evidenced but their biological affinity is unknown
		3.2 Ga				First evidence of microbial mats in terrigenous sediments	Microbial mats occur in the intertidal photic zone so could be photosynthesizers but their biological affinity is unknown

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
	Occurrence of 2-methylhopanoids and steranes in rocks and in fluid inclusions and filamentous microfossil resembling cyanobacteria		Possible existence of cyanobacteria and oxygenic photosynthesis, and eukaryotes	Cyanobacteria
	Very negative values of $\delta^{13}\text{C}$ in sediments, comparable to those produced by methanotrophic organisms		If true, methanotrophy and methanogenesis had already evolved	Archean traces of life
	Well described macrofossils (fossil stromatolites), microfossils and molecular fossils	Wide consensus about their fiability	Occurrence of microbial communities covering extensive areas on the planet	Archean traces of life; Stromatolites
U-Pb zircon dating, Rb-Sr and Sm-Nd radiometric ages on whole rocks	Volumes of continental rocks of this age. Change in magma composition (end of komatiites and TTG), in tectonic style		From geological point of view, the Earth more or less behaved as the modern Earth	Crust
	Hopanes and steranes	Possible contamination – interpretation debated	Possible presence of O_2 producers and consumers and of eukaryotes, O_2 available locally	Cyanobacteria; Archean traces of life; Eukarya
	N and Fe isotopes	Requires more data and a general interpretation	Possible indication of oxygenic photosynthesis	Cyanobacteria
	Diamictite deposits			Glaciation
Radiometric age (U-Pb zircon dating) of intrusions below, through, and on top of the host rock	Up to 300 μm in diameter spheroidal organic-walled microfossils and negative values of $\delta_{13}\text{C}$ compatible with a biological origin, in shallow marine shales and siltstones of the Moodies Group, BGB South Africa		Possible planktonic life, large single cells or empty colonial envelopes	Barberton Greenstone Belt; Archean traces of life; Acritarchs
Radiometric age (U-Pb zircon dating) of intrusions below, through, and on top of the host rock	Microbial mat structures and negative values of $\delta^{13}\text{C}$ compatible with a biological origin, in intertidal sandstone of the Moodies Group, BGB South Africa		Widespread possibly photosynthetic microbial mats along siliciclastic shorelines	Barberton Greenstone Belt; Archean traces of life

(continued)

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
ARCHEAN	Emergence of life and its context (3.8 - 2.5 Ga)	3.2 Ga				Possible prokaryotic filaments in hydrothermal deposits	Curved morphologies, exhibit putative biological behavior including preferred orientations, clustering and intertwining in rocks is interpreted as evidence for biological origin
		3.446 Ga				Possible microbial mats	
		3.46 Ga				First undisputable evidence of emerged continent	
		ca. 3.5 Ga				Potential occurrence of the oldest life traces	
		ca. 3.5 Ga				Ocean temperature of ~70 °C	
		3.7 Ga				Possible local oxidizing conditions associated with oxygenic photosynthesis	

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
Radiometric age (U-Pb zircon dating)	Filamentous microstructures replaced by pyrite in deep sea, volcanogenic, massive sulfides deposits in Australia	Await supporting lines of geochemical evidence	Possibly documenting thermophilic, chemotrophic prokaryotes in hydrothermal vents	Archean traces of life; Microbial mat
	Silicified mat structures including carbonaceous material with isotopic fractionation of carbon and sulfur compatible with life, in Pilbarra, Australia		Possibly indicating the presence of a variety of organisms including photosynthesizers (pelagic as well as sessile), heterotrophs, and chemotrophs	Barberton Greenstone Belt; Microbial mat
U-Pb radiochronology (on zircons)	Detrital sediments lying unconformably over an eroded basement	The clastic sediments deposited in Barberton belt (South Africa) as well as before (3.872 Ga) in the Isua belt (Greenland) probably originated from an emerged continent	Emersion of continents can favor the transfer of chemical elements and nutrients from continental crust to ocean. Ocean/continent interface is propice to the development of new habitable niches (pools, lakes...)	Continents
	(1) Possible fossil stromatolites (macroscopic) (2) Presence, although highly discussed, of morphological microfossils (3) Isotopic measurements and chemical analyses of kerogen in Archaean rocks (Pilbara craton and Barberton Greenstone Belt)	Putative microfossils are highly controversial; biogenicity of stromatolites is debated	Life and perhaps autotrophic organisms might have existed already	Archean traces of life; Stromatolites
	^{18}O and ^{30}Si fractionation are consistent with a hot Archean ocean	Debated, measures were done on chert such that they could reflect the temperature of hydrothermal system and not of the whole ocean	If true, hot water would favor thermophile-type forms of life	Precambrian oceans, temperature of
	C isotopes	Debated	Possible indication of oxygenic photosynthesis	Archean traces of life

(continued)

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
ARCHEAN	Emergence of life and its context (3.8 - 2.5 Ga)	3.75 Ga				Possible first evidence of hydrothermal or marine water	
		ca. 3.8–2.5 Ga		From the last common ancestor to the diversification of bacterial and archaeal lineages	Not known	Diversification of energy and carbon metabolisms simultaneously to that of prokaryotic groups	The relative order of emergence of the different metabolic pathways and the time required for their evolution is unknown. This process led to many different prokaryotic (archaeal and bacterial) lineages with specific and/or versatile metabolic capabilities
		ca. 3.8 Ga				Potential occurrence of the oldest traces of life	Life, and particularly, autotrophic organisms are present
		ca. 3.8 Ga				Potential evidence of a suprasubduction ophiolite	

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
Radiometric age on the host rock	Fluid (water) inclusions in quartz globules in pillow basalts (assumed to represent oceanic floor) from Isua (Greenland)	Isotopic water composition may have been modified by metamorphism or by reaction with basalt	Liquid water: offers the possibility to analyze early water composition (high salinity)	Precambrian oceans, temperature of
	Based on different evolutionary scenarios, eventually supported by a few isotopic observations, inferred from the contemporary diversity of prokaryotes and their metabolisms			Archea; Bacteria; Evolution (biological); Last Universal Common Ancestor; Phylogeny; Metabolism
	Negative values of $\delta^{13}\text{C}$, comparable to those generated, today, by autotrophic organisms (either photosynthesizers or chemoautotrophs), detected in 3.8 Ga West Greenland sedimentary rocks	Highly controversial	Autotrophic organisms would have had to evolved earlier	Archean traces of life; Isua Supracrustal Belt; Akilia
	Existence of almost all components of an ophiolite: ultramafic rocks, gabbros, dyke complex, pillow lavas	Debated	Existence of modern-like plate tectonics	Precambrian oceans, temperature of

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
HADEAN ← ARCHEAN → PROTEROZOIC	Prebiotic chemistry, biochemistry and emergence of life (4.4 - 2 Ga)			From the emergence of the first life form to the diversification of the different domains of life	Not known	Series of very important events, but their chronology (absolute and relative) remains totally unknown	Membranes: No data are available for the appearance of the first membranes. The class of amphipathic molecules that were involved (fatty acids, terpenoids, peptides or other compounds) is unknown
							Genetic information and translation: coupling of metabolism (energy, organic matter) and the genetic system (information). Emergence of the genetic code (and then of coded proteins and enzymes). Last common ancestor Origin of viruses (polyphyletic origin). Transition from RNA to DNA
							Metabolisms: the sequence through which energetic metabolisms and carbon metabolic pathways developed is unknown. Anaerobic metabolisms: fermentation, anaerobic respiration, anoxygenic phototrophy

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
None		No information is available about the appearance of the cytoplasmic membrane	The cytoplasmic membrane may have been present either at early stages for a life form based on the compartmentalization of a protometabolism or may have been developed later in evolution if a mineral surface ensured a reduced number of degrees of freedom or if encapsulation was not absolutely needed (e.g., RNA world)	Cell; Cell Model; Origin of life; Life; Oparin's Conception of the Origin of Life
		The problem of the first genetic system is still unsolved	First genetic system: <i>Hypothesis1</i> : stage in which RNA played both the roles of information carrier and coded catalyst (RNA world) but there is no available abiotic synthesis of nucleotides and RNA. <i>Hypothesis2</i> : Stage preceding the RNA world (pre-RNA world) based on earlier information carriers that left no traces during further evolution (no indication available). <i>Hypothesis3</i> : coevolution process involving amino acid and nucleotide chemistries and leading directly to the emergence of the translation machinery	RNA World; Nucleic acids; Genetic code; DNA; Virus; Last Universal Common Ancestor; Evolution (biological); RNA; Protein; Genome; Ribosome; Replication (genetics)
		The initial energetic metabolisms proposed are model-dependent. There is no consensus and no certainty about the nature of the oldest metabolic pathways (three of four pathways for carbon fixation have been suggested)	Production of energy: most energy metabolisms of early living beings possibly emerged and diversified very rapidly and simultaneously. Anoxygenic photosynthesis may have preceded oxygenic photosynthesis. Possible initial energetic metabolisms: if life emerged from a prebiotic soup (heterotrophic and cold origin), then fermentation likely came first. If life emerged in hydrothermal systems (autotrophic and hot origin) then, it may have been based on oxidoreduction processes. Development of carbon metabolism	Bioenergetics; Metabolism

(continued)

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
HADEAN ← ARCHEAN — PROTEROZOIC →	Prebiotic chemistry, biochemistry and emergence of life (4.4 - 2 Ga)	4.4–3.8 Ga or later		After the formation of the atmosphere and oceans and after the cessation of deleterious processes such as (irradiation, bombardments, excessive temperature. . .) – before the emergence of the first life form	Unknown	Series of very important events, but whose chronology (absolute and even, to some extent, relative) remains unknown	Chemical evolution. Formation of complex assemblies of molecules [covalently-bound polymers (peptides, polysaccharides, oligonucleotides or analogues) and/or non-covalently-bound structures (liposomes, vesicles, etc.)] from available species and energy and/or emergence of protometabolisms possibly involving the activity of mineral surfaces but needing a confined environment
							Prebiotic chemistry. Chemical synthesis starting from organogenic molecules and/or energy-releasing molecules and/or energy sources. Depending on the model, reactions occurring in solution or after adsorption and/or concentration on inorganic surfaces or in inorganic microcavities. Availability of a varied set of organic molecules and of biomonomers (“prebiotic soup”): amino acids, sugars, nucleic bases, nucleosides, polyphosphates, etc.
							Supply of organic molecules and energy. Synthesis in the atmosphere (perhaps in a reducing one) of low-molecular-weight organogenic molecules (H ₂ CO, CO, NH ₃ , H ₂ S, HNCO, HCN, etc.) and/or exogenous delivery (infall of meteorites, comets) and/or generation of organic molecules during hydrothermal activity or through reactions on clay mineral surfaces

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
None	The presented stages correspond to more or less plausible scenarios based on the present knowledge of the primitive Earth and on what is known about chemical reactivity in such environments		The increase of complexity may have involved different stages following one another in sequence or resulted from an emergence process without clearly delimited steps. Anyway, a crucial phase led to a self-sustained entity carrying both a metabolism and the information content needed for its self-reproduction at the initial stage of Darwinian evolution	Complexity; Self-replication; Self assembly; Polymer; Lipid bilayer
			Depending on the family of compounds, more or less plausible chemical pathways are available for the formation of amino acids, sugars and nucleic bases. There abiotic synthesis of nucleotides remains somewhat problematic	Formaldehyde; Formose reaction; Ammonia; Amino Acid; Ocean, chemical evolution of; Earth atmosphere, origin and evolution of; Oceans, origin of; Precambrian oceans, temperature of; Earth, formation and early evolution; Earth, surface evolution; Amphiphile; Nucleic acid base; Chirality
				Late heavy bombardment; Extraterrestrial delivery (organic compounds); Meteorites; Comets; Abiotic photosynthesis; Photochemistry; Electric discharge; Photochemistry, atmospheric; Fischer-Tropsch Type Reaction; Hydrothermal reaction; Hydrothermal environments

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
ARCHEAN HADEAN	Building of a habitable planet (4.55 - 3.8 Ga)	3.817 Ga	± 0.016 Ga			First post LHB (Late Heavy Bombardment) rocks; Important episode of crustal growth (at least in Canada and Greenland)	The existence of sedimentary rocks imply the existence of liquid water (ocean) and of continents. At Isua, clastic sediments are interpreted as evidence of emerged continents. First huge continent (Super-continent?) existed. A modern-like global geological and probably geodynamic system already in place
		3.863 Ga	± 0.012 Ga				
		3.872 Ga	± 0.010 Ga				
		3.9–3.8 Ga				End of LHB (Late Heavy Bombardment)	
		4.031 Ga	± 0.003 Ga			The oldest known rock (it survived the Late Heavy Bombardment)	This continental crust is TTG ("granitic") in composition
		4.1 to 3.9–3.8 Ga			< 200 Ma at most, > 20 Ma at least	"Late Heavy Bombardment" (LHB)	Intense bombardment episode on the Moon. This phenomenon, observable on the Moon is considered has having also taken place on Earth
		4.2 Ga				Putative oldest Hadean continental crust in Canada	
		4.4–4.0 Ga				Genesis of huge volumes of continental crust (at 4.0 Ga about 15% of the present day continental crust volume was formed)	A recycling process of continental crust existed
				$T_0 + (100\text{--}150 \text{ Ma?})$		Late veneer (dusts, bolides) especially carbonaceous chondrites	Exogeneous supply of H, C, N, O, S, P
		4.4–4.37 Ga		$T_0 + 170 \text{ to } 200 \text{ Ma}$		First proto-oceans	

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
U–Pb radiochronology (on zircons), Rb–Sr and Sm–Nd radiometric ages on whole rocks	Zircon crystals extracted from Nuvvuagittuq (Purpose Cove) volcanics and whole rocks			Nuvvuagittuq (Porpoise Cove) Greenstone Belt
	Zircon crystals extracted from Uivak gneisses and whole rocks			
	Zircons. Ultramafic rocks, sediments, including clastic sediments (Akilia, Isua, Amitsoq); BIF (Akilia et Isua) Huge volumes of TTG (which implies a “granitic” continental crust)			Isua Supracrustal Belt
	Rocks contain marine fluid (water) (–3.8 Ga), age of the great lunar basins		Potential life can be envisaged	Isua Supracrustal Belt; Late Heavy Bombardment
U–Pb radiochronology (on zircons)	U–Pb ages on zircon crystals extracted from the rock. The Acasta gneisses are the oldest rocks discovered on Earth, they represent the oldest continental crust. One Acasta zircon gave an age as old as 4.065 ± 0.008 Ga		Acasta gneisses formed during the LHB and avoided total destruction. As some parts of continental crust escaped destruction during LHB, possibly, some pre-existing forms of life could also have survived	Acasta gneiss
U–Pb radiochronology (on lunar rocks)	Dating of lunar impact craters and their relative chronology. The model more widely accepted today considers that bombardment had a maximum at about 3.9 Ga		Planet re-surfacing, most existing structures were likely destroyed, including both oceans and continents	Late Heavy Bombardment
U–Pb radiochronology (on zircons)	Dating of inherited zircon cores in Acasta gneisses		At least some parts of the Hadean crust survived the LHB	Acasta gneiss; Late Heavy Bombardment
U–Pb radiochronology (on zircons)	U–Pb ages on Jack Hills and Narryer zircons; these crystals display zones of different ages indicating several episodes of crystallization at different epochs		Huge fragments of stable continental crust existed	Archean Eon; Earth, formation and early evolution
Models	Presence of volatile species (e.g., CO ₂ , H ₂ O) on Earth despite the very high temperature during the planet accretion phase		Biogenic elements available	Late Veneer; Water delivery to Earth; Earth atmosphere, origin and evolution of
	Based on the oxygen isotopic composition of zircons and on physical models for Earth formation		Huge volumes of liquid water	Oceans, origin of; Earth atmosphere, origin and evolution of

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Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
HADEAN	Building of a habitable planet (4.55 - 3.8 Ga)	4.404 Ga	± 12 Ma			Genesis of the first continental crust, "granitic" in composition	Free water (proto-ocean) is necessary on Earth surface. If $P = 270$ Atm, the temperature can be as high as 500 K. If $PCO_2 = 25$ Atm, temperature as low as 380 K.
				$T_0 + 10$ to 70 Ma		External supply of water	
				$T_0 + 100$ Ma		Atmosphere formation	
				$T_0 + 0.1$ Ga? or $T_0 + 2$ Ga?	Few 100 Ma	Accretion of the Earth magnetic field	
	The first 100 million years: The "Telluric Planet Formation" era			Roughly $T_0 + 30$ to $T_0 + 150$ Myr	Very fast: timescale of days	Formation of the Moon from a Mars-sized impactor, sometimes called Theia	The Moon-forming impact is thought to have been the last giant impact suffered by the Earth during its formation
					100–200 Myr	Magma ocean + core segregation	Differentiation inside the magmatic ocean, formation of a proto-crust
						Primitive atmosphere	
				$T_0 + 10$ to 100 Myr	10–100 Myr	Formation of the Earth by collisional accumulation of planetary embryos and planetesimals	This is dated by $^{182}\text{Hf}/^{182}\text{W}$ radiochronology (half-life of 9 Myr), which roughly measures the time of the last core-forming episode, i.e., differentiation. This is thought to have been caused by the Moon-forming impact – the impactor is sometimes called "Theia"
				$T_0 + 10$ to 10 Myr		Formation of Mars	Differentiation of the planet (+magmatic ocean?)

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
U–Pb radiochronology (on zircons)	Core of zircon crystals from Jack Hills: they represent the oldest known terrestrial materials. The measured age is the age of the minerals (the host rock is unknown). Zircons crystals contain inclusions of minerals abundant in granites (quartz, feldspar and mica). Oxygen isotopes determined in these zircons give high $\delta^{18}\text{O}$		Emersion of the first continental masses. The amount of available liquid water could have been either small and very localized or generalized (ocean)	Cool Early Earth; Oceans origin of; Jack Hills; Earth, formation and early evolution
				Water, delivery to Earth
Radiochronology, Solar System dynamic models	Xe isotopes in atmosphere and mantle			Noble gases; Earth atmosphere, origin and evolution of
Theoretical models			Partly protects Earth surface from ionizing particles (cosmic rays) Able to indirectly favor or to disfavor some chemical reactions	
^{182}Hf – ^{182}W radiochronology	Cf. Earth's formation		Many possible (but disputed) influences of the Moon on the life evolution	Moon
^{146}Sm – ^{142}Nd and Pu–Xe radiochronology	The rocks of Isua (3.8 Ga) have recorded an early fractionation of ^{142}Nd , explainable by a magmatic ocean			Magma ocean
Theoretical models	None	Hypotheses		Atmosphere, primitive envelope
^{182}Hf – ^{182}W radiochronology	(1) Last metal silicate equilibrium on Earth registered at 30 Ma (^{182}Hf – ^{182}W ; uncertainty range 11–50 Ma); this might correspond to the Theia impact (2) Age of 45 Ma for lunar crustal differentiation (3) N-body models of telluric planet formation from planetary embryos		Core formation may have allowed Earth's magnetic field to arise, limiting the flux of potentially damaging high-energy particles on the surface. In addition, the Moon stabilizes the Earth's obliquity (although only after causing the Earth's spin period to increase to more than ~10 h).	Planetary embryos; Planetesimals; Late-stage accretion
	Isotopic analyses of meteorites originating from Mars		The differentiation is a major heat source. It influences the planetary structure, the cooling and the surface temperature. Later crust composition and volcanism	Mars

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Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
HADEAN	The first 10 Ma: The “Protoplanetary Disk” Era			T_0 + a few (3–10) million years	100,000 to a few million years (timescale for gas dispersal)	Disappearance of first generation accretion disks (i.e., gaseous disks). For solar-like stars, start of the diskless, “post-T Tauri” phase	The gas lifetime sets an upper limit on the formation timescales of gas giant planets. Age of oldest disks ~10 Myr
				T_0 + 1 to +10 Myr	Few million years	Likely formation of Giant Planets (for the Sun: Jupiter and Saturn, perhaps also Neptune)	The formation of giant planets takes place either from a core or from a gravitational instability in the disk. In the first case, the formation of the core itself starts from planetesimals, according to a process similar to (but faster than) telluric planets, and in parallel with them
				From T_0 until the dust disappears	5 Myr	Formation of km-sized “planetesimals” and ~Moon-sized “planetary embryos”	Recent models suggest that the gas in the disk helps to form planetesimals by concentrating mm- to m-sized objects into gravitationally-bound aggregates. Planetary embryos form planetesimals, and constitute the true building blocks of terrestrial planets and giant planet cores
		4.568–4.567 Gyr	±0.5 Myr	T_0	5 Myr	Formation of the first solids in the solar system (Chondrules, CAIs, some differentiated meteorites...)	CAIs (Calcium-Aluminum inclusions) are considered to be the oldest solids. In CV chondrites, they formed in less than 50,000 years. Most chondrules are 1.5 Myr younger than CAIs, though some formed within 0.5 Myr. The first differentiated bodies may have formed during this disk phase, contemporaneously with CAIs. This phase lasted ~5 Myr

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
Statistical models and observations	Direct observations of circumstellar disks around young stars are made at infrared to far-infrared wavelengths (dust), and submillimeter to mm wavelengths (cold molecular gas). Disks can also be seen in silhouette in case of a luminous background (e.g., in a bright nebula like Orion)	Circumstellar disks are spatially resolved for solar-like stars closer than $\sim 1,500$ light-years (sizes up to 500 AU), but structures smaller than ~ 10 AU cannot be distinguished yet	Stops the accretion of hydrogen in giant planets (hence: puts a limit on their mass, influences their composition, and probably the size and composition of their satellites; stops some planetary migration processes)	Protoplanetary disk; Solar nebula
Numerical models			The formation of a giant planet had a major influence on the dynamics of planetesimals, on the formation of terrestrial planets (probably), on the delivery of water, and on the “late heavy bombardment” (LHB) event	Core accretion model; Gravitational instability
Numerical methods and radiochronology based on Pb–Pb, ^{26}Al , ^{182}Hf and ^{53}Mn	Pb–Pb age of chondrules and differentiated meteorites – age of disks, and radioactive dating of iron meteorites (originating from large differentiated bodies)	Timescales and size scales in models are uncertain to 1–2 orders of magnitude but the mechanisms of planetesimal and embryo formation appear robust	The fundamental building blocks of terrestrial planets and giant planet cores. The formation time of these objects also affects their compositions: the faster they form, the more efficiently short-lived radionuclides heat them up and the less volatiles they retain	Planetesimals; Planetary embryos; Gravitational collapse; CAIs; Cosmochemistry
Radiochronology based on Pb–Pb, ^{26}Al , ^{182}Hf and ^{53}Mn	It is an assumption that CAIs age define the start of the Solar System. Some iron meteorites originating from the cores of differentiated asteroids are contemporaneous or older than CAIs according to their respective Hf–W systematics.	The individual age of CAIs is often known with a precision better than 0.5 Myr. There is however a spread in CAIs age. Because the origin of the spread is not known (analytical artifact, secondary events. . .) it is doubtful to assign a precise T_0 .	Beginning of the planet formation process, a necessary (but not sufficient!) condition for life to appear	Protoplanetary disk; Solar nebula; CAIs; Cosmochemistry

Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
				T_0 = conventional zero of the second time period = age in the case of the solar system		At T_0 , oldest dated solids formed in the solar protoplanetary disk	For the Solar System, T_0 probably took place at a time between the beginning of class 0 and the end of class I
The first million years: The "Star Formation" Era					$T_0^* + 1$ to 10 Myr	T-Tauri star: Phase 2	"Class III": end of Phase 2, disappearance of disks. This suggests a fast disk evolution between Class II and Class III. Disks disappear between 3 and 5 Myr. The reasons may be multiple: planetary formation is the leading explanation, but other phenomena like evaporation due to stellar UV and X radiation may also play an important role
				$T_0^* + 0.1$ Myr	From 1 to 10 Myr	T-Tauri star: Phase 1	"Class II": Last stages of star formation. Structured gas and dust disk (outer "flaring", i.e., thickness increasing with distance from the central star, etc.); low accretion rate ($<10^{-7}$ solar mass/year)
				$T_0^* + 0.01$ Myr	$\sim 100,000$ years	Protostar: Phase 2	"Class I" = progressive end of the strong accretion phase on the central object, which is already a (growing) star. Bipolar jet (fast ejection of gas, $v_{ej} \sim 200\text{--}400$ km/s) visible near the center, perpendicular to the dense circumstellar disk

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
				Protoplanetary disk; Solar nebula; CAIs; Cosmochemistry
Physical models: Hertzsprung–Russell diagram and evolutionary tracks	Spectrum and magnitude of the central star leads (like during T-Tauri Phase 1) to ages and masses determinations from their position in the HRD. Circumstellar disks are studied in increasing detail; structures (rings, spiral arms...) can be seen, which allow to study properties of dust grains and their growth; gaps, maybe due to planet formation; migration of giant planets towards the central star?	Possible reason for the evolution of circumstellar disks: planetary formation. Still poorly understood and subject of active research		T Tauri star; Debris disks; Activity (magnetic); Magnetic field; Sun (and young sun); X-rays (stellar)
Physical models: Hertzsprung–Russell diagram and evolutionary tracks	Spectrum and magnitude of the central star (now optically visible): The star can be placed on a Hertzsprung–Russell diagram (HRD), which allows to determine its age and mass from theoretical models; a few binary systems allow a fairly precise mass determination to test the models (using Kepler's laws). For 1 solar mass, at this stage the star is about 1 Myr old. Circumstellar disks are visible at all wavelengths; a collimated jet is also visible (on theoretical grounds, there is a causal relation accretion => jet, mediated by magnetic fields); Lifetime ~1 Myr (independent from the HRD determination)	Stellar masses determined within a factor of 2; uncertainties on the age may be large, depending on the location in the HRD. For ages >1 Myr, uncertainties within factors 2–3; very uncertain below	Conditions for protoplanetary disk and planet formation	Chemistry in protoplanetary disks; Turbulence (planetary disks); Activity (magnetic); Magnetic field; Radio astronomy; Stellar evolution; T Tauri star; X-rays (stellar)
Statistical models: statistics on classes and dynamical age	Age of Class 0 and Class I sources (see below): the ratio is proportional to the ratio of their respective observed numbers. Jets: the ratio size/velocity gives an estimate of the timescale for star formation (~100,000 years for 1 month); these jets are produced as a result of accretion by magnetic interactions in the vicinity of the central object	Theory very uncertain: no explanation for the accretion rate. The disk viscosity (which is necessary for accretion on the central object to take place) may be due to the “magnetorotational instability” (leading theory, but other theories exist)		Birthline; Chemistry in protoplanetary disks; Infrared spectroscopy; Magnetic field; Radio astronomy; X-rays (stellar)

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Eon	Phase	Age (BP)	Error	Time	Duration	Event	Comments about these events
	The first million years: The “Star Formation” Era			T_0^*	~10,000 years	Protostar: Phase 1	“Class 0” = massive envelope in free fall; matter concentration at the center, “accretion” on this nucleus ($\sim 10^{-5}$ month/year) and growth of a protostellar object from a disk (because of rotation) made of gas and dust grains. The duration of the “dynamical collapse” phase depends on the mass of the star ($\sim 10,000$ years for ~ 1 solar mass)
	Start of the “Collapse Era”			T_0^* = conventional origin of the first time period		Astrophysical start of the formation of the Sun	Start of the collapse of a molecular cloud core. The triggering mechanism is still unclear, probably external and not unique (turbulence, shock waves from distant supernovae, etc.) Stars are most often formed in clusters of several 100–1,000 stars

Dating methods	Relevant observations	Reliability	Consequence for the origin of life and evolution	Referenced entries
Theoretical models: dynamical collapse (free fall)	Large-scale central “bipolar” molecular outflow, perpendicular to the disk, entrained by a stellar jet. Causes angular momentum dissipation and eventually collapse. The stellar jet itself is invisible optically, because buried into dense material, but becomes visible at Phase 2. Cold envelope (30–100 K): observable exclusively at (sub) millimeter wavelengths. Size of the envelope: 1,000–10,000 AU, depending on the interstellar environment (dense or diffuse)	Theoretical modelling and collapse velocity roughly estimated in several objects. “Class 0” objects are visible only at millimeter wavelengths	Conditions for star formation fulfilled	Interstellar medium; Interstellar turbulence; Magnetic field; Radio astronomy; Star formation: the observations
	1 Myr (astronomy) $\equiv$ 1 Ma (geology) = 10^6 years			